Galactic Origin of Relativistic Bosons and XENON1T Excess

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Abstract

We entertain the exotic possibility that dark matter (DM) decays or annihilations taking place in our galaxy may produce a flux of relativistic very weakly-coupled bosons, axions or dark photons. We show that there exist several upper bounds for this flux on Earth assuming generic minimal requirements for DM, such as a lifetime longer than the age of the Universe or an annihilation rate that leaves unaffected the background evolution during matter domination. These bounds do not depend on the identity or the couplings of the bosons. We then show that this new flux cannot be large enough to explain the recent XENON1T excess, while assuming that the bosons’ couplings to the Standard Model are consistent with all current experimental and observational constraints. We also discuss a possible caveat to these bounds and a route to explain the excess.

1 Introduction

The XENON collaboration recently reported results from searches for new physics using low-energy electronic recoil data with an exposure of 0.65 ton-years [1]. They observe an excess of 53 ± 15 events (a 3.5σ Poisson significance) over the known background in the energy bins between (1–7) keV with a peak between (2–3) keV. An intriguing explanation for the excess, proposed by ref. [1], is the solar axion model in which relativistic axions from the Sun with energy in the keV range are absorbed by the detector. Although experimental anomalies come and go, they motivate us to think about new theoretical ideas and experimental opportunities that might have been previously overlooked.

Broadly, there could be at least four possible routes to explain the XENON1T excess using new physics: a) absorption of relativistic bosons with keV scale energy such as solar axions (which has been a benchmark scenario for direct detection experiments [2–5]); b) scattering of relativistic particles with keV scale energy such as solar neutrinos with an enhanced magnetic moment [1,6] or with new interactions [7]; c) absorption of a non-relativistic dark matter (DM) particle with mass about (2–3) keV [1,8,9]; and d) scattering of non-relativistic fast-moving particles off electrons with a speed ∼ 25 times the escape speed of our galaxy [10, 11]. The XENON preprint suggests that the fit of a peak-like excess as predicted in scenario c) above is statistically less significant.1

In this article, we will focus on scenario a): absorption of relativistic bosons, ψ, either axions or dark photons, leading to an ionization signal in a direct detection experiment. One serious issue facing

1The preprint does not quote an explicit number, but only states that the global significance of scenario c) is less than 3σ. This may mainly be due to the fact that scenario c) is subject to a look-elsewhere effect while explanations of solar axion/neutrinos do not suffer from this effect since their energies are determined by the solar temperature, which is O(keV).
Solar axions cannot explain the XENON1T excess

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We argue that the interpretation in terms of solar axions of the recent XENON1T excess is not tenable when confronted with astrophysical observations of stellar evolution. We discuss the reasons why the emission of a flux of solar axions sufficiently intense to explain the anomalous data would radically alter the distribution of certain type of stars in the color-magnitude diagram in first place, and would also clash with a certain number of other astrophysical observables. Quantitatively, the significance of the discrepancy ranges from 3.3σ for the rate of period change of pulsating White Dwarfs, up to 19σ for the $R$-parameter, which measures the ratio of Horizontal Branch over Red Giant Branch stars in globular clusters.

I. INTRODUCTION

The XENON1T collaboration [1] has recently reported an excess in low-energy electronic recoil data below 7 keV, rising towards low energies with a prominent peak around 2-3 keV. The collaboration cautions that the excess could be explained by $\beta$ decays from a trace amount of tritium, representing an unaccounted source of background, but they also explore the possibility that the signal is due to different types of new physics. The most intriguing interpretation, which also provides the best fit to the data, is given in terms of solar axions, which is favoured over the background-only hypothesis at the 3.5σ level.

There are basically three production mechanisms that contribute to the total solar axion flux: i) Atomic recombination and deexcitation, Bremsstrahlung, and Compton (ABC) interactions [2] that are controlled by the axion-electron coupling $g_{ae}$. ii) the Primakoff conversion of photons to axions in the Sun [3] induced by an axion-photon coupling $g_{a\gamma}$, and iii) axion emission in the M1 nuclear transition of $^{57}$Fe induced by the axion-nucleon coupling $g_{aN}$ [4]. The last process produces mono-energetic 14.4 keV axions, while for i) and ii) axions are produced with a wide spectrum peaking around a few keV. The production mechanisms are independent from the axion rest mass for masses below 100 eV. As far as regards detection, electron recoils occur via the axioelectric effect which is controlled by the axion-electron coupling $g_{ae}$. Because of this, and because the location of the prominent peak around 2-3 keV corresponds roughly to the maximum of the energy spectrum of axions produced via the ABC processes, the Primakoff and $^{57}$Fe components are both allowed to be absent as long as there is a nonzero ABC component. This selects $g_{ae}$ as by far the most crucial coupling to attempt to explain the data in terms of the long-sought QCD axion [5–8].

Taken at face value the strength of the XENON1T excess requires $g_{ae} \gtrsim 10^{-12}$, which would hint to an axion decay constant $f_a \sim 10^8$ GeV, and in turn to a QCD axion mass of about 0.06 eV. However, as we will discuss, astrophysical considerations indicate that such a large value for the axion-electron coupling is not tenable. While we will eventually follow the usual approach of quantifying the tension between the solar axion interpretation of the XENON1T excess and a set of astrophysical observables in terms of standard deviations, it should be kept in mind that stellar evolution would be so drastically affected by the exceedingly large energy losses due to axion emission, that the remarkable agreement between stellar evolution codes and the observed color-magnitude diagram (CMD) for clusters of stars would be basically destroyed.

The strategy that we are going to follow consists in assuming the axion couplings $g_{ae}$ and $g_{a\gamma}$ to lie in the 90% C.L. regions indicated by the XENON1T fit to their electron recoil data [1]. We will then estimate the effects of axion-related energy losses on a set of astrophysical observables that are particularly sensitive to $g_{ae}$ and $g_{a\gamma}$ induced processes. These observables are related to stars in the Red Giants Branch (RGB) and Horizontal Branch (HB), as well as to White Dwarfs (WDs). Given that the axion coupling to nucleons cannot play any role in explaining excesses of events occurring below 10 keV, we will not include in our analysis astrophysical observables sensitive to $g_{aN}$ (as for example the neutrino burst duration of SN1987A).

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1 Light axion-like particles, that do not solve the strong CP problem, and for which there is no theoretical relation between the value of the mass and the strength of the couplings, are equally suited for this explanation, but are theoretically less motivated.
Explaining the XENON1T excess with Luminous Dark Matter

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We show that the excess in electron recoil events seen by the XENON1T experiment can be explained by relatively low-mass Luminous Dark Matter candidate. The dark matter scatters inelastically in the detector (or the surrounding rock), to produce a heavier dark state with a ~2.75 keV mass splitting. This heavier state then decays within the detector, producing a peak in the electron recoil spectrum which is a good fit to the observed excess. We comment on the ability of future direct detection datasets to differentiate this model from other beyond the Standard Model scenarios, and from possible tritium backgrounds, including the use of diurnal modulation, multi-channel signals etc., as possible distinguishing features of this scenario.

I. INTRODUCTION

Recently the XENON Collaboration announced an excess of low energy electron recoil events above their expected background [1]. Though this excess may originate from a tritium β-decay that was previously not included in their background model, the collaboration also examined Beyond the Standard Model (BSM) possibilities including solar axions or a neutrino magnetic moment (μν). With a trace amount of tritium (6.2 ± 2.0 × 10^{-20} mol/mol) added to the background model, the anomaly is explained at 3.2σ, while the background plus solar axion (background plus μν) solution provides a 3.5σ (3.2σ) significance fit to the excess within certain parameter ranges. These BSM possibilities lose substantial statistical significance when combined with a tritium component in the fit - down to 2.1σ (0.9σ) for the solar axion (μν) case. Additionally, the collaboration examined the possibility of bosonic dark matter, but found no global significance above 3σ. Other studies of BSM explanations for the excess include [2–7].

The XENON1T excess is characterized by a peak at ~3 keV. In this work we consider the possibility that the XENON1T excess is generated by the interactions of Luminous Dark Matter (LDM) [8–10], with a mass splitting in the δ ~ 3 keV range. The basic idea is that dark matter scattering is purely inelastic, with the dark matter (χ) scattering off nuclei (either in the detector or in the surrounding overburden) to produce an excited dark state (χ′). The dark state then decays (χ′ → χγ) by the emission of a monochromatic photon with energy ~δ. Given the energy resolution of XENON1T, the resulting electron recoil spectrum contains a peak which is a good fit to the XENON1T excess.

The paper is organized as follows. In Section II we briefly review the setup of Luminous Dark Matter, and its application to the XENON1T excess. In Section III, we present our results. In Section IV, we discuss the prospects for future experiments to probe this model. We conclude with a discussion of our results in Section V.

II. LUMINOUS DARK MATTER

Our basic model is a species of Luminous Dark Matter. This is a two-state inelastic dark matter scenario in which the heavier dark state produces photons via its decays. Specifically, the cosmological cold dark matter is a particle χ with mass mχ, and there exists a slightly heavier dark state χ′, whose mass exceeds mχ by the mass splitting δ = mχ′ − mχ ≪ mχ. The dominant decay of χ′ is through χ′ → χγ. Indeed, if δ is sufficiently small and if χ′ and χ have the same spin, this is the only visible decay which will be accessible (a two neutrino final state would also be possible). Note that, if δ ≪ mχ, then in the rest frame of the χ′ we will find Eγ = δ + O(δ^2/mχ). Note that even if χ′ decays to χ and multiple photons, the sum of photon energies will be δ + O(δ^2/mχ), because the outgoing χ will have negligible kinetic energy for δ/mχ ≪ 1. This scenario can emerge if the dark matter is coupled to a mediator, φ, through a χχ′φ interaction with φ decaying to γγ.

In this scenario, dark matter scattering is entirely inelastic (χA → χ′A). This type of purely inelastic scattering arises generically in a variety of contexts [9, 11–26].

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Stellar Basins of Gravitationally Bound Particles

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A new physical phenomenon is identified: volumetric stellar emission into gravitationally bound orbits of weakly coupled particles such as axions, moduli, hidden photons, and neutrinos. While only a tiny fraction of the instantaneous luminosity of a star (the vast majority of the emission is into relativistic modes), the continual injection of these particles into a small part of phase space causes them to accumulate over astrophysically long time scales, forming what I call a “stellar basin”, in analogy with the geologic kind. The energy density of the Solar basin will surpass that of the relativistic Solar flux at Earth’s location after only a million years, for any sufficiently long-lived particle produced through an emission process whose matrix elements are unsuppressed at low momentum. This observation has immediate and striking consequences for direct detection experiments—including new limits on axion parameter space independent of dark matter assumptions—and may also increase the prospects for indirect detection of weakly interacting particles around compact stars.

INTRODUCTION

Stars are poor photon emitters. Their photon opacity is so high that the only effective radiating component is a thin shell near the stellar surface. Stellar energy losses per unit volume are thus suppressed by the surface-to-volume ratio. They are further diminished by thermal self-insulation: photon luminosity scales as the fourth power of the surface temperature, which is typically several orders of magnitude lower than the core temperature (a factor of about 2000 in the Sun).

Stars can thus serve as sensitive “astrophysical laboratories” of weakly coupled particles [1–3], whose contributions to the overall luminosity—via volumetric emission—and thermal transport—via long mean free paths—can be disproportionately large. Indeed, neutrino emission is the main energy loss mechanism for the first \(10^7\) y after the birth of a neutron star [4], despite neutrinos’ tiny coupling. Even the Sun has a fractional luminosity of order \(10^{-9}\) due to thermal neutrino-pair production [5], in addition to the 3% from fusion neutrons.

Stellar cooling is also a powerful probe of weakly interacting, low-mass particles beyond the Standard Model of particle physics, for the same reasons. Such particles are motivated and predicted by wide classes of high-energy field theories as well as string theory [6], for example as moduli or pseudo-Nambu-Goldstone bosons of weakly broken global symmetries. The most notable of these is the QCD axion, in a framework that offers a dynamical explanation of the strong CP problem [7–9]. If these particles exist in the spectrum, they can—but need not—be the dominant component of dark matter (DM) in our Universe, with well-established early-universe production mechanisms [10–13]. Leading constraints on the interactions of these exotic particles with “regular” matter often arise from the absence of anomalous cooling [1, 4] of the Sun [14–20], horizontal-branch (HB) stars [21], red giants (RG) [22], white dwarfs (WD) [23–31], neutron stars (NS) [32–34], and supernovae [35–37].

A vast number of experimental efforts (notable examples include [43–52]) are ongoing to detect (in a terrestrial laboratory setting) the relativistic Solar flux and a potential Galactic DM population of these particles. One leading experiment, sensitive to both types, recently reported [53] a statistically significant excess of electron-recoil events with energies just above a keV, intriguingly near the Sun’s core temperature \(T_{\odot}\). If the excess were in fact due to new fundamental physics beyond the Standard Model, many simple models appear in conflict with the aforementioned stellar cooling constraints, discounting these exotic hypotheses in favor of more mundane explanations such as unforeseen radioactive backgrounds.

In this work, I investigate a hitherto unknown effect in astroparticle physics that seems benign at first, but gives rise to dramatic observable consequences in laboratory experiments—including the limits and putative excess of Ref. [53]—and astrophysical observations. I stress that no new particle physics model is introduced; rather, I posit the occurrence of a new phenomenon that is generic within a large class of well-motivated models. The main point of this paper is simple: stars are able to emit massive particles into bound orbits. The energy loss rate for this bound emission component is typically very small (see Eq. 5). However, this peculiar ensemble of particles populates parts of phase space that may survive for millions to billions of years around isolated stars, even in the inner Solar System. Over time, the density of this “stellar basin” can exceed the density of the relativistic stellar flux, including within the Solar System (cfr. Eq. 8).

In what follows, I describe how stellar basins of low-mass, weakly interacting particles can form and evolve. I discuss general aspects of soft emission near a particle mass threshold, before delving into a case study of Solar axions coupled to electrons. Based on these results, I present new limits on axion parameter space, and suggest the possible re-interpretation of the excess of Ref. [53] as due to a Solar axion basin. I conclude with potential avenues for future work.
XENON1T Anomaly and its Implication for Decaying Warm Dark Matter

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An excess in the electronic recoil data was observed in the XENON1T detector. One of plausible explanations for the excess is absorption of a vector bosonic particle with the mass of 2–3 keV. For this, the kinetic mixing $\kappa \sim 10^{-15}$ of the dark photon with the photon is required if the dark photon explains the current DM abundance. We recently proposed a model where the main component DM today is a decaying warm dark matter (WDM) with the lifetime comparable to the age of the current universe. The WDM decays to a massless fermion and a massive dark photon. This model was originally designed for addressing both the small scale problems which $\Lambda$CDM suffers from and the $H_0$ tension. In this letter, we show that the massive dark photon produced by the WDM decay can be identified with the vector boson inducing the anomalous excess in the XENON1T experiment. Depending on a lifetime of the parent decaying WDM, the dark photon could be either the main component or the sub-component of DM population today.

I. INTRODUCTION

Recently, an incomprehensible excess in the electronic recoil data was observed in the XENON1T experiment [1]. The energy regime where the excess over the known background appears ranges from 1 keV to 7 keV with the events near 2–3 keV particularly prominent. In an effort to interpret the excess as a hint for a new physics beyond the Standard Model (SM), several possible new physics including solar axions, an anomalous neutrino magnetic moment, and bosonic dark matter were discussed and constraints on the relevant physical quantities were reported as well [1]. (See also the follow-up works about the use of the axion-like particle [2] and the dark photon for interpretation [3] and an possible explanation using an elastic scattering between a particle with the velocity $\sim O(10^{-2}c)$ and the electron [4, 5] and explanation introducing new interactions between neutrino and electron [6].) Among these, in this letter, we pay our special attention to the possibility where the excess is triggered by absorption of a vector bosonic particle [7] in the XENON1T detector via the dark photon version of photoelectric effect.

As a resolution to the small scale problems (e.g. core/cusp problem [8], missing satellite problem [9, 10], too-big-to-fail problem [11]), the fermionic warm dark matter (WDM) is an interesting possibility. By suppressing the growth of matter fluctuations at scales below its free-streaming length, it may help us understand the observed mass deficit of inner halos in galaxies and galaxy clusters [12–14]. Especially when its mass lies in sub-keV regime and its temperature is low enough, Fermi degeneracy pressure may form to prohibit the core collapse of halos. Aside from the warm nature, this quantum mechanical property is another advantage of the fermionic WDM in regard to the core-cusp problem [15–19].1 Along this line of reasoning, we recently proposed a consistent model for WDM with a non-thermal origin in Ref. [22]. (See also Ref. [23].) The possibility of decaying WDM was discussed there in which case a fermionic WDM decays to a massless fermion and a massive hidden gauge boson. The model was originally designed for not only the small scale problems but also the Hubble tension.2 Extending the framework of Ref. [22], in this letter, we consider a decaying WDM with the lifetime comparable to or greater than the current age of the Universe. We shall identify the decay product gauge boson with the vector bosonic particle causing the excess in the electronic recoil data recorded by the XENON1T detector.

To explain the anomaly, we set the mass of the gauge boson to be 2–3 keV and attribute a significant fraction of the current DM density to the gauge boson. Intriguingly, we found that this set-up motivated by the experimental anomaly provides us with an implication for non-thermal origin of the WDM in the model. This implication is

1 The sub-keV mass regime seems to be in severe tension with thermal WDM mass constraint from Lyman-α forest [20, 21]. However, for the case where the WDM has a non-thermal origin, the mass constraint can be relaxed to make the non-thermal sub-keV WDM scenario still viable.

2 Recently it was figured out that decaying DM solution to the Hubble tension is severely constrained by the cosmic microwave background (CMB) power spectrum [24]. To enable the late time accelerated evolution of the Hubble expansion rate, the shorter life time and the larger energy transfer from the decaying particle to the radiation decay product are required, which causes inconsistency with the observed CMB power spectrum by increasing the low multipole regime and enhancing oscillations at the high multipole regime. Nonetheless, it might be still probable to avoid this side effects provided a scale dependent spectral index ($n_s(k)$) is invoked, which could be still possible depending on an inflation model.
We investigate the impact of the QCD vacuum at nonzero $\theta$ on the properties of light nuclei, Big Bang nucleosynthesis, and stellar nucleosynthesis. Our analysis starts with a calculation of the $\theta$-dependence of the neutron-proton mass difference and neutron decay using chiral perturbation theory. We then discuss the $\theta$-dependence of the nucleon-nucleon interaction using a one-boson-exchange model and compute the properties of the two-nucleon system. Using the universal properties of four-component fermions at large scattering length, we then deduce the binding energies of the three-nucleon and four-nucleon systems. Based on these results, we discuss the implications for primordial abundances of light nuclei, the production of nuclei in stellar environments, and implications for an anthropic view of the universe.

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I. INTRODUCTION

One of the most outstanding questions in physics pertains to the values of the fundamental parameters in the Standard Model. These include the gauge and Yukawa couplings, the latter being responsible for fermion masses and mixings. In the case of the gauge couplings, some hint is available from grand unified theories where a single unified coupling is run down from a very high energy scale to the weak scale leading to predictions for the weak scale gauge couplings in reasonable agreement with experiment. The Yukawa coupling matrices are, however, a bigger mystery which includes the generation structure of fermion masses. The answer may lie in an as yet undefined future theory (e.g., a complete string theory) in which case there is hope of a deeper understanding. It is also possible that our Universe with its observed fundamental parameters is part of a larger structure or a Multiverse, but we have no means to know. In this case, the observed values, may be somewhat random with no deep explanation. However, even in that case, our specific measurements of these parameters can not be completely random, as not all values will permit a Universe which supports our form of life, which can carry out such measurements. This is often referred to as the anthropic principle. The anthropic principle absolves us, the Earth dwellers, from the duty of explaining the values of the governing constants, at least for the time being, until data at higher scales become available.

The term anthropic principle was coined in 1974 by Brandon Carter [1]. In the 1980s a few influential “anthropic
Tests of general relativity using multiband observations of intermediate mass binary black hole mergers

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Observation of gravitational waves (GWs) in two different frequency bands is referred to as multiband GW astronomy. With the planned Laser Interferometric Space Antenna (LISA) operating in the $10^{-4} – 0.1$ Hz range, and third generation (3G) ground-based detectors such as the Cosmic Explorer (CE) and Einstein Telescope (ET), operating in the $1–10^5$ Hz range, multiband GW astronomy could be a reality in about a decade. In this paper we present the potential of multiband observations of intermediate mass binary black holes (IMBBHs) of component masses $\sim 10^2–10^3 M_\odot$ to test general relativity (GR). We show that multiband observations of IMBBHs would permit multiparameter tests of GR—tests where more than one post-Newtonian (PN) coefficient is simultaneously measured yielding more rigorous constraints on possible modifications to GR. We also find that the improvement due to multibandling can often be much larger than the best of the bounds from either of the two observatories. The origin of this result, as we shall demonstrate, can be traced to the lifting of degeneracies among the various parameters when the information from LISA and 3G are taken together. We obtain the best multiband bounds for an IMBBH with a total redshifted mass of $200 M_\odot$ and a mass ratio of 2. For single-parameter tests, this system at 1 Gpc would allow us to constrain the deviations on all the PN coefficients to below 10% and derive simultaneous bounds on the first seven PN coefficients to below 50% (with low spins).

I. INTRODUCTION

Einstein’s general relativity (GR) has been subjected to a plethora of tests performed both in the laboratory as well as using astrophysical observations [1]. The theory has so far been consistent with each of these tests (see Refs. [2–6] for an overview of various astrophysical tests of GR). The first observation of gravitational waves (GWs) from the binary black hole (BBH) merger GW150914 [7] and several others [8–14] during the first and second observing runs, have permitted tests of GR in a regime of strong gravity and high curvature which were elusive till date [15]. The binary neutron star merger GW170817 [16] further facilitated tests of strong-field gravity during the first and second observing runs, have permitted tests of GR in a regime of strong gravity and high curvature which were elusive till date [15]. 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Parametrised tests of GR [25–30], are among the pioneering tests of the theory performed with GW data. These tests make the best use of the structure of the GW phase evolution from the post-Newtonian (PN) approximation to GR [31]. In the PN approximation, the phase evolution of the GW signal can be expanded as a power series in $v$ and $\log v$, where $v$ denotes the velocity parameter describing the orbital motion of the binary. The different PN orders (corresponding to different powers of $v$) capture the diverse physics and various nonlinear effects underlying the compact binary dynamics. Hence looking for deviations in the PN coefficients is equivalent to constraining different physics that goes into them [32, 33]. In this framework, deviations from GR are parametrized via deformation in the phasing formula at different PN orders [29, 30] whose values are put to test using the GW data. As these deformation parameters take the value zero in GR, this null test is devised to derive constraints on them at a fixed credible level.

The parametrized tests of GR branch out into several sub-classes depending on the number of PN deformation parameters that are simultaneously estimated from the data. Ideally, one aims to constrain all or several of the PN deformation parameters simultaneously using the GW data [25]. This will be referred to as multiparameter tests in this paper. One may wish to further classify these multiparameter tests into two classes, depending on whether the block of PN parameters that are tested start from the lowest PN order (in the ascending order) or from the highest PN order (in the descending order). The former would make sense in terms of verifying the predictions of GR at different PN orders with increasing levels of complexities in the nonlinear interactions. The latter perspective, starting from the highest PN order and going in the decreasing order, would be expected from modified theories such as an effective field theory where modifications to GR would start at a particular PN order and all orders above that [34, 35]. There could be other possible combinations of the PN deformation parameters that may be tested simultaneously, but we consider only these two classes of the multiparameter tests in this paper as they are the most general ones. These classes of tests, though more rigorous, yield weaker bounds, compared to single-parameter tests, due to the large correlations of the deformation parameters among themselves as well

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Charged-Current Muonic Reactions in Core-Collapse Supernovae

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The steady advance in core-collapse supernova simulations requires a more precise description of neutrino processes in hot and dense matter. In this work, we study the rates of charged-current (CC) weak processes with (anti)muons in supernova matter. At the relativistic mean field level, we derive results for the rates of CC neutrino-nucleon reactions, taking into account full kinematics, weak magnetism and pseudoscalar terms, and \( q^2 \)-dependent nucleon form factors in the hadronic current. In addition to muonic semi leptonic processes we also consider purely leptonic processes. In particular, we show that inverse muon decay can dominate the opacities for low energy \( \nu_\mu \) and \( \bar{\nu}_e \) at densities \( \gtrsim 10^{13} \text{ g cm}^{-3} \).

I. INTRODUCTION

The core-collapse of a massive star leads to the formation of a neutron star and the subsequent supernova explosion. Most of the gravitational binding energy of the neutron star is released in the form of neutrinos that in the neutrino-driven mechanism are responsible for the ejection of the stellar mantle [1]. Consequently, neutrino processes in hot and dense nuclear medium play crucial roles in many aspects of core-collapse supernovae (CCSNe), in particular for the explosion mechanism and the nucleosynthesis of heavy elements [2–5]. The successful explosion of core-collapse supernovae by the neutrino-driven mechanism in three-dimensional simulations has demonstrated the high relevance of neutrino physics as well as the necessity of an accurate description of neutrino transport in hot and dense protoneutron star (PNS) [6].

Neutrino processes in hot and dense matter have been well studied in the literature [7–22], and their impacts on CCSN simulations have also been extensively explored (see, e.g., Refs. [23–33]). However, neutrino CC processes considered for most of the studies are limited to the lightest charged lepton, i.e., \( e^\pm \). Due to a larger rest mass, the production of \( \mu^\pm \) was thought to be highly suppressed and their role in SN dynamics was traditionally ignored. Recently, the relevance of muons has been demonstrated in 2D SN simulations [34]. It showed that the formation of muons in SN matter softens the equation of state (EOS), leads to higher neutrino luminosities and mean energies, and therefore facilitates neutrino-driven explosions. It should be pointed out that the production of \( \mu^\pm \), especially the accumulation of net \( \mu \)-lepton number, is closely related to the CC reactions of \( \nu_\mu (\bar{\nu}_\mu) \), which are created via thermal pair processes like \( e^- + e^- \rightarrow \nu_\mu + \bar{\nu}_\mu \) and \( N + N \rightarrow N + N + \nu_\mu + \bar{\nu}_\mu \), and affected by neutrino transport in SN matter.

To be specific, the more abundant electrons, compared to positrons, can lead to an excess of \( \mu^- \) than \( \mu^+ \) via leptonic weak processes like \( \nu_\mu / \bar{\nu}_\mu + e^- \rightarrow \nu_e / \bar{\nu}_e + \mu^- \). This is also aided by the semileptonic process, \( \nu_\mu + n \rightarrow p + \mu^- \), which is more favoured than \( \bar{\nu}_\mu + p \rightarrow n + \mu^+ \) since neutrons are in higher energy states than protons. Due to muon number conservation, the initial excess of \( \mu^- \) is compensated by an excess of \( \bar{\nu}_\mu \). With a more abundant flux and a lower neutral-current (NC) scattering cross section with nucleon, more \( \bar{\nu}_\mu \) diffuse out of the protoneutron star, leading to a gradual buildup of net muon number, i.e., muonization. The appearance of muonization not only affects the neutrino spectra of all flavors and enhances the explosion ability, but may also play a non-negligible role in the subsequent neutron star/black hole formation [34].

In this work, we aim to study the reaction rates of all the relevant weak processes involving \( \mu^- \) or \( \nu_\mu \) (see Tab. 1), which are required as input in numerical simulations for a consistent description of muonization and neutrino transport. It has been found that weak magnetism can enhance/suppress the neutrino/antineutrino opacities significantly and thus affects the neutrino spectra and SN dynamics [13]. A relativistic treatment of both full kinematics (nuclear recoil) and weak magnetism for CC \( \nu_e (\bar{\nu}_e) \)-nucleon reactions have been studied [20, 33], with its impact recently explored in symmetric CCSN simulation [33]. For semileptonic reactions involving \( \mu^\pm \) with large energy-momenta transfer, pseudoscalar coupling term in the hadronic weak current, which is normally neglected for \( \nu_e \) reactions, is found as important as weak magnetism. Besides, the effects of nucleon form factors become comparable as energy-momenta transfer increases and need to be considered on the same footing as weak magnetism and pseudoscalar corrections. Hence, we extend the formalisms presented in [33] to include weak magnetism, pseudoscalar term and \( q^2 \)-dependent form factors in the hadronic current for CC \( \nu_\mu \)-nucleon reaction. Treating nucleons at the mean field level for
Inelastic Dark Matter Electron Scattering and the XENON1T Excess

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Detection of electron recoils by dark matter (DM) may reveal the structure of the dark sector. We consider a scenario where a heavier DM particle inelastically scatters off an electron and is converted into a lighter DM particle. A small mass difference between the two DM particles is transferred into electron recoil energy. We investigate the DM-electron interaction mediated by a massive dark photon and evaluate the inelastic DM scattering rate, taking account of the atomic structure. It is found that the scattering rate is significantly enhanced because of the small mass splitting, which allows for a small momentum transfer matched with the size of the electron wave function. We show that there exists a viable parameter space which explains the excess of electron recoil events around 2 keV recently reported by the XENON1T experiment.

I. INTRODUCTION

To understand the nature of dark matter (DM) is a central issue in modern particle physics and cosmology. Numerous candidates of DM have been proposed and at the same time numerous experiments have been conducted to search for DM. The dawn of a new era in DM physics is breaking. Recently, the XENON collaboration has reported excess of electron recoil events around 2 keV in the recoil energy \cite{1}. The observed excess was interpreted in terms of axions \cite{1,2,3,4} produced in the Sun. However, this interpretation is in strong tension with the stellar cooling constraints \cite{5,6,7,8}. Another interpretation based on a hypothetical neutrino magnetic moment is also excluded by the same reason. Then, barring the possibility that the signals come from a small amount of tritium in the detector, it is natural to consider the excess as a hint of DM.

The observed electron recoil excess cannot be explained by cold DM which elastically scatters off target electrons because such DM particles are too slow and give too large signals in the first bin of the recoil energy 1-2 keV when the second bin of 2-3 keV is fitted \cite{9}. One possible explanation of the excess is absorption of bosonic DM by electrons \cite{10}. A concrete setup to realize this idea is discussed in ref. \cite{11}. Another explanation based on a hypothetical neutrino magnetic moment is also excluded by the same reason. Then, barring the possibility that the signals come from a small amount of tritium in the detector, it is natural to consider the excess as a hint of DM.

In this paper, we propose a new interpretation of the observed excess with cold DM inelastically scattering off electrons. Inelastic DM scattering has been mostly discussed in the context of inelastic DM \cite{12,13}, where a DM particle scatters off nuclei and is converted into an excited state, motivated by the DAMA annual modulation anomaly \cite{14}. Unlike inelastic DM, we consider a cold DM particle $\chi_2$ which inelastically scatters off an electron and is converted into a lighter DM particle $\chi_1$. A DM nucleon down-scattering has been discussed in ref. \cite{15}.

The mass difference between $\chi_1$ and $\chi_2$ is converted into the electron recoil energy.

To be concrete, we investigate the DM-electron interaction mediated by a massive dark photon $A'$. A DM particle $\chi_2$ can decay into Standard Model (SM) particles and $\chi_1$, but the lifetime is sufficiently long. Also, the inelastic scattering in the early universe freezes out much before the temperature drops below the mass difference. Thus, the two particles $\chi_1$, $\chi_2$ equally contribute to the present abundance of DM. We calculate the rate of the inelastic DM scattering off electrons, taking account of the xenon atomic structure. We find that the scattering rate is significantly enhanced for a recoil energy at the mass difference, since the momentum transfer is allowed to be small and can match the size of the wave function of the electrons in the atom. We find a viable parameter space of our dark sector model where the observed excess is explained.

The rest of the paper is organized as follows. In section \textbf{II} we present our dark sector model. In section \textbf{III} we compute the inelastic scattering cross section and explain the XENON1T data in the model. Section \textbf{IV} discusses the DM production through the thermal freeze out process. In section \textbf{V} we investigate (in)direct constraints on the model. The lifetime of the heavier DM component is estimated and the constraint from various dark photon searches is shown. In section \textbf{VI} we conclude the discussion and comment on future directions.

II. THE MODEL

We introduce a new sector with two DM scalars $\chi_1$, $\chi_2$ (whose masses are $m_1 < m_2$) feebly interacting with the SM particles through a massive dark photon $A'$. Our focus is on the case where the DM masses $m_{1,2}$ are much above the MeV scale so that the DM abundance may be explained by the thermal freeze-out process as discussed
The Geometrical Origin of Dark Energy

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Abstract

The geometrical formulation of the quantum Hamilton-Jacobi theory shows that the quantum potential is never vanishing, so that it plays the role of intrinsic energy. Such a key property selects the Wheeler-DeWitt (WDW) quantum potential \(Q[g_{jk}]\) as the natural candidate for the dark energy. This leads to the WDW Hamilton-Jacobi equation with a vanishing kinetic term, and with the identification

\[ \Lambda = -\frac{\kappa^2}{\sqrt{g}} Q[g_{jk}] . \]

This shows that the cosmological constant is a quantum correction of the Einstein tensor, reminiscent of the von Weizsäcker correction to the kinetic term of the Thomas-Fermi theory. The quantum potential also defines the Madelung pressure tensor. Such a geometrical origin of the vacuum energy density, a strictly non-perturbative phenomenon, provides strong evidence that it is due to a graviton condensate. Time independence of the WDW wave-functional then would imply that the ratio between the Planck length and the Hubble radius is a time constant, providing an infrared/ultraviolet duality. This indicates that the structure of the Universe is crucial for a formulation of Quantum Gravity.
Xenon1T anomaly: Inelastic Cosmic Ray Boosted Dark Matter

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In this work, we studied the light dark matter from the decay of meson produced by the inelastic scattering of CRs and atmosphere. Due to the boost effect, we find that such a dark matter can move with a velocity close to 0.2 and may account for the very recent Xenon1T electron recoil excess.

INTRODUCTION

The existence of dark matter (DM) has been established in cosmological and astrophysical experiments. But the nature of dark matter is still elusive. So far, the direct detections [1] that aim for Weakly Interacting Massive Particle (WIMP) [2] have reached great sensitivities, and been approaching to the neutrino floor. Their null results lead to the increasing efforts on searching for light dark matter particles (for recent reviews, see [3, 4]).

Very recently, the Xenon1T collaboration has reported about 3.5σ excess events over the backgrounds in the low-energy electron recoil data (i.e. 1 keV < E_R < 7 keV) [5]. The corresponding spectrum can be well fitted by the solar axion with an axion-electron coupling g_{ae} ≈ 3.7 × 10^{-12}, however, which is in tension with the stellar cooling constraint, g_{ae} ≲ 0.3 × 10^{-12} [6]. Other possibilities, such as β decay of tritium, semi-annihilating dark matter and nearby axion star, have been discussed in [5, 7].

As known, the sensitivity of direct detections is challenged by the low energy threshold of detectors. The average velocity of dark matter is around 10^{-3}c in the Milky Way halo. Therefore, the light dark matter moving with a low velocity will fit the Xenon1T poorly due to the small recoil energy. In order to interpret the Xenon1T anomaly, one need the light dark matter to be energetic. Several mechanisms of accelerating light DM have been proposed [8–11]. Among them, the cosmic rays (CRs) play an important role. For example, a fraction of light dark matter can be boosted to (semi-)relativistic speeds through its elastic scattering with the high energy cosmic rays [12].

In this paper, we will focus on the light boosted dark matter from the decay of meson produced in the inelastic CRs collision [13], namely inelastic cosmic ray boosted dark matter. Different from the upscattering mechanism, this scheme is independent of the density of pre-existing dark matter, and thus naturally provides a sufficient source of boosted dark matter to explain the Xenon1T excess.

INELASTIC COSMIC RAY BOOSTED DARK MATTER

The main source of the inelastic boosted dark matter arises from the inelastic high energy CRs collision with the atmosphere on Earth. The incoming cosmic ray (proton) flux can be parameterized as in Ref. [14]. The differential cosmic ray flux dφ_p(T_p, h)/dT_p is the function of proton energy T_p and height from the ground level h, which will be diluted as traveling through the atmosphere.

\[ \frac{d}{dh} \frac{d\phi_p(T_p, h)}{dT_p} = \sigma_{pN}(T_p)n_N(h)\frac{d\phi_p(T_p, h)}{dT_p}. \]  

(1)

Here \( \sigma_{pN} \) is the inelastic proton-nitrogen cross section and \( n_N \) is the number density of nitrogen. The initial value of the flux is evaluated at \( h_{\text{max}} = 180\text{km} \).

Since the inelastic proton-nitrogen cross section is approximately constant in the relevant energy range, we can absorb the \( h \)-dependence of \( \phi_p \) into a dilution factor \( y_p(h) \) for simplicity,

\[ \frac{d\phi_p(T_p, h)}{dT_p} = y_p(h)\frac{d\phi_p(T_p, h_{\text{max}})}{dT_p}, \]  

(2)

where we set the boundary condition of suppression factor as \( y_p(h_{\text{max}} = 180\text{km}) = 1 \). Then, we can substitute the Eq. 2 into suppression function Eq.1 and yields,

\[ \frac{dy_p(h)}{dh} = \sigma_{pN}n_N(h)y_p(h). \]  

(3)

After integration over the height, we can obtain the dilution factor,

\[ y_p(h) = \exp \left( -\sigma_{pN} \int_h^{h_{\text{max}}} d\tilde{h}n_N(\tilde{h}) \right). \]  

(4)
On special case of the Bañados-Silk-West effect

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If two particles collide near the rotating extremal black hole and one of them is fine-tuned, the energy $E_{c.m.}$ can grow unbounded. This is the so-called Bañados-Silk-West (BSW) effect. Recently, another type of high energy collisions was considered in which all processes happen in the Schwarzschild background with free falling particles. If the Killing energy $E$ of one of particle is sufficiently small, $E_{c.m.}$ grows unbounded. We show that, however, such a particle cannot be created in any precedent collision with finite energies, angular momenta and masses. Therefore, in contrast to the standard BSW effect, this one cannot be realized if initial particles fall from infinity. If the black hole is electrically charged, such a type of collisions is indeed possible, when a particle with very small $E$ collides with one more particle coming from infinity. Thus the BSW effect is achieved due to collisions of neutral particles in the background of a charged black hole. This requires, however, at least two-step process.

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I. INTRODUCTION

If two particles collide near a rotating black hole, under certain condition this leads to the unbounded growth of the energy in the center of mass frame $E_{c.m.}$ This is the essence of the so-called Bañados-Silk-West (BSW) effect [1] (see also more early works [2] - [4]). The

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Higher-order gravitational-wave modes will allow for percent-level measurements of Hubble’s constant with single binary neutron star merger observations

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The first multi-messenger gravitational-wave observation of a binary neutron star merger allowed for the first distance-ladder independent measure of Hubble’s constant, albeit with an uncertainty of $\sim 15\%$ at the 68$\%$ credible level. We show that a single future observation of a binary neutron star merger with a network of detectors sensitive to the post-merger remnant at a few kHz, and commensurate improvement in cosmological redshift measurements, will allow for percent-level uncertainties in measurement of Hubble’s constant. To achieve such sensitivity, higher-order modes must be taken into account to break the intrinsic degeneracy between luminosity distance and inclination of the source. We show how higher-order modes can be exploited in astrophysical parameter estimation in both the inspiral phase, and also the post-merger remnant. While the former suffices in the case of unequal-mass binaries to obtain major improvements in the distance estimates, the latter is crucial for equal-mass cases. We show how the distribution of interferometers across the globe affects these measurements, and discuss this in terms of science drivers for 2.5- and third-generation gravitational-wave detectors.

**Introduction**

The joint detection of gravitational-wave (GW) and electromagnetic (EM) radiation from the binary neutron star (BNS) merger GW170817 is a milestone for astrophysics $[1,2]$ and has already driven major leaps forward in a number of research areas. Among the many profound science outcomes, GW170817 provided the first distance-ladder independent measure of the expansion of the Universe $[3-5]$, as parameterized by Hubble’s constant. The increasing number of confirmed and putative binary neutron star candidates in the third LIGO/Virgo $[6,7]$ observing run $[8]$, coupled with the planned sensitivity increase of current- and future-generation gravitational-wave detectors $[9,11]$, will see significant increases in both the number of detected neutron star mergers, as well as their signal-to-noise ratios. Improvements in the high-frequency regime ($\gtrsim 1$ kHz) will also see the first detections of the post-merger phase of BNS mergers [e.g., $[12,13]$ where matter effects play a significant role in the gravitational waveform.

Determining Hubble’s constant from coincident observations of BNS mergers relies on measuring the redshift from the EM counterpart and the luminosity distance to the source from the gravitational-wave signal $[14]$; although seeRefs. $[15,16]$ for other methods). A key limitation of the latter is the degeneracy between luminosity distance and the inclination of the binary. In this Letter, we study how this degeneracy can be broken in the context of future GW detectors in two ways: via the inclusion of higher-order modes (HMs) in the GW parameter estimation, and by accessing the ratio of the two GW polarisation using multiple detectors. For face-on binaries, we show that inclusion of HMs leads to major improvements of the distance and inclination estimates, independently of the detector network configuration. For edge-on binaries, we find that a three-detector network that can constrain the polarisation ratio and sky-location of the binary is key to correctly estimate the distance, regardless of whether HMs are used in the analysis or not. In both cases, we find that measurements of $H_0$ will not be limited by our ability to infer the luminosity distance via GWs, but by the accuracy of the redshift measurement. With redshift-measurement improvements, 1.5% level measurements of $H_0$ could be possible with the observation of a single BNS located at $\sim 40$ Mpc, consistent with the distance of GW170817. We show that for unequal mass systems, these improvements can be achieved with the inspiral phase only, independent of whether there is matter in the system or not; i.e., the method works for binary systems containing neutron stars and/or black holes. For equal-mass systems, we show that inclusion of matter effects in the post-merger phase is key to improve distance estimates.

We note that percent-level measurements of $H_0$ could be performed in a five year time-frame making use of five second-generation detectors $[17]$, namely the two Advanced LIGO detectors $[6]$, Advanced Virgo $[7]$, KAGRA $[18]$, and the forthcoming LIGO India $[19]$. However, this relies on the combination of many observations, therefore assuming that $H_0$ is the same in all directions and distances; i.e., the Universe is statistically isotropic and homogeneous on the scales of interest. While our results will help to improve this strategy, percent-level measurements with a single observation may enable the measurement to investigate anisotropies $[20]$ and time-evolution of $H_0$ $[21]$. 

Multi-scalar Gauss-Bonnet gravity – hairy black holes and scalarization

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In the present paper we consider multi-scalar extension of Einstein-Gauss-Bonnet gravity. We focus on multi-scalar Einstein-Gauss-Bonnet models whose target space is a three-dimensional maximally symmetric space, namely either $S^3$, $H^3$ or $R^3$, and in the case when the map spacetime $\rightarrow$ target space is nontrivial. We prove numerically the existence of black holes in this class of models for several Gauss-Bonnet coupling functions, including the case of scalarization. We also perform systematic study of a variety of black hole characteristics and the space-time around them, such as the area of the horizon, the entropy and the radius of the photon sphere. One of the most important properties of the obtained solutions is that the scalar charge is zero and thus the scalar dipole radiation is suppressed which leads to much weaker observational constraints compared to the majority of modified theories possessing a scalar degree of freedom. For one of the coupling functions we could find branches of scalarized black holes which have a nontrivial structure – there is non-uniqueness of the scalarized solutions belonging to a single branch and there is a region of the parameter space where most probably stable scalarized black holes coexist with the stable Schwarzschild black holes. Such a phenomena can have a clear observational signature.

I. INTRODUCTION

The unifying theories predict one or more scalar partners of the tensor graviton. The scalar degrees of freedom are usually coupled to the curvature invariants of spacetime [1, 2]. A notable example is the Einstein-scalar-Gauss-Bonnet (ESGB) gravity. In this theory the scalar degree is coupled to the Gauss-Bonnet invariant and the field equations are of second differential order as in general relativity (GR). ESGB gravity with only one dynamical scalar field and different coupling functions has recently attracted a lot of interest. A particular class of ESGB theories is the Einstein-dilaton-Gauss-Bonnet gravity whose coupling function is exponential. Various aspects of black holes in this model were studied in a number of papers [3]–[19] including their quasinormal modes [17, 18]. The ESGB gravity with more general coupling functions were studied in [20]–[22].

It was recently shown in [23, 24] that in a certain class of ESGB theories and in the extreme curvature regime there exist new black hole solutions which are formed by spontaneous scalarization

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Direct Measurement of the Solar-Wind Taylor Microscale using MMS Turbulence Campaign Data

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ABSTRACT

Using the novel Magnetospheric Multiscale (MMS) mission data accumulated during the 2019 MMS Solar Wind Turbulence Campaign, we calculate the Taylor microscale ($\lambda_T$) of the turbulent magnetic field in the solar wind. The Taylor microscale represents the onset of dissipative processes in classical turbulence theory. An accurate estimation of Taylor scale from spacecraft data is, however, usually difficult due to low time cadence, the effect of time decorrelation, and other factors. Previous reports were based either entirely on the Taylor frozen-in approximation, which conflates time dependence, or that were obtained using multiple datasets, which introduces sample-to-sample variation of plasma parameters, or where inter-spacecraft distance were larger than the present study. The unique configuration of linear formation with logarithmic spacing of the 4 MMS spacecraft, during the campaign, enables a direct evaluation of the $\lambda_T$ from a single dataset, independent of the Taylor frozen-in approximation. A value of $\lambda_T \approx 7000$ km is obtained, which is about 3 times larger than the previous estimates.

Keywords: turbulence, plasmas, solar wind

1. INTRODUCTION: TURBULENCE SCALES

Turbulence is a multi-scale phenomena. The turbulent solar wind possesses structures and processes with broad range of length scales (Verscharen et al. 2019). The different characteristic length scales enter into the dynamics in various ways. For example, the correlation scale represents the sizes of the most energetic eddies (Smith et al. 2001). The mean-free path between collisions determine the collisionality of the plasma. Proton kinetic physics dominates near the proton inertial length and gyro-radius (Leamon et al. 1998); similarly electron physics becomes important at the electron inertial length and gyro-radius (Alexandrova et al. 2012). These different characteristic scales can provide useful information regarding the propagation of energetic particles, such as cosmic rays in the solar wind (Jokipi 1973).

Of these various scales there are several related directly to fundamental turbulence properties, and understanding these in various space and astrophysical venues contributes in the understanding of physical effects ranging from reconnection to particle heating and scattering. For an initial orientation, we can appeal to analogies with hydrodynamics, to outline relationships that exist among these scales in classical turbulence. Accordingly, we use as a reference point the case in which the dissipation is controlled by a simple scalar kinematic viscosity $\nu$. We may begin with the scale at which the bulk of turbulence energy resides, or is injected; we call this the energy-containing scale $\lambda_c$. For a turbulence amplitude

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One residue to rule them all:
Electroweak symmetry breaking, inflation and field-space geometry

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We point out that the successful generation of the electroweak scale via gravitational instanton configurations in certain scalar-tensor theories can be viewed as the aftermath of a simple requirement: the existence of a quadratic pole with a sufficiently small residue in the Einstein-frame kinetic term for the Higgs field. In some cases, the inflationary dynamics may also be controlled by this residue and therefore related to the Fermi-to-Planck mass ratio, up to possible uncertainties associated with the instanton regularization. We present here a unified framework for this hierarchy generation mechanism, showing that the aforementioned residue can be associated with the curvature of the Einstein-frame target manifold in models displaying spontaneous breaking of dilatations. Our findings are illustrated through examples previously considered in the literature.

I. INTRODUCTION AND SUMMARY

The seminal discovery of the Higgs field at the LHC has left us with a perfect Standard Model (SM) of particle physics potentially valid up to energies well above the Planck scale $M_P = 2.48 \times 10^{18}$ GeV. At the same time, it left unsolved one of the most mysterious puzzles in particle physics: the so-called hierarchy problem.1 This has two facets. The first one is the extreme sensitivity of the Higgs mass to whatever happens above the electroweak scale. Several ways of overpassing this difficulty have been proposed in the literature. One of them is to require new physics to appear around the TeV scale (e.g. low-energy supersymmetry, technicolor/composite Higgs, large extra dimensions, see for instance Refs. [2–4]). Another option is to postulate a dynamical relaxation mechanism, like the cosmological attractor scenario [5–8] or its recent variants and generalizations [9, 10]. Alternatively, one could require the absence of additional particle states all the way up till the Planck scale [11–16]. Of course, the long-standing question of what happens around and beyond that point still remains. A priori, it is conceivable that quantum gravity corrections may either turn out to be negligibly small, or take care of the problem completely [17, 18]. In addition, it might be the case that the fundamental gravitational degrees of freedom above $M_P$ are black holes [19], being their influence on low-energy physics exponentially suppressed at least by a Boltzmann factor proportional to the entropy [20]. We will content here with assuming that, if such contributions are present to start with, the theory is liberated from them in one way or another. This leaves us with the second facet of the hierarchy problem: the origin of the 16 orders of magnitude difference between the electroweak and the Planck scale.

Non-perturbative effects constitute a natural tool for obtaining “small numbers,” especially in models with negligible perturbative corrections. This possibility has been advocated in certain scalar-tensor theories [21] and generalized to scale-invariant models where the Planck mass is generated by the spontaneous breaking of dilatations [22, 23], showing explicitly that a second scale can be dynamically generated by an instanton configuration. This idea was recently extended to the Palatini formulation of gravity [24].

In this short paper we generalize the findings of Refs. [21–24], isolating the fundamental ingredients for successfully generating the electroweak scale via instanton effects. In particular, we argue that:

1. Any scenario able to bring the (conformal) SM scalar sector at large Higgs values to the approximate form

$$\mathcal{L} \approx \frac{M_P^2}{2} R - \frac{1}{2} \frac{M_P^2}{|\kappa_c|} \Theta^2 - V_0,$$

with $g$ the metric determinant, $R$ the scalar curvature, $\Theta \propto h^{-1}$, $h$ the Higgs field in the unitary gauge and $V_0$ an approximately constant potential, will be able to generate a large hierarchy among the electroweak and the Planck scale for sufficiently large values of the inverse residue $|\kappa_c|$.

2. Provided that the scale $V_0$ is compatible with the COBE normalization [25], the inverse residue $|\kappa_c|$ controls also the inflationary observables. Consequently, if the above splitting mechanism is operative, inflation is intimately related to the electroweak symmetry breaking, making a priori possible to infer the value of the Fermi scale from CMB observations [24, 26].

3. The above reasoning holds true irrespectively of the nature of the gravitational interaction. The differ-
Discovering Symbolic Models from Deep Learning with Inductive Biases

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Abstract

We develop a general approach to distill symbolic representations of a learned deep model by introducing strong inductive biases. We focus on Graph Neural Networks (GNNs). The technique works as follows: we first encourage sparse latent representations when we train a GNN in a supervised setting, then we apply symbolic regression to components of the learned model to extract explicit physical relations. We find the correct known equations, including force laws and Hamiltonians, can be extracted from the neural network. We then apply our method to a non-trivial cosmology example—a detailed dark matter simulation—and discover a new analytic formula which can predict the concentration of dark matter from the mass distribution of nearby cosmic structures. The symbolic expressions extracted from the GNN using our technique also generalized to out-of-distribution-data better than the GNN itself. Our approach offers alternative directions for interpreting neural networks and discovering novel physical principles from the representations they learn.

1 Introduction

The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve. We should be grateful for it and hope that it will remain valid in future research and that it will extend, for better or for worse, to our pleasure, even though perhaps also to our bafflement, to wide branches of learning.—Eugene Wigner

“The Unreasonable Effectiveness of Mathematics in the Natural Sciences” (I).

For thousands of years, science has leveraged models made out of closed-form symbolic expressions, thanks to their many advantages: algebraic expressions are usually compact, present explicit interpretations, and generalize well. However, finding these algebraic expressions is difficult. Symbolic regression is one option: a supervised machine learning technique that assembles analytic functions to model a given dataset. However, typically one uses genetic algorithms—essentially a brute force procedure as in [2]—which scale exponentially with the number of input variables and operators. Many machine learning problems are thus intractable for traditional symbolic regression.

On the other hand, deep learning methods allow efficient training of complex models on high-dimensional datasets. However, these learned models are black boxes, and difficult to interpret.

Preprint. Under review.

Anonymized example code can be found at https://github.com/MilesCranmer/symbolic_deep_learning

The Hubble Tension in Light of the Full-Shape Analysis of Large-Scale Structure Data

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\textbf{Abstract} The disagreement between direct late-time measurements of the Hubble constant from the SH0ES collaboration, and early-universe measurements based on the $\Lambda$CDM model from the Planck collaboration might, at least in principle, be explained by new physics in the early universe. Recently, the application of the Effective Field Theory of Large-Scale Structure to the full shape of the power spectrum of the SDSS/BOSS data has revealed a new, rather powerful, way to measure the Hubble constant and the other cosmological parameters from Large-Scale Structure surveys. In light of this, we analyze two models for early universe physics, Early Dark Energy and Rock ‘n’ Roll, that were designed to significantly ameliorate the Hubble tension. Upon including the information from the full shape to the Planck, BAO, and Supernovae measurements, we find that the degeneracies in the cosmological parameters that were introduced by these models are well broken by the data, so that these two models do not significantly ameliorate the tension.
Mitigation of LEO Satellite Brightness and Trail Effects on the Rubin Observatory LSST

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ABSTRACT

We report studies on mitigation of optical effects of bright Low-Earth-Orbit (LEO) satellites on Vera C. Rubin Observatory and its Legacy Survey of Space and Time (LSST). These include options for pointing the telescope to avoid satellites, laboratory investigations of bright trails on the Rubin Observatory LSST Camera sensors, algorithms for correcting image artifacts caused by bright trails, experiments on darkening SpaceX Starlink satellites, and ground-based follow-up observations. Starlink satellites with no brightness mitigation are presently $g \sim 5.1$ mag, and an initial experiment “DarkSat” is $g \sim 6.1$ mag. Future Starlink darkening plans may reach $g \sim 7$ mag, a brightness level that enables non-linear image artifact correction to the same level as background noise. However, the satellite trails will still exist at $S/N \sim 100$, generating systematics that may impact data analysis and limiting some science. LEO satellite trails are wider than a point-spread function because satellites are slightly out of focus due to their finite distance; for Rubin Observatory’s 8.4-m mirror and a satellite at 550 km, this widening effect is about 3 arcsec, which helps avoid saturation by decreasing the trail’s peak surface brightness.

Keywords: LSST — satellite constellations — miscellaneous — catalogs — surveys

1. INTRODUCTION

Innovation in spacecraft manufacturing and launch technology have resulted in a profusion of proposals to build, launch and operate constellations of many Low-Earth-Orbit (LEO) commercial satellites. Currently there are about a thousand operational LEO satellites (LEOsats) providing communications and earth imagery services, but regulatory applications filed with international agencies project an increase by as much thirtyfold in the next 5–10 years. Many such constellations are either U.S. licensed or have sought permission to operate in the U.S. There are also several other LEOsat operators in other countries with plans to launch their own constellations. Several LEOsat projects plan to offer global broadband services. In order to offer low-latency Internet access to less-populated areas of the

1 For the purposes of this paper, we apply the Low Earth Orbit definition of satellites in a spherical region that extends from the Earth’s surface up to an altitude (Z) of 2,000 km, as identified in the Space Debris Mitigation Guidelines of the Inter-Agency Debris Coordination Committee (IADC) of the United Nations Office Of Outer Space Affairs (UNOOSA).

The impact of exoplanets’ measured parameters on the inferred internal structure

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ABSTRACT

Context. Exoplanet characterization is one of the main foci of current exoplanetary science. For super-Earths and sub-Neptunes, we mostly rely on mass and radius measurements, which allow to derive the body’s mean density and give a rough estimate of the planet’s bulk composition. However, the determination of planetary interiors is a very challenging task. In addition to the uncertainty in the observed fundamental parameters, theoretical models are limited due to the degeneracy in determining the planetary composition.

Aims. We aim to study several aspects that affect internal characterization of super-Earths and sub-Neptunes: observational uncertainties, location on the M-R diagram, impact of additional constraints as bulk abundances or irradiation, and model assumptions.

Methods. We use a full probabilistic Bayesian inference analysis that accounts for observational and model uncertainties. We employ a Nested Sampling scheme to efficiently produce the posterior probability distributions for all the planetary structural parameter of interest. We include a structural model based on self-consistent thermodynamics of core, mantle, high-pressure ice, liquid water, and H-He envelope.

Results. Regarding the effect of mass and radius uncertainties on the determination of the internal structure, we find three different regimes: below the Earth-like composition line and above the pure-water composition line smaller observational uncertainties lead to better determination of the core and atmosphere mass respectively, and between them internal structure characterization only weakly depends on the observational uncertainties. We also find that using the stellar Fe/Si and Mg/Si abundances as a proxy for the bulk planetary abundances does not always provide additional constraints on the internal structure. Finally we show that small variations in the temperature or entropy profiles lead to radius variations that are comparable to the observational uncertainty. This suggests that uncertainties linked to model assumptions can eventually become more relevant to determine the internal structure than observational uncertainties.

Conclusions. The masses and radii can be used to estimate a planet’s interior structure and composition. However, determining the internal structure is extremely challenging due to the intrinsic degeneracy as several compositions can lead to identical mass and radius (e.g. Rogers & Seager 2010; Lopez & Fortney 2014; Dorn et al. 2015, 2017; Lozovsky et al. 2018). Furthermore, for a planet of given mass and composition, the radius depends on several aspects as the choice of Equation of State (EOS), the envelope structure (differentially, fully mixed or with a compositional gradient) or the temperature. This degeneracy is critical due to the large number of free parameters needed to model the interior of an exoplanet and the few observational constraints. In order to determine how well one interior model compares with the other possible models that also fit the data and which structural parameters can be actually constrained, Dorn et al. (2017) presented a generalized Bayesian inference method to quantify the degeneracy and correlation of the planetary structural parameters.

1. Introduction

Over the past few years, the characterization of planet interiors has been subject of extensive research. The large amount and diversity of discovered exoplanets has allowed to identify different planet populations. Among them, there is an increasing interest on super-Earths and sub-Neptunes, which cover the transition from terrestrial planets to gas giants and have no analog in our Solar System. Major improvements in observational techniques allow for relatively precise measurements of mass and radius. The precision of the planetary radius is limited by the uncertainty of the stellar size, since the transit depth scales as $R_p^2/R_*^2$. Recently Berger et al. (2018) presented revised radii of more than 180,000 Kepler stars, leading to a remarkable improvement of the median radius precision.

In some cases space missions can perform high precision photometry and asteroseismology, and can reach relative radius uncertainties of about 3% (e.g. Hatzes 2016). In addition, current most advanced spectrographs have radial velocity precision of 1m/s, which was recently improved with instruments like ESPRESSO (e.g., Pepe et al. 2018 and references therein), which is expected to have an accuracy close to 10 cm/s. Therefore it is also expected a significant improvement in the mass determination, allowing to reach a relative better than 10%.

The masses and radii can be used to estimate a planet’s interior structure and composition. However, determining the internal structure is extremely challenging due to the intrinsic degeneracy as several compositions can lead to identical mass and radius (e.g. Rogers & Seager 2010; Lopez & Fortney 2014; Dorn et al. 2015, 2017; Lozovsky et al. 2018). Furthermore, for a planet of given mass and composition, the radius depends on several aspects as the choice of Equation of State (EOS), the envelope structure (differentially, fully mixed or with a compositional gradient) or the temperature. This degeneracy is critical due to the large number of free parameters needed to model the interior of an exoplanet and the few observational constraints. In order to determine how well one interior model compares with the other possible models that also fit the data and which structural parameters can be actually constrained, Dorn et al. (2017) presented a generalized Bayesian inference method to quantify the degeneracy and correlation of the planetary structural parameters.

In this work we explore the limitations to constrain the internal structure of super-Earths and sub-Neptunes (focusing on planets with masses up to 25M⊕ and radii up to 3.5M⊕). We use a Bayesian inference analysis together with a Nested Sampling technique (e.g. Skilling 2004) to discuss several aspects that affect interior characterization: observational uncertainties, loca-
Astronomical Classification of Light Curves with an Ensemble of Gated Recurrent Units

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ABSTRACT
With an ever-increasing amount of astronomical data being collected, manual classification has become obsolete; and machine learning is the only way forward. Keeping this in mind, the Large Synoptic Survey Telescope (LSST) Team hosted the Photometric LSST Astronomical Time-Series Classification Challenge (PLAsTiCC) in 2018. The aim of this challenge was to develop ML models that accurately classify astronomical sources into different classes, scaling from a limited training set to a large test set. In this text, we report our results of experimenting with Bidirectional Gated Recurrent Unit (GRU) based models to deal with time series data of the PLAsTiCC data. We demonstrate that GRUs are indeed suitable to handle time series data. With minimum preprocessing and without augmentation, our stacked ensemble of GRU and Dense networks achieves an accuracy of 76.243%. Data from astronomical surveys such as LSST will help researchers answer questions pertaining to dark matter, dark energy and the origins of the universe; accurate classification of astronomical sources is the first step towards achieving this.

Our code is open-source and has been made available on GitHub here: https://github.com/AKnightWing/Astronomical-Classification-PLASTICC

Key words: methods: data analysis – techniques: photometric

1 INTRODUCTION
Over the last decade, numerous large scale astronomical surveys have been conducted to systematically collect images of the night sky using various spectroscopic and photometric methods. These surveys have, in turn, led to the discovery of an unprecedented number of transients as well as variable astronomical objects. However, with the ever-increasing size of available data, these surveys have also brought to light the problem of astronomical classification for big data.

NASA’s Kepler Space Telescope, designed to determine the occurrence rate of Earth-sized planets in temperate orbits around Sun-like stars, photometrically observed about 200,000 stars (Jenkins et al. (2010); Koch et al. (2010); Christiansen et al. (2015)) and discovered thousands of transiting exoplanets (Borucki et al. (2011a), Borucki et al. (2011b); Batalha et al. (2011); Burke et al. (2014); Rowe et al. (2014)). In the first stage of its operation, Sloan Digital Sky Survey (SDSS; Frieman et al. (2007)) measured the spectra of more than 700,000 celestial objects, and the SDSS Supernova Survey measured light curves for a few hundred supernovae, of which spectroscopic confirmations for 500 SN Ia and about 80 core-collapsed supernovae were obtained. Between 2013 and 2019, the Dark Energy Survey (DES; Collaboration: et al. (2016)) recorded information from about 300 million galaxies. The Zwicky Transient Facility (ZTF; Kulkarni (2016)), a collaboration project by Caltech and other notable institutions, had first light at Palomar Observatory in 2017. ZTF produced ~1 terabyte (TB) of raw image data and ~4 TB of real-time data products each night (on an average uninterrupted observing night spanning ~8 hr 40 min), and over the course of the nominal three-year survey, this would amount to ~50 TB of light curve data, ~60 TB of reference image products; the total volume of data amounting to ~3.2 petabytes (PB) (260 good weather observing nights) (Masci et al. 2018). ZFT will form the basis of even larger surveys such as the LSST which will build on ZFT’s rapid scans of the sky. The enormous Vera C. Rubin Telescope and its ambitious Legacy Survey of Space and Time will usher in a new-age by generating ~20 TB of data per night, with the final dataset expected to be ~15 PB. During its ten-year survey duration, it is expected to observe $2 \times 10^{10}$ galaxies, $1.7 \times 10^{10}$ resolved stars and discover $10^7$ supernovae (Collaboration et al. 2009).

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Note: Any bugs can be reported on Github itself.

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Scaling relations for dark matter core density and radius from Chandra X-ray cluster sample

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A large number of studies have found that the dark matter surface density, given by the product of the dark matter core radius ($r_c$) and core density ($\rho_c$) is approximately constant for a wide range of galaxy systems. However, there has been only one systematic study of this ansatz for galaxy clusters by Chan [1], who found that the surface density for clusters is not constant and $\rho_c \sim r_c^{-1.46}$. We implement a test of this ansatz for an X-ray sample of 12 relaxed clusters from Chandra observations, studied by Vikhlinin et al [2], implementing the same procedure as in Chan [1], but also accounting for the gas and star mass. We find that $\rho_c \propto r_c^{-1.08 \pm 0.055}$ with an intrinsic scatter of about 18%. Therefore, we get a much shallower slope for the relation between core density and radius as compared to previous estimates, and the dark matter surface density shows deviations from a constant value at only about 1.4σ.

I. INTRODUCTION

The current concordance ($\Lambda$CDM) cosmological model consisting of 25% cold dark matter and 70% dark energy, agrees very well with Planck CMB and large scale structure observations [3]. However, at scales smaller than about 1 Mpc, the cold dark matter paradigm runs into a number of problems such as the core/cusp problem, missing satellite problem, too big to fail problem, satellites plane problem etc (See Refs. [4, 5] for recent reviews on this subject). At a more fundamental level, another issue with the $\Lambda$CDM model is that there is no laboratory evidence for any cold dark matter candidate, or theories beyond the Standard Model of Particle Physics, which predict such candidates [6]. Therefore, a large number of theoretical alternatives to $\Lambda$CDM model have been proposed, and a variety of observational tests devised to test these myriad alternatives.

An intriguing observational result discovered more than a decade ago is that the dark matter halo surface density is constant, for a wide variety of systems spanning over 18 orders in blue magnitude for a diverse suite of galaxies, such as spiral galaxies, low surface brightness galaxies, dwarf spheroidal satellites of Milky way [7–16] etc. See however Refs. [17–21] and references therein, which dispute these claims and argue for a mild dependence of the dark matter surface density with halo mass. These results for a constant dark matter surface density were obtained by fitting the dark matter distribution in these systems to a cored profile, either Burkert [22], pseudo-isothermal profile [7], or a simple isothermal sphere [23]. All these cored profiles can be parameterized by a central density ($\rho_c$) and core radius ($r_c$); and the halo surface density is defined as the product of $\rho_c$ and $r_c$. The existence of a constant dark matter surface density was found to be independent of which cored profile was used [8]. Alternately, some groups have also calculated a variant of the above dark matter halo density, which has been referred to as the dark matter column density [17, 19] $^1$, whose value remains roughly invariant with respect to the choice of the dark matter profile. This column density is equivalent to the product of $\rho_c$ and $r_c$ for a Burkert profile [19], and provides a more precise value of the surface density for non-cored profiles, such as the widely used NFW profile [24]. The best-fit values for the dark matter surface density for single galaxy systems using the latest observational data is given by $\log(\rho, r_c) = 2.15 \pm 0.2M_{\odot}pc^{-2}$ [16].

A large number of theoretical explanations have been proposed to explain the constancy of dark matter halo density. Within the standard $\Lambda$CDM model, some explanations include: transformation of cusps to cores due to dynamical feedback processes [25], self-similar secondary infall model [17, 19, 26], dark matter-baryon interactions [27], ultralight scalar dark matter [28], super-fluid dark matter [29], self-interacting dark matter [30–33], MOND [34], etc. This observation may be in tension with some fuzzy dark matter models [35].

It behooves us to test the same relation for galaxy clusters. Galaxy clusters are the most massive collapsed objects in the universe and are a wonderful laboratory for a wide range of topics from cosmology to galaxy evolution [36, 37]. In the last two decades a large number of new galaxy clusters have been discovered through dedicated optical, X-ray, and SZ surveys, which have provided a wealth of information on Astrophysics and Cosmology. However, tests of the constancy of dark matter surface density for galaxy clusters have been very few.

The first such study for galaxy clusters was done by Boyarsky et al [38], who used the dark matter profiles from literature for 130 galaxy clusters and showed that the dark matter column density ($S$) goes as $S \propto M_{200}^{21}$. $^1$ See Eq. 1 of Ref. [17] for the definition of dark matter column density.
Inferring contributions from unresolved point sources to diffuse emissions measured in UV sky surveys: general method and SOHO/SWAN case study

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ABSTRACT

In observations of diffuse emissions like, e.g., the Lyman-α heliospheric glow, contributions to the observed signal from point sources (e.g., stars) are considered as a contamination. There are relatively few brightest point sources that are usually properly resolved and can be subtracted or masked. We present results of analysis of the distribution of point sources using UV sky-survey maps from the SOHO/SWAN instrument and spectrophotometry data from the IUE satellite. The estimated distribution suggests that the number of these sources increases with decreasing intensity. Below a certain threshold, these sources cannot be resolved against the diffuse signal from the backscatter glow, that results in a certain physical background from unresolved point sources.

Detection, understanding and subtraction of the point-source background has implications for proper characterization of diffuse emissions and accurate comparison with models. Stars are also often used as standard candles for in-flight calibration of satellite UV observations, thus proper understanding of signal contributions from the point sources is important for the calibration process. We present a general approach to quantify the background radiation level from unresolved point sources in UV sky-survey maps. In the proposed method, a distribution of point sources as a function of their intensity is properly integrated to compute the background signal level. These general considerations are applied to estimate the unresolved-point-sources background in the SOHO/SWAN observations that on average amounts to 28.9 R. We discuss also the background radiation anisotropies and general questions related to modeling the point-source contributions to diffuse UV-emission observations.

1. INTRODUCTION

Diffuse UV radiation from various regions of the sky is an interesting problem in several space physics and astrophysical contexts, e.g., for diagnostics of astrophysical plasmas,
High-energy processes in starburst-driven winds

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23 June 2020

ABSTRACT
Starburst galaxies generate large-scale winds powered by the activity in the star-forming regions located in the galactic disks. Fragmentation of the disk produced by the outbreak of the wind results in the formation of clouds. Bowshocks caused by the supersonic outflow appear around such clouds. In this paper we discuss the acceleration of relativistic particles and the production of non-thermal radiation in such scenario. Cosmic rays accelerated at the bowshocks do not reach the highest energies, although the high-energy luminosity generated is significant. We show that up to $\sim 10\%$ of the gamma-ray emission in starbursts might come from these sources outside the galactic disks. Discrete X-ray sources with a power-law component are also expected.

Key words: acceleration of particles – radiation mechanisms: non-thermal – cosmic rays – ISM: clouds – galaxies: starburst – shock waves

1 INTRODUCTION
Starburst galaxies have intense episodes of star formation in their galactic disks. This activity results in the formation of a galactic wind that breaks out from the disk and expands into the halo of the galaxy, sweeping gas and forming a hot region that is usually detected in X-rays. The galactic wind transports metals created in the disk and injects them into the halo and the intergalactic medium (for a recent review see, e.g., Veilleux et al. (2005)). The standard model for the production of galactic winds was proposed long ago by Chevalier & Clegg (1985): the combined effect of supernova explosions and stellar winds creates a very hot bubble in the star forming region ($T \sim 10^{6} K$). The internal pressure of this gas is so high that it exceeds the gravitational binding energy and the gas disrupts the disk, expanding adiabatically through the halo and dragging with it fragments of the cold matter that formed the disk. The wind sweeps the ambient gas creating a multi-phased bubble with cold, warm, and hot components (Strickland et al. 2002).

Because of the existence of multiple shocks, a high-metallicity environment, and a huge energy budget, starbursts are considered as sites of non-thermal particle acceleration and high-energy radiation (Paglione et al. 1996; Bykov 2001; Romero & Torres 2003; Domingo-Santamaria & Torres 2005; Rephaeli et al. 2010; Bykov 2014; Peretti et al. 2019). This has been confirmed by the gamma-ray detection of nearby starburst galaxies (Acero et al. 2009; Abdo et al. 2010; Ackermann et al. 2012; Ohm 2016).

The indication of a non-zero metallicity content in the ultra high-energy cosmic ray spectrum also suggests nearby starbursts as possible sites of cosmic ray acceleration up to energy of around $10^{20}$ eV. This was first proposed by Anchordoqui et al. (1999) and recently revisited by Anchordoqui et al. (2018) and Romero et al. (2018). However, Romero et al. (2018) have found that the conditions necessary to achieve energies of $\sim 10^{20}$ eV in the hot wind region seem to be unphysical and at odds with the observational data. Typical velocities of the galactic winds are of the order of

$$v_{\text{wind}} \approx \sqrt{2E/M} \sim 10^{3} \text{ km s}^{-1},$$

where $E$ and $M$ are the total energy released in the starburst region and the mass input, respectively. The magnetic field in the halo of the galaxy NGC 253, a southern well-known galaxy with star forming activity, has been determined through radio polarization observations by Heesen et al. (2009) and is of the order of 5 $\mu$G. The average particle density in the galactic wind bubble of radius $R_b \sim 5$ kpc is $n_p \sim 2 \times 10^{-3}$ cm$^{-3}$ (Strickland et al. 2002). With such parameters, diffusive shock acceleration yields maximum energies of $\sim 10^{16}$ and $\sim 5 \times 10^{17}$ eV for protons and iron nuclei, respectively (see Romero et al. 2018 for a detailed discussion). Anchordoqui (2018) invokes higher values of the magnetic field, of $\sim 300 \mu$G. With such a value the magnetic energy density $u_B = B^2/8\pi$ is $\sim 4 \times 10^{-9}$ erg cm$^{-3}$. But the ram pressure of the gas is $u_g \approx n_w m_p v_w^2 \sim 10^{-11}$ erg cm$^{-3}$.
MEMS Mirror Manufacturing and Testing for Innovative Space Applications

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Abstract: In the framework of the GLARE-X (Geodesy via LAser Ranging from spacE X) project, led by INFN and funded for the years 2019-2021, aiming at significantly advance space geodesy, one shows the initial activities carried out in 2019 in order to manufacture and test adaptive mirrors. This specific article deals with manufacturing and surface quality measurements of the passive substrate of ‘candidate’ MEMS (Micro-Electro-Mechanical Systems) mirrors for MRRs (Modulated RetroReflectors); further publications will show the active components. The project GLARE-X was approved by INFN for the years 2019-2021: it involves several institutions, including, amongst the other, INFN-LNF and FBK. GLARE-X is an innovative R&D activity, whose at large space geodesy goals will concern the following topics: inverse laser ranging (from a laser terminal in space down to a target on a planet), laser ranging for debris removal and iterative orbit correction, development of high-end ToF (Time of Flight) electronics, manufacturing and testing of MRRs for space, and provision of microreflectors for future NEO (Near Earth Orbit) cubesats. This specific article summarizes the manufacturing and surface quality measurements activities performed on the passive substrate of ‘candidate’ MEMS mirrors, which will be in turn arranged into MRRs. The final active components, to be realized by 2021, will inherit the manufacturing characteristics chosen thanks to the presented (and further) testing campaigns, and will find suitable space application to NEO, Moon, and Mars devices, like, for example, cooperative and active lidar scatterers for laser altimetry and lasercomm support.

Keywords: CCR (Cube Corner Retroreflector); MEMS; MRR.

1. Introduction

The SCF_Lab (Satellite/lunar/GNSS laser ranging/altimetry and cube/microsat Characterization Facilities Laboratory) is an infrastructure devoted to space R&D, which has been operational for the last 15 years. It belongs to INFN-LNF, and it has got widely recognized capabilities for the design, test and space qualification of space laser retroreflectors, and laser ranging systems and services. The laboratory itself is located within an 85 m² class 10,000 (ISO 7) clean room, with separate entry areas for operators and equipment. The clean room hosts two OGSEs (Optical Ground Support Equipments): respectively, the SCF, and the SCF-G (especially thought for satellite navigation applications) apparatus. Each one of the OGSE can independently run thermo-optical qualification tests, thanks to a substantial dotation of hardware, including: cryostat, positioning system, thermal control system, control electronics, vacuum system, AM0 solar simulator, optical bench with imagers, and laser wavefront Fizeau interferometer (Figure 1).
New H\textsc{i} observations of KK 69.
Is KK 69 a dwarf galaxy in transition?

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Abstract

We present new H\textsc{i} data of the dwarf galaxy KK 69, obtained with the Giant Metrewave Radio Telescope (GMRT) with a signal-to-noise ratio that almost doubles previous observations. We carried out a Gaussian spectral decomposition and stacking methods to identify the cold neutral medium (CNM) and the warm neutral medium (WNM) of the H\textsc{i} gas. We found that 30\% of the total H\textsc{i} gas, which corresponds to a mass of $\sim 10^7$ M\textsubscript{$\odot$}, is in the CNM phase. The distribution of the H\textsc{i} in KK 69 is not symmetric. Our GMRT H\textsc{i} intensity map of KK 69 overlaid onto a Hubble Space Telescope image reveals an offset of $\sim 4$ kpc between the H\textsc{i} high-density region and the stellar body, indicating it may be a dwarf transitional galaxy. The offset, along with the potential truncation of the H\textsc{i} body, are evidence of interaction with the central group spiral galaxy NGC 2683, indicating the H\textsc{i} gas is being stripped from KK 69. Additionally, we detected extended H\textsc{i} emission of a dwarf galaxy member of the group as well as a possible new galaxy located near the north-eastern part of the NGC 2683 H\textsc{i} disk.

Keywords galaxies: groups: individual: KK 69, KK 70, NGC 2683 — galaxies: interactions — radio lines: galaxies

1 Introduction

The dwarf transition galaxies share properties with dwarf irregular (dIrr) galaxies (such as the H\textsc{i} content) as well as with dwarf spheroidal (dSph) galaxies (low luminosity and old stellar populations, see for instance Grebel \textit{et al.} (2003)). In most of these galaxies, a positional offset is observed between the stellar and the H\textsc{i} component. Mateo (1998), Skillman \textit{et al.} (2003), and Grebel \textit{et al.} (2003) proposed a classification scheme for dwarf transition galaxies based on H\textsc{i} and H\textsc{a} flux. According to this classification, dwarf transition galaxies are detected in H\textsc{i} with very little or no H\textsc{a} flux indicating a gas depletion timescale higher than 100 Gyr. Even though the origin of the dwarf transition galaxies are not fully understood, many studies contemplate the idea that these galaxies could be the precursors of the dSph galaxies (see, e.g. Kormendy and Bender 2012; Grecevich and Putman 2009). Hence, the dwarf transition galaxies could serve as a link between the late-type and early-type dwarf galaxies.

The shallow potential well of dwarf galaxies makes their interstellar medium highly susceptible to disruptions by environmental forces as well as internal processes. The star formation bursts are the primary internal reason of disarrangement and mass loss in dwarf galaxies (Larson 1974; Vader 1986; Dekel and Silk 1986), while the ram-pressure stripping and tidal interactions are the main external mechanisms of gas removal. The efficiency of ram-pressure stripping depends on the intragroup medium density and the velocity of the galaxy through the medium (Gunn and Gott 1972); it is common to observe a tail feature in the
A Generalized Kompaneets Formalism for Inelastic Neutrino-Nucleon Scattering in Supernova Simulations

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Based on the Kompaneets approximation, we develop a robust methodology to calculate spectral redistribution via inelastic neutrino-nucleon scattering in the context of core-collapse supernova simulations. The resulting equations conserve lepton number to machine precision and scale linearly, not quadratically, with number of energy groups. The formalism also provides an elegant means to derive the rate of energy transfer to matter which, as it must, automatically goes to zero when the neutrino radiation field is in thermal equilibrium. Furthermore, we derive the next-higher-order in $\epsilon/mc^2$ correction to the neutrino Kompaneets equation. Unlike other Kompaneets scheme, ours also generalizes to the case of anisotropic angular distributions, while retaining the conservative form that is a hallmark of the classical Kompaneets equation. Our formalism enables immediate incorporation into supernova codes that follow the spectral angular moments of the neutrino radiation fields.

I. INTRODUCTION

Due to substantial progress over the last decade on many fronts, the general viability of the neutrino heating mechanism of core-collapse supernovae (CCSNe) has been put on a firmer foundation. Though most spherical (1D) models do not explode, most, though not all, two-dimensional (2D) axisymmetric and three-dimensional (3D) models incorporating sophisticated neutrino physics, state-of-the-art numerical tools, realistic nuclear equations of state (EOSes), and detailed massive-star progenitor models do explode. Despite the resource intensity of many of these complex models, theorists are now able to explore suites of multidimensional simulations and map the parameter dependencies of the remaining ambiguities. What has emerged is a nuanced understanding of the factors of explosion. The latter include sufficient neutrino heating behind a temporarily-stalled bounce shock wave as the direct agency of explosive power; the crucial role of anisotropic turbulence in augmenting the driving stress behind the shock; the breaking of spherical symmetry to allow simultaneous accretion and explosion (the former to ensure the continuance of sufficient driving neutrino emissions from the residual proto-neutron star (PNS), despite the reversal of infall implied by explosion); and core progenitor structures that are conducive to eventual explosive instability. In addition, the potential roles of many-body neutrino-matter interactions, of turbulence in the progenitor cores themselves, of remaining uncertainties in the nuclear EOS, and of rotation and magnetic fields in a subset of massive-star explosions continue to exercise the community. At least as important, the precise mapping between progenitor structure and outcome, importantly including explosion energy, residual mass (and whether a neutron star or black hole is birthed), recoil kicks, pulsar and magnetic fields, and nucleosynthetic yields, has yet to be convincingly determined. Hence, despite the palpable progress claimed above, much remains to be done.

Neutrino heating of material behind a stalled shock itself drives the turbulence and they together seem central to reversing an accretion shock into explosion. Therefore, the energy deposition rate due to neutrino-matter interactions in the semi-transparent “gain region” between the PNS left behind and the shock assumes a pivotal role. The dominant processes are super-allowed charged-current absorption of electron neutrinos ($\nu_e$) and anti-electron neutrinos ($\bar{\nu}_e$) on nucleons, via the reactions $\nu_e + n \rightarrow e^- + p$ and $\bar{\nu}_e + p \rightarrow e^+ + n$, respectively. Though the cross sections for these processes involve some subtleties, they are well understood. However, inelastic scattering of neutrinos of all neutrino species on electrons and on nucleons also heat the matter, though at a lower rate. However, when a model is near explosion, even 10% – 20% effects can loom large and such is the case here. The low cross sections of neutrino-electron scattering coupled with the high average energy transfer to the electrons (due to the low electron mass) competes with the high cross section of neutrino-nucleon scattering coupled with its correspondingly low recoil energies (due to the high nucleon mass). The net result is comparable matter heating rates. Therefore, it is important to handle inelasticity for both reaction classes in sophisticated transport schemes. For neutrino-electron

1 though the so-called “SASI” (Standing Accretion Shock Instability) can play a subdominant role

2 It is in part turbulence and its chaotic character that mitigates against a simple correspondence between progenitor structure and outcome and makes theoretical prediction complex. As a result, current thinking is that Nature provides distribution functions of final state properties (explosion energy, kick speed, morphology, nucleosynthesis, proto-neutron star mass, etc.) for a given progenitor. What these distribution functions may be is a topic of future research.
Abstract

The authors of this white paper met on 16-17 January 2020 at the New Jersey Institute of Technology, Newark, NJ, for a 2-day workshop that brought together a group of heliophysicists, data providers, expert modelers, and computer/data scientists. Their objective was to discuss critical developments and prospects of the application of machine and/or deep learning techniques for data analysis, modeling and forecasting in Heliophysics, and to shape a strategy for further developments in the field. The workshop combined a set of plenary sessions featuring invited introductory talks interleaved with a set of open discussion sessions. The outcome of the discussion is encapsulated in this white paper that also features a top-level list of recommendations agreed by participants.
I. INTRODUCTION

Determining the compositions and internal structures of planets is a key objective in planetary science. Modelling planetary interiors, however, is not possible without knowledge of the behaviour of materials at high pressures and temperatures. The requirement to have a proper description of the EOS of various elements at planetary conditions sets the connection between the high-pressure physics and planetary science communities. At the same time, planets are natural laboratories for material in exotic conditions, providing qualitative information about materials at high pressures. In this review, we concentrate on the gas giant planets Jupiter and Saturn that are mostly composed of hydrogen (H) and helium (He). These two elements account for about 87% and 75% of their total mass, respectively.

Understanding dense hydrogen at planetary conditions
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H-He are the lightest and most common elements in the Universe, and they account for nearly all the nuclear matter. Nevertheless, their behaviour at high pressures is still not fully understood and is subject of intense research [1]. Understanding the nature of the giant planets is linked to the equation of state (EOS) of H-He: for example, the bulk density of Jupiter and Saturn is larger than that of pure H-He composition. From their densities it can already be concluded that both planets must include heavier elements (typically assumed to be rock/ices), with Saturn being more enriched than Jupiter. The predicted total mass of heavier elements depends on the H-He EOS. This in turn leads to different inferred total heavy-element masses in the planets and their distributions (see section IV for details).

In addition, the fact that both Jupiter and Saturn have strong magnetic fields implies that the material in their deep interiors is electrically conductive. Since both planets are primarily composed of H it suggests that hydrogen, which is a non-conducting molecular gas at standard conditions, changes its behaviour drastically when compressed to high densities and becomes a mono-atomic metal. Metallisation of solid H has been predicted by Wigner & Huntington [2] to occur at 25 GPa already in 1935 based on the nearly free electron model. The quest for metallic hydrogen has been a major stimulus for high-pressure research since then which has led to many breakthroughs in high-pressure experimental techniques, in particular using diamond anvil cells (DACs). Up to now five solid phases were identified with increasing pressure up to the 400 GPa region (for a recent review, see [3]): a hcp solid phase I which is a molecular insulator, a broken-symmetry phase II above 60 GPa and below 100 K with partially ordered molecules, a hcp solid phase III with an unusual intense infrared activity. Further high-pressure solid phases were detected only recently. Phase IV has drastically changed optical properties and structure search studies suggest that it consists of alternating layers of exciton rings and free-molecules. This phase transforms gradually into phase V between 275 GPa and 325 GPa at 300 K which is perhaps partially atomic, i.e., it is a precursor for mono-atomic, pure metallic hydrogen. The great influence of correlations in strongly compressed hydrogen, of quantum mechanical effects, and of the complex high-pressure structures as well as their mutual interconnections hinder a full understanding of the transformations from a molecular solid to a mono-atomic metal, in particular, the role of pressure-driven dissociation.

Conducting fluid hydrogen was observed in reverberating shock-wave experiments 60 years later [4] which showed that magnetic field generation in Jupiter starts at about 140 GPa, i.e., much closer to its surface than previously thought. In this review, we focus on the gas giant planets Jupiter and Saturn and therefore the behavior of H (and He), but similar arguments hold for water and ammonia, simple compounds that we observe as insulating in our everyday life, but should be conductive at high pressures to explain the magnetic fields of Uranus and Neptune that both planets must include heavier elements (typically assumed to be rocks/ices), with Saturn being more enriched than Jupiter. The predicted total mass of heavier elements depends on the H-He EOS. This in turn leads to different inferred total heavy-element masses in the planets and their distributions (see section IV for details).

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The availability of accurate measurements of the planets' gravitational and magnetic fields requires the development of detailed structural models of the planets. The planetary internal structure is inferred from theoretical models that fit the available observational constraints by using theoretical EOSs for H, He, their mixtures, and the heavier elements. These models are guided by experiments and theoretical calculations of the thermodynamic properties of the relevant materials at high pressures. Planetary interior models however, are non-unqiue and several of the assumptions made by the models rely on physical and chemical processes that are not fully understood (see section IV for discussion). Nevertheless, modeling giant planets is not possible without having a reliable EOS for H. Since laboratory experiments cannot cover the entire phase diagram for all relevant compositions, especially at extreme conditions (see section II.A), they need to be accompanied and complemented by theoretical calculations of the strongly interacting quantum systems of electrons and nuclei. Numerical simulations solve the corresponding N-particle Schrödinger equation using techniques like quantum Monte Carlo (QMC) or Density Functional Theory (DFT) simulations as discussed in section II.B. Figure 1 shows the hydrogen phase diagram in the typical ranges of pressure and temperature relevant for the giant planets.

This review provides an overview of the EOS of hydrogen, and hydrogen-helium EOS at planetary conditions, and the link between planetary interiors and high-pressure phases. In section II, we survey the progress in the experimental and theoretical/numerical fronts. In section III, we discuss the behavior of hydrogen and a hydrogen-helium mixture at planetary conditions. Section IV briefly discusses key planetary interiors are models, focusing on Jupiter and Saturn. The current challenges and future are summarized in section V.
VTXO: the Virtual Telescope for X-ray Observations

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ABSTRACT

The Virtual Telescope for X-ray Observations (VTXO) will use lightweight Phase Frensel Lenses (PFLs) in a virtual X-ray telescope with 1 km focal length and with nearly 50 milli-arcsecond angular resolution. Laboratory characterization of PFLs have demonstrated near diffraction-limited angular resolution in the X-ray band, but they require long focal lengths to achieve this quality of imaging. VTXO is formed by using precision formation flying of two SmallSats: a smaller, 6U OpticsSat that houses the PFLs and navigation beacons while a larger, ESPA-class DetectorSat contains an X-ray camera, a charged-particle radiation monitor, a precision star tracker, and the propulsion for the formation flying. The baseline flight dynamics uses a highly-elliptical supersynchronous geostationary transfer orbit to allow the inertial formation to form and hold around the 90,000 km apogee for 10 hours of the 32.5-hour orbit with nearly a year mission lifetime. The guidance, navigation, and control (GN&C) for the formation flying uses standard CubeSat avionics packages, a precision star tracker, imaging beacons on the OpticsSat, and a radio ranging system that also serves as an inter-satellite communication link. VTXO’s fine angular resolution enables measuring the environments nearly an order of magnitude closer to the central engines of bright compact X-ray sources compared to the current state of the art. This X-ray imaging capability allows for the study of the effects of dust scattering nearer to the central objects such as Cyg X-3 and GX 5-1, for the search for jet structure nearer to the compact object in X-ray novae such as Cyg X-1 and GRS 1915+105, and for the search for structure in the termination shock of in the Crab pulsar wind nebula. The In this paper, the VTXO science performance, SmallSat and instrument designs, and mission description is be described. The VTXO development was supported as one of the selected 2018 NASA Astrophysics SmallSat Study (AS3) missions.
Dependence of the Fundamental Plane of Early-type Galaxies on Age and Internal Structure

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\textbf{ABSTRACT}

We investigate the scatter in the fundamental plane (FP) of early-type galaxies (ETGs) and its dependence on age and internal structure of ETGs, using 16,283 ETGs with $M_r \lesssim -19.5$ and $0.025 \leq z < 0.055$ in Sloan Digital Sky Survey data. We use the relation between the age of ETGs and photometric parameters such as color, absolute magnitude, and central velocity dispersion of ETGs and find that the scatter in the FP depends on age. The FP of old ETGs with age $\gtrsim 9$ Gyr has a smaller scatter of $\sim 0.06$ dex ($\sim 14\%$) while that of young ETGs with age $\lesssim 6$ Gyr has a larger scatter of $\sim 0.075$ dex ($\sim 17\%$). In the case of young ETGs, less compact ETGs have a smaller scatter in the FP ($\sim 0.065$ dex; $\sim 15\%$) than more compact ones ($\sim 0.10$ dex; $\sim 23\%$). On the other hand, the scatter in the FP of old ETGs does not depend on the compactness of galaxy structure. Thus, among the subpopulations of ETGs, compact young ETGs have the largest scatter in the FP. This large scatter in compact young ETGs is caused by ETGs that have low dynamical mass-to-light ratio ($M_{\text{dyn}}/L$) and blue color in the central regions. By comparing with a simple model of the galaxy that has experienced a gas-rich major merger, we find that the scenario of recent gas-rich major merger can reasonably explain the properties of the compact young ETGs with excessive light for a given mass ($\text{low } M_{\text{dyn}}/L$) and blue central color.

\textbf{Keywords:} galaxies: elliptical and lenticular, cD — galaxies: fundamental parameters — galaxies: structure

1. INTRODUCTION

Early-type galaxies (ETGs) are virialized systems, so that they are expected to satisfy the balance between potential and kinetic energy such as

$$\sigma^2 \propto \frac{M_{\text{dyn}}}{R} \propto \frac{M_{\text{dyn}}}{L} I R,$$

where $\sigma$ is the velocity dispersion of a galaxy, $R$ is the galaxy size, $M_{\text{dyn}}/L$ is the dynamical mass-to-light ratio, and $I$ is the surface brightness ($I \propto L/R^2$). According to this condition, ETGs form a plane, known as the fundamental plane (FP; Djorgovski & Davis 1987; Dressler \textit{et al.} 1987), in the space of three observational quantities:

$$\log_{10} R_e = a \log_{10} \sigma_0 + b \mu_e + c,$$

in which $R_e$ is the half-light radius, $\sigma_0$ is the central velocity dispersion, and $\mu_e$ is the mean surface brightness within $R_e$ ($\mu_e = -2.5 \log_{10} I_e$).

The FP forms a basis of scaling relations of ETGs, since many other scaling relations on ETGs are variations or projections of the FP. For example, two-dimensional scaling relations on ETGs that were found earlier, such as the Faber–Jackson relation\textsuperscript{1} (Faber & Jackson 1976) and the Kormendy relation\textsuperscript{2} (Kormendy 1977), are now regarded as projections of the FP. The mass–size (or luminosity–size) relation of ETGs (Shen \textit{et al.} 2003; Yoon \textit{et al.} 2017) is also a scaling relation related to the FP.

If all ETGs are fully virialized and perfectly homologous with a constant $M_{\text{dyn}}/L$, the coefficients $a$ and $b$ of the FP should be 2 and 0.4, respectively, according to the virial relation (Equation 1). However, previous studies based on observational data found smaller values of $a$ ($\sim 1–1.5$) and $b$ ($\sim 0.3$) (Bernardi \textit{et al.} 2003a; Jun \& Im 2008; Hyde & Bernardi 2009; La Barbera \textit{et al.} 2010; Cappellari \textit{et al.} 2013; Saulder \textit{et al.} 2013). The discrepancy between observational values and expectations from the virial relation is named the tilt of the FP. Determining the origin of the tilt of the FP is directly related to understanding the nonhomology of ETGs and how ETGs are formed and evolved (Bertin \textit{et al.} 2002; Trujillo \textit{et al.} 2004; Cappellari \textit{et al.} 2006; Dekel & Cox 2006; Robertson \textit{et al.} 2006; Hopkins \textit{et al.} 2008a). For instance, different degrees of dissipation effects in the

\textsuperscript{1} A relation between the luminosity and the velocity dispersion
\textsuperscript{2} A relation between the size and the surface brightness
Quantification of the expected residual dispersion of the MICADO Near-IR imaging instrument

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ABSTRACT

MICADO, a near-infrared imager for the Extremely Large Telescope, is being designed to deliver diffraction limited imaging and 50 micro arcsecond (µas) astrometric accuracy. MICADO employs an atmospheric dispersion corrector (ADC) to keep the chromatic elongation of the point spread function (PSF) under control. We must understand the dispersion and residuals after correction to reach the optimum performance. Therefore, we identified several sources of chromatic dispersion that need to be considered for the MICADO ADC. First, we compared common models of atmospheric dispersion to investigate whether these models remain suitable for MICADO. We showed that the differential dispersion between common atmospheric models and integration over the full atmosphere is less than 10 µas for most observations in H-band. We then performed an error propagation analysis to understand the uncertainty in the atmospheric dispersion as a function of atmospheric conditions. In addition, we investigated the impact of photometric color on the astrometric performance. While the differential refraction between stars within the same field of view can be significant, the inclusion of an ADC rendered this effect negligible. For MICADO specifically, we found that the current optomechanical design dominates the residual dispersion budget of 0.4 milli arcseconds (mas), with a contribution of 0.31 mas due to the positioning accuracy of the prisms and up to 0.15 mas due to a mismatch between the dispersive properties of the glass and the atmosphere. We found no showstoppers in the design of the MICADO ADC for achieving 50 µas relative astrometric accuracy.

Key words: atmospheric effects – methods: analytical – methods: numerical – telescopes

1 INTRODUCTION

The next generation of large telescopes, such as the Extremely Large Telescope (ELT) (ESO 2011), the Thirty Meter Telescope (Sanders 2014) and the Giant Magellan Telescope (Johns et al. 2012), offer a significant increase in aperture diameter. With this increase in telescope size, several unwanted optical effects become important or can no longer be assumed negligible and have to be reconsidered (e.g. Devaney et al. (2008); Jolissaint & Kendrew (2010); Trippe et al. (2010); Ellerbroek (2013)). This directly follows from the relation between the angular size of the point spread function (PSF), θPSF, the telescope diameter, D, and the wavelength, λ.

\[ θ_{PSF} = 1.22 \frac{λ}{D} \]  

Besides an increase in resolution, these large telescopes will offer capabilities for high precision relative astrometry, allowing astronomers to measure relative angular distances between stars to several tens of micro arcseconds (Trippe et al. 2010; Schoeck et al. 2013; Massari et al. 2016). Consequently, the precise PSF shape and position must be understood to a new level of precision.

The near infrared instrument offering such astrometric accuracy on the ELT will be MICADO, the Multi-Adaptive Optics Imaging Camera for Deep Observations (Davies et al. 2016). It will offer relative astrometric accuracy of 50 micro arcseconds (µas). In order to reach this level of performance it is essential to correct for various at-
Abstract

The aim of this thesis is to question some of the basic assumptions that go into building the ΛCDM model of our universe. The assumptions we focus on are the initial conditions of the universe, the fundamental forces in the universe on large scales and the approximations made in analysing cosmological data. For each of the assumptions we outline the theoretical understanding behind them, the current methods used to study them and how they can be improved and finally we also perform numerical analysis to quantify the novel solutions/methods we propose to extend the previous assumptions.

The work on the initial conditions of the universe focuses on understanding what the most general, gauge invariant, perturbations are present in the beginning of the universe and how they impact observables such as the CMB anisotropies. We show that the most general set of initial conditions allows for a decaying adiabatic solution which can have a non-zero contribution to the perturbations in the early universe. The decaying mode sourced during an inflationary phase would be highly suppressed and should have no observational effect, thus, if these modes are detected they could potentially rule out most models of inflation and would require a new framework to understand the early universe such as a bouncing/cyclic universe.

After studying the initial conditions of the universe, we focus on understanding the nature of gravity on the largest scales. It is assumed that gravity is the only force that acts on large scales in the universe and we propose a novel test of this by cross-correlating two different types of galaxies that should be sensitive to fifth-forces in the universe. By focusing on a general class of scalar-tensor theories that have a property of screening, where the effect of the fifth force depends on the local energy density, we show that future surveys will have the power to constrain screened fifth-forces using the method we propose.

Finally, to test theoretical models with observations a complete understanding of the statistical methods used to compare data with theory is required. The goal of a statistical analysis in cosmology is usually to infer cosmological parameters that describe our theoretical model from observational data. We focus on one particular aspect of cosmological parameter estimation which is the covariance matrix used during an inference procedure. The usual assumption in modelling the covariance matrix is that
The physical drivers of the atomic hydrogen–halo mass relation

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ABSTRACT

We use the state-of-the-art semi-analytic galaxy formation model, SHARK, to investigate the physical processes involved in dictating the shape, scatter and evolution of the H\textsc{i}–halo mass relation at $0 \leq z \leq 2$. We compare SHARK with H\textsc{i} clustering and spectral stacking of the H\textsc{i}–halo mass relation derived from observations finding excellent agreement with the former and a deficiency of H\textsc{i} in SHARK at $M_{\text{halo}} \approx 10^{12.5} M_\odot$ in the latter, but otherwise great agreement below and above that mass threshold. In SHARK, we find that the H\textsc{i} mass increases with the halo mass up to a critical mass of $\approx 10^{11.8} M_\odot$; between $\approx 10^{11.8} M_\odot$ and $10^{12.5} M_\odot$, the scatter in the relation increases by 0.7 dex and the H\textsc{i} mass decreases with the halo mass on average (till $M_{\text{halo}} \sim 10^{12.5} M_\odot$, after which it starts increasing); at $M_{\text{halo}} > 10^{13} M_\odot$, the H\textsc{i} content continues to increase with increasing halo mass, as a result of the increasing H\textsc{i} contribution from satellite galaxies. We find that the critical halo mass of $\approx 10^{12.5} M_\odot$ is largely set by feedback from Active Galactic Nuclei (AGN), and the exact shape and scatter of the H\textsc{i}–halo mass relation around that mass is extremely sensitive to how AGN feedback is modelled, with other physical processes (e.g. stellar feedback, star formation and gas stripping in satellites) playing a less significant role. We also determine the main secondary parameters responsible for the scatter of the H\textsc{i}–halo mass relation, namely the halo spin parameter at $M_{\text{vir}} < 10^{11.8} M_\odot$, and the fractional contribution from substructure to the total halo mass ($M_{\text{vir}} / M_{\text{vir}}$) for $M_{\text{vir}} > 10^{13} M_\odot$. The scatter at $10^{11.8} M_\odot < M_{\text{vir}} < 10^{13} M_\odot$ is best described by the black-hole-to-stellar mass ratio of the central galaxy, reflecting the relevance of AGN feedback. We present a numerical model to populate dark matter-only simulations with H\textsc{i} at $0 \leq z \leq 2$ based solely on halo parameters that are measurable in such simulations.

Key words: galaxies: formation – galaxies: evolution – galaxies: haloes

1 INTRODUCTION

Understanding the distribution and evolution of neutral hydrogen (H\textsc{i}) in the Universe provides key insights into cosmology, galaxy formation and the epoch of cosmic reionisation (Blanton & Moustakas 2009; Pritchard & Loeb 2012; Somerville & Davé 2015; Rhee et al. 2018). A long-standing challenge in galaxy formation and evolution is addressing the relationship between stars, gas and metals in galaxies, haloes and the large-scale structure. H\textsc{i} is a primary ingredient for star formation and a key input to understand how various processes govern galaxy formation and evolution. The H\textsc{i} content of dark matter (DM) haloes forms an intermediate state in the baryon cycle that connects the largely ionised gas in the intergalactic medium (IGM), the shock heated gas at the virial radius and the star-forming, cold gas in the interstellar medium (ISM) of galaxies (Putman et al. 2012; Krumholz & Dekel 2012). Constraints on H\textsc{i} at all relevant scales (IGM, halo and galaxy scales) are therefore key to reveal the role of gas dynamics, cooling and regulatory processes such as stellar feedback, gas inflows and outflows (Prochaska & Wolfe 2009; van de Voort et al. 2011), and the effect of environment in galaxy formation (Fabello et al. 2012; Zhang et al. 2013).

When studying galaxy formation and evolution, the exploration of scaling relations is particularly useful as a way of reducing the inherit complexity of the process and providing a quantitative means of examining physical properties of galaxies. The dependence of the abundance of baryons on the host halo mass is considered one of the most fundamental scaling relations (Wechsler & Tinker 2018). In particular, the stellar–halo mass relation has been studied in detail, and has been shown to have little scatter ($\approx 0.2$ dex, see Behroozi et al. 2010; Moster et al. 2010) and a shape that reflects the mismatch between the halo and stellar mass functions - the latter has a much shallower low-mass end slope and a more abrupt break at the high-mass end than the former (see review Wechsler & Tinker 2018). The

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Development and application of metamaterial-based Half-Wave Plates for the NIKA and NIKA2 polarimeters

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ABSTRACT

Context. Large field-of-view imaging/polarimetry instruments operating at millimeter and submm wavelengths are fundamental tools to understand the role of magnetic fields (MF) in channeling filament material into prestellar cores providing a unique insight in the physics of galactic star-forming regions. Among other topics, at extra-galactic scales, polarization observations of AGNs will allow us to constrain the possible physical conditions of the emitting plasma from the jets and/or exploring the physics of dust inside supernova remnants. The kilo-pixel NIKA2 camera, installed at the IRAM 30-m telescope, represents today one of the best tools available to the astronomers to produce simultaneous intensity/polarimetry maps over large fields at 260 GHz (1.15 mm).

Aims. The polarisation measurement, in NIKA and NIKA2, is achieved by rapidly modulating the total incoming polarisation. This allows in the end to safely isolate the small science signal from the large, un-polarised and strongly variable, atmospheric background.

Methods. The polarisation modulation is achieved by inserting a fast rotating Half-Wave Plate (HWP) in the optical beam. In order to allow wide field-of-view observations, the plate has to be large, with a diameter exceeding 250 mm. The modulation of the polarised signal, at 12 Hz, requires also the waveplate to be sufficiently light. In addition, this key optical element has to exhibit optimal electromagnetic characteristics in terms of transmission and differential phase-shift. For this purpose, three metamaterial HWPs have been developed using the mesh-filter technology. The knowledge acquired in developing the first two single-band HWPs was used to achieve the more challenging performance requirements of the last dual-band HWP. The first and the third waveplates met the requirements for both the NIKA and NIKA2 instruments.

Results. We first illustrate the design, the technical developments, the fabrication and laboratory characterisation of the three mesh-HWPs. The deployment of two such elements in the NIKa and NIKA2 instruments at the 30-meter telescope is then described. We conclude with representative examples of astrophysical maps integrating polarimetry.

Key words. polarimetry - polarization modulation - half-wave plates

1. Introduction

The polarization state of the radiation coming from astrophysical sources carries important information about the astrophysical environments at the origin of the electromagnetic wave. Generally, only a small fraction of the total signal is polarized and this is embedded within a more intense signal arising from unpolarized light and radiation from other astrophysical sources. However, a linearly polarized signal can be modulated and lifted above the noise level by using a rotating Half-Wave Plate (HWP) operating directly on the incoming beam of the instrument. The rotation of the HWP at a frequency \( \omega \) induces a rotation of the polarized signal at twice the mechanical angular rotation speed, \( 2\omega \). Detectors sensitive to orthogonal polarizations will eventually detect signals at a frequency \( 4\omega \) (Ritacco, A. et al. 2017).

The New IRAM KIDs Array (NIKA) (Monfardini et al. 2011; Catalano, A. et al. 2014) instrument, operated at the IRAM 30-meter telescope in the period 2010-2015, has represented a scientific and technological pathfinder for instrumentation based on Kinetic Inductance Detectors (KIDs). The advantage of KIDs, when compared to the competing technology of bolometers, and in the context of polarization modulation, is the fast (i.e. \( 0.1 \) ms) response time. NIKA2 (Adam, R. et al. 2018) is the successor of NIKA and represents, with around 3k-pixels and three distinct arrays, the ultimate instrument for dual-band (150 and 260 GHz) imaging and polarimetry (260 GHz) at the 30-meter telescope. NIKA2 is a general purpose camera open to the astronomical community via periodic competitive calls. The NIKA2 collaboration is, however, independently pursuing five science objectives spanning from cosmology (e.g. observations of clusters of galaxies via the Sunyaev-Zel’dovich effect, deep integration on cosmological fields) to the study of extra-galactic scales, exploration of new physics of AGNs, understanding the physics of dust inside supernova remnants, investigating the physics of the ISM in the context of the Galactic Center, and characterizing the physical properties of the HI and CO ISM toward massive stars, and more.
Lithium evolution in the Milky Way discs: the view using large stellar samples

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Abstract. This contribution presents an overview of the evolution of Li abundances in stars of the Galactic thin and thick discs, from the observational point of view. The focus is on Li abundances obtained by recent projects and surveys. To separate thin and thick disc stars, both chemical abundances, kinematics, and ages can be used. For thick disc stars, the Li evolution is uncertain, as differences appear depending on how the stars were separated. Nevertheless, it seems clear that most of the Galactic enrichment in Li takes place in the thin disc. Literature consensus also seems to exist regarding the decrease in the Li abundances of stars with metallicity above solar. A brief discussion is included on some of the uncertainties that should be kept in mind when trying to understand the Li observations. This review ends listing two interesting open questions regarding Li abundances in Milky Way disc stars.

Key words. Galaxy: abundances – Galaxy: disc – Stars: abundances

1. Introduction

The Milky Way “disc” is itself divided into two apparently distinct structural components: the thin and the thick discs. The thick disc was first identified by Yoshii (1982) and Gilmore & Reid (1983) in studies of the stellar vertical density distribution. The thick disc becomes the dominant population on heights above 1-2 kpc from the plane.

Thick disc stars have been found to be old (> 10 Gyr) and to have enhanced $[\alpha/\text{Fe}]$ ratio (see, e.g., Fuhrmann et al. 2017, and references therein). Thin disc stars, instead, are younger and have lower levels of the $[\alpha/\text{Fe}]$ ratio. Thin and thick disc stars also have different kinematic properties (see, e.g., Soubiran & Girard 2005). How the thick disc was formed is still under discussion (see, e.g., Robin et al. 2014, and references therein).

The distributions of ages, abundances of $\alpha$-elements, and kinematics can be used to tentatively separate thin disc stars from the thick disc ones. However, it is important to realize that while the distributions of those quantities are different in each disc population, some overlap can and does exist. These overlaps are one of the aspects that introduce uncertainties when assigning an individual star to a given disc component.

2. Li in the Milky Way discs

Ideally, to constrain the evolution of Li in the Milky Way, we would like to study the stellar Li abundances as a function of time. Stellar ages, however, are not easily derived with the required accuracy (see Soderblom 2010, for a review). Therefore, the evolution of Li abun-
The decaying and scattering properties of the $d^*(2380)$ hexaquark 
Bose Einstein Condensate dark matter

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ABSTRACT

Recently, a study has shown that the Bose Einstein Condensates formed by the $d^*(2380)$ hexaquarks ($d^*(2380)$-BECs) can be thermally produced in the early universe and they are stable enough to be a competitive candidate of dark matter. Searching for the decaying signature of $d^*(2380)$-BECs is a possible way to verify this dark matter model. In this article, we discuss the scattering and decaying properties of the $d^*(2380)$-BECs and we show that the decay rate of the $d^*(2380)$-BECs is correlated with the TeV cosmic-ray flux. The predicted average decay rate in our Galaxy is several orders of magnitude larger than the current observed upper limit. Therefore, it would be very difficult for us to search for the decaying signature of the $d^*(2380)$-BEC dark matter model. Nevertheless, the size of the $d^*(2380)$-BECs may be large enough to have self-interaction so that we can possibly detect them in the future.

Subject headings: dark matter

1. Introduction

Observational data of galaxies, galaxy clusters and the cosmic microwave background reveal that some unknown dark matter particles exist in our universe. However, all of the known fundamental particles in the Standard Model do not exhibit the properties of dark matter. Although many theoretical models have suggested some possible dark matter candidates such as Weakly Interacting Massive Particles (WIMPs) or sterile neutrinos, there is no promising observed signal of these hypothetical particles so far. Current observational data of direct detections (Tan et al. 2016; Aprile et al. 2017, 2018), indirect detections (gamma-ray, radio or cosmic-ray detections) (Calore et al. 2015; Daylan et al. 2016;
Inference of chromospheric plasma parameters on the Sun
Multilayer spectral inversion of strong absorption lines
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ABSTRACT

The solar chromosphere can be observed well through strong absorption lines. We infer the physical parameters of chromospheric plasmas from these lines using a multilayer spectral inversion. This is a new technique of spectral inversion. We assume that the atmosphere consists of a finite number of layers. In each layer the absorption profile is constant and the source function varies with optical depth with a constant gradient. Specifically, we consider a three-layer model of radiative transfer where the lowest layer is identified with the photosphere and the two upper layers are identified with the chromosphere. The absorption profile in the photosphere is described by a Voigt function, and the profile in the chromosphere by a Gaussian function. This three-layer model is fully specified by 13 parameters. Four parameters can be fixed to prescribed values, and one parameter can be determined from the analysis of a satellite photospheric line. The remaining 8 parameters are determined from a constrained least-squares fitting. We applied the multilayer spectral inversion to the spectral data of the Hα and the Ca ii 854.21 nm lines taken in a quiet region by the Fast Imaging Solar Spectrograph (FISS) of the Goode Solar Telescope (GST). We find that our model successfully fits most of the observed profiles and produces regular maps of the model parameters. The combination of the inferred Doppler widths of the two lines yields reasonable estimates of temperature and nonthermal speed in the chromosphere. We conclude that our multilayer inversion is useful to infer chromospheric plasma parameters on the Sun.

Key words. Sun: atmosphere - Sun: photosphere - Sun: chromosphere - methods: data analysis - line: profiles - radiative transfer

1. Introduction

Strong absorption lines in the visible and infrared wavelengths are important spectral windows into the solar chromosphere. These lines are observable from the ground and contain useful information of chromospheric plasmas. The Hα line of hydrogen has been the most popular of these windows. This line is favored because it is strong, and broad enough for filtergraph observations. The Hα filter images of solar regions display a great variety of intensity structures (Rutten 2008; Lencarts et al. 2012). Even though the image data of the intensity directly provide much useful (mostly morphological) information of the underlying plasma structures, they do not provide estimates of plasma parameters, which are crucial for understanding the physical conditions. The inference of plasma parameters requires the spectral data of the strong absorption lines and a successful spectral inversion.

Spectral inversion is the process of inferring the plasma parameters from the observed profile of a spectral line. Two types of spectral inversion have been popular in solar observations that assume the constancy of physical parameters. One is the Milne-Eddington inversion, and the other is the cloud model inversion (Beckers 1964). The Milne-Eddington inversion is based on the assumption that the spectral line is formed in a plasma layer of infinite optical thickness where the absorption profile is constant over optical depth and the source function varies with a constant gradient. This inversion has been used mainly to model spectral lines formed in the photosphere and to infer the magnetic fields from their Stokes profiles (Unno 1956; Skumanich & Lites 1987).

The cloud model inversion, on the other hand, assumes that the line is formed in a plasma layer of finite optical depth where the source function as well as the absorption profile is constant over optical depth. This model has been used mostly to infer the physical parameters of cloud-like features lying far above the solar surface (Tziotziou 2007), as was well illustrated in Fig. 1 of Heinzel et al. (1999). A number of variants have been proposed to generalize the original cloud model of Beckers (1964) by incorporating the varying source function (Mein et al. 1996; Heinzel et al. 1999; Tsiropoula et al. 1999), the presence of multiple clouds (Gu et al. 1996), the concept of the embedded cloud (Steinitz et al. 1977; Chae 2014), etc. Despite these variants, the usage of the cloud model inversion is still limited, and is often hampered by the difficulty of choosing the incident intensity profile. Because the incident intensity below the feature of interest cannot be determined from observations, it has to be assumed to be the same as that in its neighborhood, for instance.

Here we present a multilayer inversion for modeling the spectral profiles of strong absorption lines. This represents a combined generalization of the two types of spectral inversion. A strong line is formed over a wide height range of the atmosphere from the photosphere to the chromosphere. The formation of the line in the photosphere can be mod-
A stripped-companion origin for Be stars: clues from the putative black holes HR 6819 and LB-1

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ABSTRACT

HR 6819 is a bright \( V = 5.36 \), blue star recently proposed to be a triple containing a detached black hole (BH). We show that the system is a binary and does not contain a BH. Using spectral decomposition, we disentangle the observed composite spectra into two components: a rapidly rotating Be star and a slowly rotating B star with low surface gravity \( \log g = 2.75 \). Both stars show periodic radial velocity (RV) variability, but the RV semi-amplitude of the B star’s orbit is \( K_B = (62.7 \pm 1) \, \text{km} \, \text{s}^{-1} \), while that of the Be star is only \( K_{\text{Be}} = (4.5 \pm 2) \, \text{km} \, \text{s}^{-1} \). This implies that the B star is less massive by at least a factor of 10. The surface abundances of the B star bear imprints of CNO burning. We argue that the B star is a bloated, recently stripped helium star with mass \( \approx 0.5 \, M_\odot \) that is currently contracting to become a hot subdwarf. The orbital motion of the Be star obviates the need for a BH to explain the B star’s motion. A stripped-star model reproduces the observed luminosity of the system, while a normal star with the B star’s temperature and gravity would be more than 10 times too luminous. HR 6819 and the binary LB-1 probably formed through similar channels. We use MESA models to investigate their evolutionary history, finding that they likely formed from intermediate-mass \( (3 - 7 \, M_\odot) \) primaries stripped by slightly lower-mass secondaries and are progenitors to Be + sdOB binaries such as \( \phi \) Persei. The lifetime of their current evolutionary phase is on average \( 2 \times 10^7 \) years, of order half a percent of the total lifetime of the Be phase. This implies that many Be stars have hot subdwarf and white dwarf companions, and that a substantial fraction (20 – 100%) of field Be stars form through accretion of material from a binary companion.

Key words: binaries: spectroscopic – stars: emission-line, Be – stars: subdwarfs

1 INTRODUCTION

Large-scale multi-epoch radial velocity (RV) surveys have identified a number of binaries in recent years that are proposed to contain stellar mass black holes (BHs; e.g. Casares et al. 2014; Khokhlov et al. 2018; Giesers et al. 2018, 2019; Thompson et al. 2019). Confirmation of these BH candidates is challenging precisely because BHs are expected to be rare. That is, all plausible alternate explanations for observed data, even those which are rare, must be ruled out before a candidate BH can be considered reliable.

Recently, Rivinius et al. (2020) identified the object HR 6819 as a candidate host of a stellar-mass BH. Phase-resolved optical spectra of the object revealed two luminous components: a B star with relatively narrow, RV-variable absorption lines, which were observed to follow a nearly circular orbit with \( P = 40.3 \) days and velocity semi-amplitude \( K_B \approx 61 \, \text{km} \, \text{s}^{-1} \), and a classical Be star whose broad emission and absorption lines appeared to be stationary. No component was found to orbit in anti-phase with the B star. Assuming the mass of the B star to be at least \( 5 \, M_\odot \), as expected for a normal star of its spectral type, Rivinius et al. (2020) argued that any stellar companion massive enough to explain the B star’s orbit would also contribute to the spectrum at a detectable level. They thus concluded that the companion is a BH, with an estimated minimum mass of \( 4.2 \, M_\odot \). In this hierarchical triple scenario, the Be star must be at least a few AU from the B star and BH for the system to be dynamically stable, and its status as a Be star would likely be unrelated to the B star or BH.

HR 6819 is in many ways similar to the binary LB-1 (Liu et al. 2019), which was also proposed to contain a stellar-mass BH. Like HR 6819, LB-1 contains an RV-variable B star and apparently stationary emission lines. The emission lines were initially proposed to originate in an accretion disk, either around the BH (Liu et al. 2019) or around the binary (El-Badry & Quataert 2020; Abdul-Masih et al. 2020; Irgang et al. 2020). Rivinius et al. (2020) proposed that LB-1 and HR 6819 are both hierarchical triples with a B star and a BH companion in the inner binary, and a distant Be star – the source of the emission lines – orbiting both components.

Shenar et al. (2020), however, recently used spectral disentangling to fit the multi-epoch spectra of LB-1 as a sum of two luminous components. They also found evidence for a Be star, including both
The distances to molecular clouds in the fourth Galactic quadrant

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ABSTRACT
Distance measurements to molecular clouds are essential and important. We present directly measured distances to 169 molecular clouds in the fourth quadrant of the Milky Way. Based on the near-infrared photometry from the Two Micron All Sky Survey and the Vista Variables in the Via Lactea Survey, we select red clump stars in the overlapping directions of the individual molecular clouds and infer the bin averaged extinction values and distances to these stars. We track the extinction versus distance profiles of the sightlines toward the clouds and fit them with Gaussian dust distribution models to find the distances to the clouds. We have obtained distances to 169 molecular clouds selected from Rice et al. The clouds range in distances between 2 and 11 kpc from the Sun. The typical internal uncertainties in the distances are less than 5 per cent and the systematic uncertainty is about 7 per cent. The catalogue presented in this work is one of the largest homogeneous catalogues of distant molecular clouds with the direct measurement of distances. Based on the catalogue, we have tested different spiral arm models from the literature.

Key words: dust, extinction – ISM: clouds – Galaxy: structure

1 INTRODUCTION
Distance is the fundamental parameter to estimate all other physical properties like the size and mass of molecular cloud. Estimating the distance to molecular cloud is a tough task and astronomers have explored several different techniques.

A first method is to derive the distance kinematically, which convert the radial velocity of a cloud to a distance by assuming that the cloud follows the Galactic rotation curve (e.g., Roman-Duval et al. 2009; Miville-Deschênes et al. 2017). However, the kinematic distances are problematic due to the large uncertainty of the rotation curve and the influence of the peculiar velocities and the non-circular motions. Furthermore, a well-known geometric ambiguity exists for the kinematic distance of cloud in the inner Galaxy, where one velocity can be related to two distances. A second method is to obtain the distance of a given cloud by identifying its associated objects having the same distance as the cloud, such as the OB stars and young stellar objects, whose distances can be estimated (e.g., Gregorio-Hetem 2008). However, this method is only applied to individual clouds of interest. A third method is to estimate the distance from the extinction of starlight, i.e., the extinction distance. As the density of the dust grains in the molecular cloud is much higher than that in diffuse medium, one can expect a sharp increase of stellar extinction at the location of the cloud. Thus the distance to the cloud can be obtained by finding the position where the extinction increases sharply.

The extinction method is directly measured and robust. However, it relies on the accurate estimates of distances and extinction values of a large number of stars. Thanks to a number of large-scale astrometric, photometric and spectroscopic surveys, we can obtain accurate values of distance and dust extinction for tens of millions of individual stars (e.g., Chen et al. 2014; Green et al. 2015). Thus the estimation of precise extinction distances to large samples of molecular clouds has become possible. Schlafly et al. (2014) obtain distances to dozens of molecular clouds selected from the literature by the three-dimensional (3D) extinction mapping method based on PanSTARRS-1 data. Zucker et al. (2019) improve their work by combining the optical and near-IR photometry with the Gaia Data Release 2 (Gaia DR2; Gaia Collaboration et al. 2018) parallaxes. Lindegren et al. (2018), Yan et al. (2019) derive extinction distances to 11 molecular clouds in the third Galactic quadrant. Chen et al. (2020) present accurate distance determinations to a catalogue of 567 molecular clouds based on estimates of colour excesses and distances of stars presented in Chen et al. (2019b). Zhao et al. (2018, 2020) estimate the extinction distances to 33 su-
We report the discovery of a mid-infrared (MIR) flare using WISE data in the center of the nearby Seyfert 1.9 galaxy MCG-02-04-026. The MIR flare began in the first half of 2014, peaked around the end of 2015, and faded in 2017. During these years, energy more than $7 \times 10^{50}$ erg was released in the infrared, and the flare’s MIR color was generally turning red. We detected neither optical nor ultraviolet (UV) variation corresponding to the MIR flare based on available data. We explained the MIR flare using a dust echo model in which the radiative transfer is involved. The MIR flare can be well explained as thermal reradiation from dust heated by UV-optical photons of a primary nuclear transient event. Although the transient event was not seen directly due to dust obscuration, we can infer that it may produce a total energy of at least $\sim 10^{51}$ erg, most of which was released in less than $\sim 3$ years. The nature of the transient event could be a stellar tidal disruption event by the central supermassive black hole (SMBH), or a sudden enhancement of the existing accretion flow onto the SMBH, or a supernova which was particularly bright.

1. Introduction

Recently, in the nuclear regions of some active galaxies, transient events involving rapid and great rise in the luminosity have been reported. The examples are CSS100217:102913+404220 (Drake et al. 2011), PS16dtm (Blanchard et al. 2017), an event in F01004-2237 (Tadhunter et al. 2017), PS1-10adi (Kankare et al. 2017), an event in W0948+0318 (Kankare et al. 2017; Assef et al. 2018), AT 2017bgt (Trakhtenbrot et al. 2019), OGLE17aaaj (Gromadzki et al. 2019), and some
Searching for anisotropy in the distribution of binary black hole mergers

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The standard model of cosmology is underpinned by the assumption of the statistical isotropy of the Universe. Observations of the cosmic microwave background, galaxy distributions, and supernovae, among other media, support the assumption of isotropy at scales $\gtrsim 100$ Mpc. Recent detections of gravitational waves from merging stellar-mass binary black holes provide a new probe of anisotropy; complementary and independent of all other probes of the matter distribution in the Universe. We present an analysis using a spherical harmonic model to determine the level of anisotropy in the first LIGO/Virgo transient catalog. We find that the ten binary black hole mergers within the first transient catalog are consistent with an isotropic distribution. We carry out a study of simulated events to assess the prospects for future probes of anisotropy. Within a single year of operation, third-generation gravitational-wave observatories will probe anisotropies with an angular scale of $\sim 36^\circ$ at the level of $\lesssim 0.1\%$.

I. INTRODUCTION

Two key assumptions in the standard $\Lambda$CDM model of modern cosmology are the isotropy and homogeneity of the Universe [1–3]. Since $\Lambda$CDM cosmology underlies our current understanding of the Universe, rigorous tests are required to validate this fundamental assumption. The Universe has been observed to be isotropic at scales $\gtrsim 100$ Mpc, with smaller-scale deviations considered to be statistically isotropic on an overall homogeneous structure produced by phenomena such as baryon acoustic oscillations or gravitational interactions [4–6]. Verifying the lack of large scale anisotropy in the Universe is important for the validity of the $\Lambda$CDM cosmology.

Evidence for large-scale isotropy of the Universe has been presented through numerous observations of various sources [6–14]. The most stringent measurements on the anisotropy of the Universe come from the cosmic microwave background, which generally show small-scale statistical deviations on the order of $10^{-3}$–$10^{-5}$ [13, 14]. Meanwhile, multiple studies hint at the existence of deviations from isotropy at large angular scales in the cosmic microwave background [15, 16], supernovae [17, 18] and galaxy [19] distributions, as well as large bulk flows [20, 21]. While these inferences are speculative [e.g., 22, 24], they can be supported or contradicted by independent measures of the Universe’s isotropy using gravitational-wave observations.

Studies of the gravitational-wave stochastic background have placed limits of anisotropy from unresolved sources [25, 30], however observations of gravitational waves from resolved binary black hole (BBH) mergers present another tool to probe anisotropy. Prior to the third observing run, Advanced LIGO (aLIGO) [31] and Advanced Virgo (aVirgo) [32] released the details for ten binary black holes over the first (O1) and second (O2) observing runs [33]. These observations are collated in the first gravitational-wave transient catalog, GWTC-1. With the third observing run (O3) complete, the total number of gravitational-wave BBH merger candidates has increased to more than 50 [34]. Furthermore, the addition of aVirgo for the entirety of O3 has already resulted in many well-localized sources (e.g. [35]), providing further motivation for utilizing BBH mergers to study the anisotropy of the Universe.

In this paper, we use LIGO/Virgo data to probe anisotropies in the distribution of BBH mergers, taking care to handle selection bias associated with the detection of gravitational-wave sources. We explore the future prospects of anisotropy measurements with gravitational waves. In Ref. [36], a HEALPix [37] basis was adopted to parameterize the anisotropy of binary black hole mergers. In Ref. [38], a two-dimensional correlation function was implemented (see also [39]). Both analyses find results consistent with isotropy. In contrast, our method utilizes a spherical harmonic basis to define a probability distribution, providing results in terms of typical spherical harmonic functions. Our results are qualitatively similar to those of [30, 38]. However, there are some potential advantages to the spherical harmonic approach: the method lends itself straightforwardly to comparison with results from the cosmic microwave background, and it could be argued that at least some plausible deviations from anisotropy are more clearly visible in the spherical harmonic basis than the pixel basis, which emphasizes hot spots.

The remainder of the manuscript is structured as follows. In Sec. [11], we outline a method of hierarchically analysing binary black hole mergers to determine the level of anisotropy, including a parameterization of the distribution of BBH merger events in spherical harmonics and a discussion of the observational selection biases. The analysis of the previously observed BBH
An Extremely Bright QSO at $z = 2.89$

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ABSTRACT

We report the discovery and confirmation of a bright quasi-stellar object (QSO), 2MASS J13260399+7023462, at $z = 2.889$. This QSO is the first spectroscopically confirmed candidate from an ongoing search using the combination of Gaia and WISE photometry to identify bright QSOs at $z > 2$, the redshift regime for which the Lyman-α forest is accessible with ground-based facilities. With a Gaia apparent magnitude $G = 16.07$, 2MASS J13260399+7023462 is one of the brightest QSOs known at $z > 2$, with only 15 currently known brighter QSOs. Given its inferred $M_{1450\,AB}$ magnitude and redshift, it is among the most luminous objects in the Universe; the inferred black hole mass and corresponding Eddington ratio are $(2.7 \pm 0.4) \times 10^{10} \, M_{\odot}$ and $1.3 \pm 0.3$, respectively. Follow-up Hubble observations confirm it is not gravitationally lensed.

Keywords: Quasars – Radio quiet quasars – Supermassive black holes – High-luminosity AGN

1. INTRODUCTION

The epoch from reionization to the era of peak star formation (2 $\lesssim z \lesssim 7$, Madau & Dickinson 2014) is a time of rapid galaxy growth and assembly (Bell 2004), as well as commensurate growth of supermassive black holes (SMBHs) in galaxies. Indeed, one of the outstanding challenges in galaxy formation is explaining the existence of the most massive SMBHs at $z \gtrsim 7$ (Volonteri 2012; Bañados et al. 2018), which are observed as quasi-stellar objects (QSOs). More generally, evolution of the bright end of the quasar luminosity function (QLF) provides an observational benchmark which must be reproduced by theoretical models (Yu & Tremaine 2002).

Beyond evolution of the QLF, ultraluminous QSOs are also of interest as physical probes of the Universe. Bright, lensed QSOs can be used for time delay measurements to constrain the Hubble constant $H_0$, as first described by Refsdal (1964). Bright, unlensed QSOs can serve as backlights for studying the Lyman-α forest (Harris et al. 2016) and as tools for detecting cosmological redshift drift, as described in Loeb (1998). The latter of these is an extension of a test first proposed by Sandage (1962), in which one measures the change in the expansion velocity of the Universe via the Lyman-α forest absorption lines superposed on the QSO spectrum. Liske et al. (2008) demonstrated that with a small sample of bright QSOs and a 30-meter class telescope, direct measurements of acceleration in the expansion are possible. Ground-based Lyman-α forest studies and cosmological redshift drift require QSOs at $z > 2$ so that Lyman-α lies in the optical window.

Significant progress has been made in recent years in quantifying the bright end of the QLF (Wisotzki 2000; Richards et al. 2006; Ross et al. 2013; Schindler et al. 2019b), including development of machine learning techniques and utilization of wide-area optical surveys like Pan-STARRS (Schindler et al. 2018, 2019a,b). This census remains incomplete, as until recently all-sky optical data was unavailable and discrimination of QSOs from faint stars can be challenging. The combination of all-sky data from the Gaia and WISE missions offers a uniquely powerful means of completing this census. Our team has initiated a search to identify the brightest $z > 2$ quasars using these data sets. In this work, we report on the discovery of the first optically bright, ultraluminous QSO identified in this search. For pure luminosity evolution, the QLF is best described by a broken double power law consisting of a faint-end slope, a bright-end slope, the break magnitude between these slopes, and the overall density normalization (Boyle et al. 1988; Pei 1995; Boyle et al. 2000). As shown in McGreer et al. (2013), the break magnitude evolves strongly in the redshift range 2.8 $< z < 4.5$, affecting both the bright-end slope and density normalization (Schindler et al. 2019b). Discoveries from high-z QSO searches such as the one presented here will pro-
Primordial black hole formation by vacuum bubbles II

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Abstract

Recent interest in primordial black holes has been largely stimulated by the discoveries of LIGO/Virgo black holes. In this work we investigate a mechanism where primordial black holes are formed by vacuum bubbles that randomly nucleate during inflation through quantum tunneling. After inflation, these bubbles typically run into the ambient radiation fluid with a large Lorentz factor. In our previous work, we assumed the bubble fields are strongly coupled to the standard model particles so that the bubble wall is impermeable. Here we complete this picture by considering bubbles interacting with the fluid only through gravity. By studying the scenario in several limits, we found that black holes could form in either subcritical or supercritical regime. Depending on the model parameters, the resulting mass spectrum of the black holes could be wide or narrow, and may develop two peaks separated by a large mass range. With different spectra, these black holes may account for the LIGO/Virgo black holes, supermassive black holes, and may play an important role in dark matter.

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LETTER TO THE EDITOR

Prospects for radio detection of stellar plasma beams

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ABSTRACT

Violent solar eruptions are often accompanied by relativistic beams of charged particles. In the solar context, they are referred to as SPEs (Solar Particle Events) and are known to generate a characteristic swept-frequency radio burst. Due to their ionizing potential, such beams influence atmospheric chemistry and habitability. Radio observations provide a crucial discriminant between stellar flares that do and do not generate particle beams. Here I use solar empirical data and semi-quantitative theoretical estimates to gauge the feasibility of detecting the associated radio bursts. My principal conclusion is that a dedicated search for swept frequency radio bursts on second-timescales in existing low-frequency ($\nu \leq 10^2$ MHz) datasets, while technically challenging, will likely evidence high energy particles beams in Sun-like stars.


1. Introduction

Stellar activity can have a detrimental effect on the habitability of exoplanets. Violent releases of energy in the chromosphere and corona emit ionizing radiation and eject plasma at high speeds into the interplanetary medium. The characteristic bolometric energy release in typical solar flare is about $10^{26} - 10^{28}$ ergs over minutes to hour-long timescales (Emslie et al. 2012). Although this is comparable to or smaller than the bolometric output of the quiescent solar disc, unlike quiescent solar emission, a large fraction of the flare energy goes into three components that are detrimental to the habitability: (a) ionizing UV and X-ray radiation, (b) ejection of a large mass of coronal plasma at high speeds (CMEs) and (c) acceleration of charges to near-light-speeds, the so-called Solar Particle Events (SPE).

Ever since the discovery of solar radio bursts, it was suspected that the radio emission is related to violent energy releases on the Sun (Payne-Scott 1949; Wild & McCready 1950). It is now well established that certain types of solar radio bursts are tell-tale signatures of SPE events (Winter & Ledbetter 2015; Miteva et al. 2017). In this paper, I concentrate on SPEs and the unique value of radio observations in evidencing their nature on stars other than the Sun.

SPEs from solar flares usually carry about 5% of the total flare energy (Emslie et al. 2013). The particles range from keV-level suprathermal energies to GeV-scale relativistic energies (Schwenn 2006). Broadly speaking, the beam particles can be accelerated in two ways: (a) magnetic reconnection in the chromosphere and lower corona leading to ‘impulsive’ events on timescales of seconds to minutes, and (b) Fermi acceleration in a shock front leading to ‘gradual’ events on timescales of several minutes to an hour (Schwenn 2006; Desai & Giacalone 2016; Cairns et al. 2003).

1 Hence we do not notice solar flares with our eyes.
2 Shock formation requires bulk ejection of thermal coronal plasma at super-Alfvénic speeds and does not happen in flares.

A beam of high energy particles moving in a dense thermal plasma leads to radio emission at the fundamental plasma frequency and its second harmonic (Benz 2002; Zheleznyakov 1996, and references therein). The characteristic radio bursts typically associated with impulsive and gradual particle beams are called type-III and type-II bursts respectively (Ameri et al. 2019). The unique diagnostic value of radio bursts of type-II and type-III lies in the fact that the ambient plasma frequency must monotonically decrease as the particle beam moves radially outward from the flare site on an unbound trajectory. Plasma emission from such beams therefore sweeps down in frequency as a function of time providing clear evidence that the flare accelerated particles will enter interplanetary space and influence the space weather around exoplanets.

Such radio bursts from the Sun have been extensively studied both observationally and theoretically (Saint-Hilaire et al. 2013; Nita et al. 2002; Melrose 1980; Reid & Ratcliffe 2014). Analogous radio bursts have not been detected from other Sun-like stars, primarily due to sensitivity and time-on-sky limitations of previous searches. Furthermore, with few notable exceptions (see for e.g. Bastian et al. 2018), previous searches have almost exclusively focused on highly active M-dwarfs (Villadsen & Hallinan 2019; Osten & Bastian 2006; Crosley & Osten 2018b, 2018a; Lynch et al. 2017) whose large-scale magnetic fields are about three orders of magnitude larger than the solar value. It is unclear if such stars emit interplanetary plasma beams or mass ejections at all (see below). In addition, the primary mechanism for bursts on these stars (and the underlying plasma instability) may be cyclotron emission due to their large magnetic field. In this case, the emission likely traces high energy plasma in magnetic traps rather than unbound plasma that streaming into interplanetary space and influence space-weather around exoplanets. Consequently, the flare dynamics and phenomenology of the radio emission is likely to be fundamentally different from those on Sun-like stars with weak magnetic fields.
GREGOR: Optics Redesign and Updates from 2018-2020

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ABSTRACT

The GREGOR telescope was inaugurated in 2012. In 2018, we started a complete upgrade, involving optics, alignment, instrumentation, mechanical upgrades for vibration reduction, updated control systems, and building enhancements and, in addition, adapted management and policies. This paper describes all major updates performed during this time. Since 2012, all powered mirrors except for M1 were exchanged. Starting from 2020, GREGOR observes with diffraction-limited performance and a new optics and instrument layout.

Key words. Telescopes – Sun: general – Techniques: high angular resolution

1. Introduction

Solar telescopes have always strived to evolve in diameter and thus spatial resolution (e.g. review by Kleint & Gandorfer [2017]). Before the year 2000, their diameters have remained below 1 m, with the exception of the Mc Math Pierce telescope at Kitt Peak, which however mostly observed in the infrared (Penny [2013]). A new generation of telescopes started in the 21st century with the Swedish Solar Telescope (SST) in 2002 with a clear aperture of 0.98 m, which was optimized for a very high image quality and routinely delivers impressive high-resolution solar images, especially also at wavelength in the blue (Scharmer et al. [2003] 2013). It was followed in 2009 by the Goode Solar Telescope (GST, Goode et al. [2010]), with a 1.6 m clear aperture, which for example has obtained the highest resolution flare images to date (Jing et al. [2016]).

GREGOR, Europe’s largest solar telescope, became operational a few years later. Its 1.5 m diameter with an optical footprint of 1.44 m allows us to resolve structures on the Sun as small as 50 km at 400 nm. The GREGOR project started with its proposal in the year 2000 (von der Lühe et al. [2001]) and carried out a science verification phase from 2012 to 2013. The state of GREGOR at that time was published in a series of articles in Astronomische Nachrichten Vol. 333, No. 9, in particular the GREGOR overview by Schmidt et al. [2012]. GREGOR was designed to explore solar features at smaller scales than other telescopes at that time. Its theoretical spatial resolution surpasses the SST and is similar to the GST and all three telescopes have significantly improved their image quality with state-of-the-art adaptive optics (AO) systems (Schmidt et al. [2016] Berkefeld et al. [2018] Scharmer et al. [2019]). Their designs differ though, with GREGOR focusing on high-precision polarimetry, which has enabled investigations of polarization signals as small as \(10^{-4} \text{I_c}\) to detect spatial variations of turbulent magnetic fields (Bianda et al. [2018] Dhara et al. [2019]). Another advantage of GREGOR is its potential for polarimetric night observations, which has been used to study the polarization of planets and thus their atmospheres (Gisler et al. [2016]). A past drawback of GREGOR was that its image quality did not reach the theoretical limit, partly because a risk was taken with untested technologies, such as silicon carbide mirrors, which could not be polished well enough and partly because of design issues. These issues have recently been solved by replacing all silicon carbide mirrors with mirrors made of Zerodur, which can be polished to the required quality, and by redesigning the AO relay optics, and GREGOR now operates at its diffraction limit. The goal of this paper is to summarize recent upgrades and enhancements that were carried out from 2018-2020. We will only briefly summarize GREGOR’s general properties and we refer the reader to the article series from 2012 for more details.

GREGOR obtained its name by being a Gregory system with three imaging mirrors (M1, M2, M3) whose properties are summarized in Table I. More than 99% of the sunlight is reflected away at the cooled primary field stop F1. Only a beam with circular diameter of 150′′ passes through its central hole to M2. The F1 field stop is recoated yearly, currently with an aluminum layer on top of a nickel layer. The mirrors M4-M11 are flat mirrors with the purpose of directing the beam into the optics lab one story below the telescope level. M8-M10 are rotatable about the optical axis, thus acting as a derotator, which compensates for the solar image rotation induced by the alt-az mount of the telescope. A schematic drawing of GREGOR is shown in Fig. 1.

2. Optics

2.1. Redesign of the optics lab

The original optics lab layout was devised during GREGOR’s design phase before 2008. It focused on the first light instruments GRIS, a spectropolarimeter based on a grating spectrograph (Collados et al. [2012]), GFPI, a dual-etalon spectroscopic imager (Puschmann et al. [2012]), plus an associated broad-band imager, and BBI as a standalone im-
THE NEAREST DISCOVERED BLACK HOLE IS LIKELY NOT IN A TRIPLE CONFIGURATION

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ABSTRACT

HR6819 was recently claimed to be a hierarchical triple system of a Be star in a wide orbit around an inner binary system of a black hole (BH) and a B III type star. We argue that this system is unlikely to be a hierarchical triple due to three reasons: (i) Given that this system is discovered in a magnitude limited Bright Star Catalog, the expected number of such systems in the Milky Way amounts to about $10^4$ while the estimate for the MW budget for such systems is between $10^2 - 10^3$ systems under generous assumptions. Such a large gap cannot be reconciled as it would otherwise likely overflow the MW budget for BHs; (ii) The dynamical stability of this system sets lower bounds on the orbital separation of the outer Be star, while it not being resolved by Gaia places an upper limit on its projected sky separation. We show that these two constraints would imply a narrow range for the outer orbit without resorting to geometrical fine-tuning; (iii) The triple system should have survived the stellar evolution prior to the formation of the BH in the inner binary. We perform numerical simulations starting with conservative initial conditions of this system and show that a small parameter space for BH progenitor star’s mass loss, BH natal kicks, and initial orbital separation can reproduce HR6819. Therefore, we propose this system is a chance superposition of a Be star with a binary.

1. INTRODUCTION

The recent unexpected discoveries of unusual black holes (BHs), either in mass (Liu et al. 2019) or in companions (Rivinius et al. 2020) provides exciting opportunity to re-visit our assumption regarding the formation of the BHs. LB-1 was originally claimed to be a 70 M$_\odot$ BH in a wide orbit around an 8 M$_\odot$ star (Liu et al. 2019), and more recently HR6819 is claimed to be a hierarchical triple system with a BH in its inner binary (Rivinius et al. 2020).

While theorists have had a difficult time explaining the formation of LB-1 as a 70 M$_\odot$ BH in a wide orbit around an 8 M$_\odot$ star (Safarzadeh et al. 2019; Abdul-Masih et al. 2019; El-Badry & Quataert 2019; Eldridge et al. 2019), more detailed modelings and observations suggested the system to be a binary of a Be type star and a stripped star (Shenar et al. 2020). Rivinius et al. (2020) claims both systems to be hierarchical triples with a Be type star in a wide orbit around an inner binary of a class B star around a BH. The lower limits on the mass of the BH in the inner binary is about $\geq 4.2 (6.3)$ M$_\odot$, and the mass of the B star in the inner binary is found to be $\geq 5.0 (8.2)$ M$_\odot$ for HR6819 (LB-1).

While it is possible to explain the presence of a particular system with certain mass and structure through unconventional channels, three issues are often neglected: (i) Budget: detecting a system by studying a sample of targets with size $N_t$, implies the presence of $N_{MW}/N_t$ such systems in the MW where $N_{MW}$ is the expected number of similar targets in the MW. One has to check whether the implied number density of such systems is within the allowed range for the MW and if it is higher than the expectations, one has to explain why that is the case; (ii) Stability: dynamical stability of a system can be perturbed either by the cumulative effect of long-distance encounters of passing by objects or a catastrophic collision with an equal mass object at short distances or internally due to the constituents of the system itself, where the last possibility is relevant to the hierarchical triple systems (Mardling & Aarseth 2001); and (iii) Lifetime: a short-lived system has a lower detection probability compared to long lived systems.

The structure of this Letter is as follows: In §2 we discuss the inferred budget of the BHs in binaries and triples given the HR6819 claimed discovery. In §3 we consider limits on the orbital separation of the outer Be star in this system and argue there is only a narrow possible range for this system to a be a hierarchical triple. In §4 we perform numerical simulation of this system from conservative initial conditions showing the survival of such a system needs fine-tuning in initial conditions, and in §5 we summarize our result and discuss the implications.

2. MW BUDGET FOR BLACK HOLES IN TRIPLE SYSTEMS

HR6819 is initially discovered in the magnitude limited Bright Star Catalog (BSC; Hoffleit & Jaschek 1991),
Type II Cepheids as stellar tracers and distance indicators

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Abstract. Type II Cepheids are both useful distance indicators and tracers of old age stellar populations in their host galaxy. We summarize near-infrared observations of type II Cepheids in the Large Magellanic Cloud and discuss the absolute calibration of their Period-Luminosity relations. Combining with the near-infrared data for type II Cepheids in the Galactic bulge from the VISTA VVV survey, we estimated a robust distance to the Galactic center. We found that type II Cepheids trace the spherically symmetric spatial distribution with a possible evidence of ellipsoidal structure, similar to RR Lyrae stars. Together with Gaia and VVV proper motions, type II Cepheids were found to trace the old, metal-poor, kinematically hot stellar populations in the Galactic bulge.

1. Introduction

Type II Cepheids (T2Cs) typically belong to low mass, old age (>10 Gyr) stellar populations found in the globular clusters, Galactic bulge and disc (Wallerstein 2002). T2Cs are generally classified in three subclasses based on their pulsation period: BL Herculis (BLH, 1 ≲ P ≲ 4 d), W Virginis (WVI, 4 ≲ P ≲ 20 d) and RV Tauri (RVT, P ≳ 20 d). These subclasses represent different evolutionary states going from post-horizontal branch to asymptotic giant branch (AGB) and post AGB stars. A subclass of peculiar W Virginis (PWV) was suggested by Soszyński et al. (2008) for the most blue and bright WVI stars due to their distinct lightcurves.
The Fornax Deep Survey with VST

IX. On the assembly history of the bright galaxies and intra-group light in the Fornax A subgroup

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ABSTRACT

Context. We present the study of the south-west group in the Fornax cluster centred on the brightest group galaxy (BGG) Fornax A, observed as part of the Fornax Deep Survey (FDS). This includes the analysis of the bright group members (\(m_g < 16\) mag) and the intra-group light (IGL).

Aims. The main objective of this work is to investigate the assembly history of the Fornax A group and to compare its physical quantities as a function of the environment to that of the Fornax cluster core.

Methods. For all galaxies, we extract the azimuthally averaged surface brightness profiles in three optical bands (g, r, i) by modelling the galaxy’s isophotes. We derive their colour (g – i) profiles, total magnitude, effective radius in all respective bands, stellar mass, and the break radius in r-band. The long integration time and large covered area of the FDS allow us to also estimate the amount of IGL.

Results. The majority of galaxies in the Fornax A group are late-type-galaxies (LTGs), spanning a range of stellar mass of \(8 < \log(M_{*}/\text{M}_{\odot}) < 10.5\). Six out of nine LTGs show a Type III (up-bending) break in their light profiles, which is either suggestive of strangulation halting star-formation in their outskirts or their H-richness causing enhanced star-formation in their outer-discs. Overall, we do not find any correlations of their physical properties with group-centric distances. The estimated luminosity of the IGL is \(6 \pm 2 \times 10^{11}L_{\odot}\) in g-band, which corresponds to about 16% of the total light in the group.

Conclusions. The Fornax A group appears to be in an early-stage of assembly with respect to the cluster core. The environment of the Fornax A group is not as dense as that of the cluster core, with all galaxies except the BGG showing similar morphology, comparable colours and stellar masses, and Type III disc-breaks, without any clear trend of these properties with group-centric distances. The low amount of IGL is also consistent with this picture, since there were no significant gravitational interactions between galaxies that modified the galaxies’ structure and contributed to the build-up of the IGL. The main contribution to the IGL is from the minor merging in the outskirts of the BGG NGC 1316 and, probably, the disrupted dwarf galaxies close to the group centre.


1. Introduction

Galaxies tend to gather in gravitationally bound systems during their evolution, which are seen as dense knots in the cosmic web filaments. In the local universe, it has been found that about half of the population of galaxies are found in groups and clusters (Karachentsev 2005). According to the hierarchical structure formation, these galaxy clusters are formed from merging of smaller structures like galaxy groups (e.g. Blumenthal et al. 1984; Sommer-Larsen 2006; Rudick et al. 2009). The terminology ‘galaxy group’ and ‘galaxy cluster’ depends on various factors e.g. the galaxy number density, the virial mass, X-ray luminosity, velocity dispersion. Groups of galaxies or poor clus-
High-Sensitivity Observations of Molecular Lines with the Arecibo Telescope

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ABSTRACT
We report on one of the highest sensitivity surveys for molecular lines in the frequency range 6.0 to 7.4 GHz conducted to date. The observations were done with the 305 m Arecibo Telescope toward a sample of twelve intermediate/high-mass star forming regions. We searched for a large number of transitions of different molecules, including CH$_3$OH and OH. The low RMS noise of our data (∼5 mJy for most sources and transitions) allowed detection of spectral features that have not been seen in previous lower sensitivity observations of the sources, such as detection of excited OH and 6.7 GHz CH$_3$OH absorption. A review of 6.7 GHz CH$_3$OH detections indicates an association between absorption and radio continuum sources in high-mass star forming regions, although selection biases in targeted projects and low sensitivity of blind surveys imply incompleteness. Absorption of excited OH transitions was also detected toward three sources. In particular, we confirm a broad 6.035 GHz OH absorption feature in G34.26+0.15 characterized by an asymmetric blue-shifted wing indicative of expansion, perhaps a large scale outflow in this HII region.

Key words: HII regions — ISM: molecules — masers — radio lines: ISM — stars: formation

1 INTRODUCTION

In the past two decades, high sensitivity receivers have been deployed in major observatories around the world for observations at 6 GHz frequencies. Different molecular transitions have been detected at these frequencies, particularly in regions of high-mass star formation. The main examples are excited OH transitions (e.g., Avison et al. 2016, Al-Marzouk et al. 2012) and the widespread 6.7 GHz methanol line.

The 6.7 GHz methanol transition was first detected in the interstellar medium by Menten (1991) using the 140 foot telescope of the NRAO. Menten (1991) detected strong methanol masers associated with star forming regions, as well as methanol absorption toward eight regions (NGC 2264, G34.57−0.09, NGC 6334−C, Sgr A−F, Sgr A−A, Sgr B2, G10.62−0.38, W33). Since then, most observations have focused on studies of the 6.7 GHz CH$_3$OH maser as part of blind surveys (e.g., Breen et al. 2015; Pandian et al. 2007), targeted observations of high-mass star forming regions (e.g., Olmi et al. 2014), or to investigate periodic maser flares (e.g., Rajabi et al. 2019, MacLeod et al. 2018, Szymczak et al. 2018, Araya et al. 2010, Goedhart et al. 2004). While most observations reported in the literature have focused on bright lines, high-sensitivity observations have resulted in detection of weak lines, such as 6.7 GHz methanol absorption in the low-mass star forming region NGC1333 (Pandian et al. 2008). In this case, the line is due to an anti-inversion (over-cooling) effect that allows absorption against the Cosmic Microwave Background (CMB), as observed for example in 6 cm H$_2$CO (e.g., Araya et al. 2006) and 12 GHz CH$_3$OH transitions (Walsmeijer et al. 1988, Peng & Whiteoak 1991). Pandian et al. (2008) concluded that the methanol absorption in NGC1333 is tracing dense (∼10$^6$ cm$^{-3}$) cold/warm (∼15 to 30 K) gas.

In extragalactic environments, high-sensitivity observations have shown that 6.7 GHz methanol absorption is
Abstract A joint campaign of various space-borne and ground-based observatories, comprising the Japanese Hinode mission (HOP 338, 20 – 30 September 2017), the GREGOR solar telescope, and the Vacuum Tower Telescope (VTT), investigated numerous targets such as pores, sunspots, and coronal holes. In this study, we focus on the coronal hole region target. On 24 September 2017, a very extended non-polar coronal hole developed patches of flux emergence, which contributed to the decrease of the overall area of the coronal hole. These flux emergence patches erode the coronal hole and transform the area into a more quiet-Sun-like area, whereby bipolar magnetic
Measurement of Hubble Constant: Do Different Cosmological Probes Provide Different Values?

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Abstract

Different measurements of the Hubble constant ($H_0$) are not consistent and a tension between the CMB based methods and cosmic distance ladder based methods has been observed. Measurements from various distance based methods are also inconsistent. To aggravate the problem, same cosmological probe (Type Ia SNe for instance) calibrated through different methods also provide different value of $H_0$.

We compare various distance ladder based methods through the already available unique data obtained from Hubble Space Telescope (HST). Our analysis is based on parametric (T-test) as well as non-parametric statistical methods such as the Mann-Whitney U test and Kolmogorov-Smirnov test. Our results show that different methods provide different values of $H_0$ and the differences are statistically significant. The biases in the calibration would not account for these differences as the data has been taken from a single telescope with common calibration scheme. The unknown physical effects or issues with the empirical relations of distance measurement from different probes could give rise to these differences.

Keywords: Cosmology, Supernovae, Hubble constant

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Solar Flare–CME Coupling Throughout Two Acceleration Phases of a Fast CME

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ABSTRACT

Solar flares and coronal mass ejections (CMEs) are closely coupled through magnetic reconnection. CMEs are usually accelerated impulsively within the low solar corona, synchronized with the impulsive flare energy release. We investigate the dynamic evolution of a fast CME and its associated X2.8 flare occurring on 2013 May 13. The CME experiences two distinct phases of enhanced acceleration, an impulsive one with a peak value of $\sim 5 \, \text{km} \, \text{s}^{-2}$ followed by an extended phase with accelerations up to $0.7 \, \text{km} \, \text{s}^{-2}$. The two-phase CME dynamics is associated with a two-episode flare energy release. While the first episode is consistent with the “standard” eruption of a magnetic flux rope, the second episode of flare energy release is initiated by the reconnection of a large-scale loop in the aftermath of the eruption and produces stronger nonthermal emission up to $\gamma$-rays. In addition, this long-duration flare reveals clear signs of ongoing magnetic reconnection during the decay phase, evidenced by extended HXR bursts with energies up to $100–300 \, \text{keV}$ and intermittent downflows of reconnected loops for $>4$ hours. The observations reveal that the two-step flare reconnection substantially contributes to the two-phase CME acceleration, and the impulsive CME acceleration

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Chemical Variation among Protostellar Cores: Dependence on Prestellar Core Conditions

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ABSTRACT

Hot corino chemistry and warm carbon chain chemistry (WCCC) are driven by gas-grain interactions in star-forming cores: radical-radical recombination reactions to form complex organic molecules (COMs) in the ice mantle, sublimation of CH4 and COMs, and their subsequent gas-phase reactions. These chemical features are expected to depend on the composition of ice mantle which is set in the prestellar phase. We calculated the gas-grain chemical reaction network considering a layered ice-mantle structure in star-forming cores, to investigate how the hot corino chemistry and WCCC depend on the physical condition of the static phase before the onset of gravitational collapse. We found that WCCC becomes more active, if the temperature is lower, or the visual extinction is lower in the static phase, or the static phase is longer. Dependence of hot corino chemistry on the static-phase condition is more complex. While CH3OH is less abundant in the models with warmer static phase, some COMs are formed efficiently in those warm models, since there are various formation paths of COMs. If the visual extinction is lower, photolysis makes COMs less abundant in the static phase. Once the collapse starts and visual extinction increases, however, COMs can be formed efficiently. Duration of the static phase does not largely affect COM abundances. Chemical diversity between prototypical hot corinos and hybrid sources, in which both COMs and carbon chains are reasonably abundant, can be explained by the variation of prestellar conditions. Deficiency of gaseous COMs in prototypical WCCC sources is, however, hard to reproduce within our models.

Keywords: astrochemistry — stars:formation

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SIMULATIONS OF PROMINENCE ERUPTION PRECEDED WITH LARGE AMPLITUDE LONGITUDINAL OSCILLATIONS AND DRAINING

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ABSTRACT

We present magnetohydrodynamic (MHD) simulations of the evolution from quasi-equilibrium to eruption of a prominence-forming twisted coronal flux rope under a coronal streamer. We have compared the cases with and without the formation of prominence condensations, and the case where prominence condensations form but we artificially initiate the draining of the prominence. We find that the prominence weight has a significant effect on the stability of the flux rope, and can significantly increase the loss-of-equilibrium height. The flux rope can be made to erupt earlier by initiating draining of the prominence mass. We have also performed a simulation where large amplitude longitudinal oscillations of the prominence are excited during the quasi-static phase. We find that the gravity force along the magnetic field lines is the major restoring force for the oscillations, in accordance with the “pendulum model”, although the oscillation periods are higher (by about 10% to 40%) than estimated from the model because of the dynamic deformation of the field line dips during the oscillations. The oscillation period is also found to be slightly smaller for the lower part of the prominence in the deeper dips compared to the upper part in the shallower dips. The oscillations are quickly damped out after about 2-3 periods and are followed by prominence draining and the eventual eruption of the prominence. However we do not find a significant enhancement of the prominence draining and earlier onset of eruption with the excitation of the prominence oscillations compared to the case without.

Keywords: magnetohydrodynamics (MHD) — methods: numerical — Sun: corona — Sun: coronal mass ejections (CMEs) — Sun: filaments, prominences

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GASP XXVI. HI gas in jellyfish galaxies

The case of JO201 and JO206.


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ABSTRACT

We present atomic hydrogen (H I) observations of the Jansky Very Large Array of one of the jellyfish galaxies in the GAs Stripping Phenomena sample, JO201. This massive galaxy (M⊙ = 3.5 × 1010 M⊙) is falling along the line-of-sight towards the centre of a rich cluster (M200 ∼ 1.6 × 1015 M⊙, σcl ∼ 982 ± 55 km s−1) at a high velocity ≥3363 km s−1. Its Hα emission shows a ∼40 kpc tail, which is closely confined to its stellar disc and a ∼100 kpc tail extending further out. We find that H I emission only coincides with the shorter clumpy Hα tail, while no H I emission is detected along the ∼100 kpc Hα tail. In total, we measured an H I mass of MHI = 1.65 × 109 M⊙, which is about 60% lower than expected based on its stellar mass and stellar surface density. We compared JO201 to another jellyfish in the GASP sample, JO206 (of a similar mass but living in a ten times less massive cluster), and we find that they are similarly H I deficient. Of the total H I mass in JO201, about 30% lies outside the galaxy disc in projection. This H I fraction is probably a lower limit since the velocity distribution shows that most of the H I is redshifted relative to the stellar disc and could be outside the disc. The global star formation rate (SFR) analysis of JO201 suggests an enhanced star formation for its observed H I content. The observed SFR would have been expected if JO201 had ten times its current H I mass. The disc is the main contributor of the high star formation efficiency at a given H I gas density for both galaxies, but their tails also show higher star formation efficiencies compared to the outer regions of field galaxies. Generally, we find that JO201 and JO206 are similar based on their different environments. A toy model comparing the ram pressure of the intracluster medium (ICM) versus the restoring forces of these galaxies suggests that the ram pressure strength exerted on them could be comparable if we consider their 3D orbital velocities and radial distances relative to the clusters.

Key words. galaxies: clusters - intracluster medium: star formation: radio lines - galaxies

1. Introduction

In the dense environment of galaxy clusters, the hydrodynamical interaction between galaxies’ interstellar medium (ISM) and the intracluster medium (ICM) plays a key role in transforming galaxies from late types to early types. Among the several types of interactions discussed in the literature (e.g., Gunn & Gott 1972; Cowie & Songaila 1977; Nulsen 1982), the ram pressure exerted by the ICM on galaxies’ ISM can be very efficient at removing gas from galaxies as well as affecting their star formation activity. The degree of this effect may vary depending on the strength of the ram pressure exerted on a galaxy and its physical properties.

In some cases, the diffuse atomic hydrogen (H I) gas is only partially removed or displaced from the stellar disc (Boselli et al. 1997; Vollmer et al. 2001; Chung et al. 2009; Scott et al. 2010; Steinhauser et al. 2016). However, the dense molecular gas cloud may remain unperturbed after the diffuse gas has been stripped and continue to form stars at a low rate. In this case, the star formation (SF) essentially stops as soon as molecular gas is consumed and not replenished (Abramson & Kenney 2014).

Article number, page 1 of 9

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The dynamical evolution and the force model
for asteroid (196256) 2003 EH1
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Abstract
This paper is devoted to the dynamics of asteroid (196256) 2003 EH1 that belongs to the Amor group. It is known that the asteroid 2003 EH1 is associated with one of the main annual meteor showers – the Quadrantids. In this work we analyze the influence of various perturbing factors on the asteroid motion. The perturbation’s estimation was done by five different methods based on the nominal orbit evolution and the size of the initial confidence region. The most significant influences on the dynamical evolution of 2003 EH1 are gravitational forces from the Sun, major planets and the Moon, and the relativistic effects (RE) of the Sun. Of less importance are the Earth, the Sun and Jupiter oblateness; gravitational perturbations from Pallas, Ceres, Vesta and Pluto; and the RE of planets, the Moon, and Pluto.

The researches of chaoticity and evolution of asteroid 2003 EH1 were examined by integrating its motion equations along with 500 clones. The time interval (1000-4000 years) has been determined by integration precision estimation. We calculated the mean exponential growth factor of nearby orbits (MEGNO) and found that MEGNO < 2 only in the interval 1700-2300. After 2300 year the MEGNO parameter increases that indicates motion instability. It shows that the orbit may be considered as regular on the time interval of ±300 years from now, and as chaotic outside this interval. The reason, as we suppose, is frequent close approaches of the asteroid with Jupiter and the overlap of apsidal-nodal resonances.

Key words: (196256) 2003 EH1, force model, the dynamical evolution, close encounters, apsidal-nodal resonances.

1. Introduction

The motion simulation plays a special role in the study of the dynamical properties of Solar System objects. The choice of the approach for estimating an optimal model depends on many factors. The initial assumption concerning a force model for an investigated object is one of the most complicated and important aspects. Using the full model is not always justified. The accuracy of obtaining initial and current
Testing the Weak Equivalence Principle and Lorentz Invariance with Multiwavelength Polarization Observations of GRB Optical Afterglows

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Abstract Violations of both the weak equivalence principle (WEP) and Lorentz invariance can produce vacuum birefringence, which leads to an energy-dependent rotation of the polarization vector of linearly polarized emission from a given astrophysical source. However, the search for the birefringent effect has been hindered by our ignorance concerning the intrinsic polarization angle in different energy bands. Considering the contributions to the observed linear polarization angle from both the intrinsic polarization angle and the rotation angles induced by violations of the WEP and Lorentz invariance, and assuming the intrinsic polarization angle is an unknown constant, we simultaneously obtain robust bounds on possible deviations from the WEP and Lorentz invariance, by directly fitting the multiwavelength polarimetric data of the optical afterglows of gamma-ray burst (GRB) 020813 and GRB 021004. Here we show that at the 3σ confidence level, the difference of the parameterized post-Newtonian parameter γ values characterizing the departure from the WEP is constrained to be Δγ = (−4.5 ± 10.0) × 10−24 and the birefringent parameter η quantifying the broken degree of Lorentz invariance is limited to be η = (6.5 ± 15.0 ± 14.0) × 10−7. These are the first simultaneous verifications of the WEP and Lorentz invariance in the photon sector. More stringent limits can be expected as the analysis presented here is applied to future multiwavelength polarization observations in the prompt gamma-ray emission of GRBs.

Keywords astroparticle physics – gravitation – polarization – gamma-ray burst: general

1 Introduction

The weak equivalence principle (WEP) is a fundamental postulate of general relativity as well as of many other metric theories of gravity. One statement of the WEP is that the trajectory of any freely falling, uncharged test body does not depend on its internal structure and composition [1, 2]. It implies that different species of messenger particles (e.g., photons, neutrinos, or gravitational waves), or the same species of particles but with different internal structures (e.g., energies or polarization states), if radiated simultaneously from the same astrophysical source and passing through the same gravitational field, should arrive at our Earth at the same time. The WEP test can therefore be performed by comparing the arrival-time differences between correlated particles from the same astrophysical source (e.g., [3–29]). Additionally, if the WEP is invalid then arrival times of photons with right- and left-handed circular polarizations should differ slightly, leading to a frequency-dependent rotation of the polarization plane of a linearly polarized light. Thus, polarimetric observations of astrophysical sources can also be used to test the WEP [30–32]. Currently, the best upper limit on a deviation from the WEP has been obtained from the gamma-ray polarization measurement of gamma-ray burst (GRB) 061122 [31]. The WEP passes this extraordinarily stringent test with an accuracy of $O(10^{-33})$.

Lorentz invariance is a foundational symmetry of Einstein’s theory of relativity. However, many quantum gravity theories seeking to unify quantum mechanics and general relativity predict that Lorentz invariance may be broken at the Planck energy scale $E_{\text{Pl}} \simeq 1.22 \times 10^{19}$ GeV [33–40]. As a consequence of Lorentz invariance violation (LIV), the polarization vector of linearly polarized photons would make an energy-dependent rotation, also known as vacuum birefringence. Lorentz invariance can therefore be tested with astrophysical polarization measurements (e.g., [41–60]). The
WHAT IF THE NEUTRON STAR MAXIMUM MASS IS BEYOND $\sim 2.3M_\odot$?

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ABSTRACT

By assuming the formation of a black hole soon after the merger event of GW170817, Shibata et al. updated the constraints on the maximum mass ($M_{\text{max}}$) of a stable neutron star within $\lesssim 2.3 M_\odot$, but there is no solid evidence to rule out $M_{\text{max}} > 2.3 M_\odot$ from the point of both microphysical and astrophysical views. In order to explain massive pulsars, it is naturally expected that the equation of state (EOS) would become stiffer beyond a specific density. In this paper, we consider the possibility of EOSs with $M_{\text{max}} > 2.3 M_\odot$, investigating the stiffness and the transition density in a polytropic model. Two kinds of neutron stars are considered, i.e., normal neutron stars (the density vanishes on gravity-bound surface) and strange stars (a sharp density discontinuity on self-bound surface). The polytropic model has only two parameter inputs in both cases: ($\rho_t$, $\gamma$) for gravity-bound objects, while ($\rho_s$, $\gamma$) for self-bound ones, with $\rho_t$ the transition density, $\rho_s$ the surface density and $\gamma$ the polytropic exponent. In the matter of $M_{\text{max}} > 2.3 M_\odot$, it is found that the smallest $\rho_t$ and $\gamma$ should be $\sim 0.50 \rho_0$ and $\sim 2.65$ for normal neutron stars, respectively, whereas for strange star, we have $\gamma > 1.40$ if $\rho_s > 1.0 \rho_0$ and $\rho_s < 1.58 \rho_0$ if $\gamma < 2.0$ ($\rho_0$ is the nuclear saturation density). These parametric results could guide further research of the real EOS with any foundation of microphysics if a pulsar mass higher than $2.3 M_\odot$ is measured in the future. We also derive rough results of common neutron star radius range, which is $9.8 \text{ km} < R_{1.4} < 13.8 \text{ km}$ for normal neutron stars and $10.5 \text{ km} < R_{1.4} < 12.5 \text{ km}$ for strange stars.

Keywords: equation of state - stars: neutron

1. INTRODUCTION

The equation of state (EOS) of dense matter, especially of ultra-dense matter, is a key issue in nuclear physics and astrophysics (Weber 2005). There are two kinds of neutron star scenarios, gravity-bound system, and self-bound system. The conventional neutron star is a gravity-bound system, with gravity-bound surface, usually has smaller radius with larger mass. In contrast, strange star (strange quark star (Alcock, et al. 1986) and strangeon star (Lai & Xu 2017)) as self-bound system, that their surface are self-bounded, has larger radius with larger mass. The normal neutron star is divided into the core part and the crust part. Physicists developed many-body theories to describe the core and inner crust EOS, which is unclear at high density, such as Green Function Monte Carlo (GFMC) method (Pieper & Wiringa 2001), chiral perturbation theory (ChPT) (Gasser & Leutwyler 1984, 1985), Brueckner-Hartree-Fock (BHF) (Brockmann & Machleidt 1971), quark mean-field (QMF) model (Toki et al. 1998), quark meson coupling (QMC) model (Guichon 1988, Saito & Thomas 1994, 1995), relativistic mean-field (RMF) model (Serot & Walecka 1986) et al. The Baym-Pethick-Sutherland (BPS) (Baym et al. 1971) EOS is commonly used to describe the neutron star out crust (lower than neutron drip density).

Neutron star merger event GW170817 offers a limit of tidal deformability, $70 \leq \Lambda_{1.4} \leq 580$ (Abbott, et al. 2017, 2018). Based on various many-body methods and this tidal deformability range, a roughly consistent 1.4 $M_\odot$ neutron star radius constraint refers $R_{1.4} \leq 13.6 \text{ km}$ (Annala, et al. 2018, Krastev & Li 2019, Tews 2018) using the original findings $\Lambda_{1.4} \leq 800$ (Abbott, et al. 2017). Based on NASA’s Neutron Star Interior Composition Explorer (NICER; Gendreau et al. 2016) data set, it is able to estimate neutron star mass and radii using X-ray pulse-profile modeling (Raaijmakers et al. 2019). Neutron star radii as a observable quantity is valuable to restrict the EOS. We conclude this $R_{1.4} \leq 13.6$ restrict in our paper as a contrast of the tidal deformability constraint. It is believed the merger event may form a transitory state like hypermassive or supermassive neu-
Characteristics and applications of interplanetary coronal mass ejection composition

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In situ measurements of interplanetary coronal mass ejection (ICME) composition, including elemental abundances and charge states of heavy ions, open a new avenue to study coronal mass ejections (CMEs) besides remote-sensing observations. The ratios between different elemental abundances can diagnose the plasma origin of CMEs (e.g., from the corona or chromosphere/photosphere) due to the first ionization potential (FIP) effect, which means elements with different FIP get fractionated between the photosphere and corona. The ratios between different charge states of a specific element can provide the electron temperature of CMEs in the corona due to the freeze-in effect, which can be used to investigate their eruption process. In this review, we first give an overview of the ICME composition and then demonstrate their applications in investigating some important subjects related to CMEs, such as the origin of filament plasma and the eruption process of magnetic flux ropes. Finally, we point out several important questions that should be addressed further for better utilizing the ICME composition to study CMEs.

coronal mass ejection, interplanetary coronal mass ejection, elemental abundance, ionic charge state, magnetic flux rope, magnetic cloud, filament, flare

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1 Introduction

Interplanetary coronal mass ejections (ICMEs) refer to the counterpart of coronal mass ejections (CMEs) in the interplanetary space, which are an energetic explosive phenomenon occurred in the solar atmosphere [1–4]. When interacting with the Earth’s atmosphere, ICMEs can induce strong geomagnetic activity [5, 6] and seriously influence our high-technology activities through damaging satellites, over-loading power grids, and disrupting GPS navigation systems [7, 8]. Therefore, it is of great significance to investigate CMEs/ICMEs for both astrophysics and space weather.

Theoretical studies suggest that CMEs take place due to the eruption of magnetic flux rope (MFR, a coherently helical magnetic structure with its field lines winding around one central axis more than one turn), which can be formed prior to [9–11] or during solar eruptions [12–14] through magnetic reconnection occurred in the corona. So far, none of physical mechanisms can produce a CME without involving the MFR. In the case that the MFR has existed in the corona before eruption, theoretical studies propose an alternative mechanism to answer where and how the MFR is built up, which suggests that the MFR is formed in the convection zone and can emerge into the corona by buoyancy [15–17]. This mechanism is supported by some observations [18]. However, simulations found that only the upper part of the MFR can emerge into the corona [19] and the reconnection is necessary to transfer some emerged magnetic fluxes into a new MFR structure in the corona [20].

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Stellar Spectral Interpolation using Machine Learning

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ABSTRACT

Theoretical stellar spectra rely on model stellar atmospheres computed based on our understanding of the physical laws at play in the stellar interiors. These models, coupled with atomic and molecular line databases, are used to generate theoretical stellar spectral libraries (SSLs) comprising of stellar spectra over a regular grid of atmospheric parameters (temperature, surface gravity, abundances) at any desired resolution. Another class of SSLs is referred to as empirical spectral libraries; these contain observed spectra at limited resolution. SSLs play an essential role in deriving the properties of stars and stellar populations. Both theoretical and empirical libraries suffer from limited coverage over the parameter space. This limitation is overcome to some extent by generating spectra for specific sets of atmospheric parameters by interpolating within the grid of available parameter space. In this work, we present a method for spectral interpolation in the optical region using machine learning algorithms that are generic, easily adaptable for any SSL without much change in the model parameters, and computationally inexpensive. We use two machine learning techniques, Random Forest (RF) and Artificial Neural Networks (ANN), and train the models on the MILES library. We apply the trained models to spectra from the CFLIB for testing and show that the performance of the two models is comparable. We show that both the models achieve better accuracy than the existing methods of polynomial based interpolation and the Gaussian radial basis function (RBF) interpolation.

Key words: stars: fundamental parameters - stars: general - methods: data analysis - techniques: spectroscopic - astronomical data bases: miscellaneous

1 INTRODUCTION

Empirical and synthetic stellar spectral libraries (SSLs) consisting of stellar spectra with their atmospheric parameters and/or spectral classes have played a key role in exploring the physics of stars and stellar populations through various studies. Empirical libraries such as the Indo-U.S. Library of Coudé Feed Stellar Spectra (CFLIB; Valdés et al. 2004), MILES (Sánchez-Blázquez et al. 2006), and ELODIE (Prugniel et al. 2007) comprise of observed stellar spectra and span a wide range of parameter space in the H-R diagram. Empirical SSLs have been extensively used in the past for stellar classification (Gulati et al. 1994; Bailer-Jones et al. 1998; Singh et al. 1998; Navarro et al. 2012; Liu et al. 2015), parameter determination (Wu et al. 2011; Prugniel et al. 2011; Sharma et al. 2016), chemical and evolutionary studies of stellar populations and galaxies (Buzzoni et al. 1994; Koleva et al. 2008). Some studies involving stellar populations require the presence of stellar spectra at the edges of the parameter space (e.g., for brown dwarfs) or specific wavelength coverage in high-resolution for studying detailed abundances. In such scenarios, synthetic libraries are found to be more useful. Primary ingredients for developing synthetic SSLs are models of stellar atmosphere, e.g. ATLAS (Kurucz 1993), PHOENIX (Hauschildt & Baron 1999), MARCS (Gustafsson et al. 2008), which are used by computer programs to generate synthetic stellar spectra to create synthetic spectral libraries (Munari et al. 2005; Husser et al. 2013; Coelho 2014). Synthetic libraries do not have the limitation of spectral resolution or wavelength coverage. They can provide the spectrum in the regions of the parameter space (say extreme edges of metallicity bins) which are sparsely populated in the empirical libraries. Therefore, the synthetic libraries

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Chapter 29  
Beyond a pale blue dot : how to search for possible bio-signatures on earth-like planets

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Abstract The Earth viewed from outside the Solar system would be identified merely like a pale blue dot, as coined by Carl Sagan. In order to detect possible signatures of the presence of life on a second earth among several terrestrial planets discovered in a habitable zone, one has to develop and establish a methodology to characterize the planet as something beyond a mere pale blue dot. We pay particular attention to the periodic change of the color of the dot according to the rotation of the planet. Because of the large-scale inhomogeneous distribution of the planetary surface, the reflected light of the dot comprises different color components corresponding to land, ocean, ice, and cloud that cover the surface of the planet. If we decompose the color of the dot into several principle components, in turn, one can identify the presence of the different surface components. Furthermore, the vegetation on the earth is known to share a remarkable reflection signature; the reflection becomes significantly enhanced at wavelengths longer than 760nm, which is known as a red-edge of the vegetation. If one can identify the corresponding color signature in a pale blue dot, it can be used as a unique probe of the presence of life. I will describe the feasibility of the methodology for future space missions, and consider the direction towards astrobiology from an astrophysicist’s point of view.

Key words: bio-signatures, pale-blue-dot, red-edge, Copernican Principle

29.1 Introduction

Discovery of an amazing number of exoplanetary systems since 1995 has completely changed our view of the world itself. In particular, we learned once again the universal validity of the Copernican Principle; we do not occupy any special place in the universe. Indeed, this is exactly the very important philosophical lesson that we have learned in the history of astronomy over and over again.

A straightforward corollary of the Copernican Principle is that our earth is simply just one of numerous planets in the universe that harbor the life. This will be easily expected from a very crude, order-of-magnitude argument shown below.
2D RETRIEVAL FRAMEWORKS FOR HOT JUPITER PHASE CURVES
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ABSTRACT

Spectroscopic phase curves provide unique access to the three-dimensional properties of transiting exoplanet atmospheres. However, a modeling framework must be developed to deliver accurate inferences of atmospheric properties for these complex data sets. Here, we develop an approach to retrieve temperature structures and molecular abundances from phase curve spectra at any orbital phase. In the context of a representative hot Jupiter with a large day-night temperature contrast, we examine the biases in typical one-dimensional (1D) retrievals as a function of orbital phase/geometry, compared to two-dimensional (2D) models that appropriately capture the disk-integrated phase geometry. We guide our intuition by applying our new framework on a simulated HST+Spitzer phase curve data set in which the “truth” is known, followed by an application to the spectroscopic phase curve of the canonical hot Jupiter, WASP-43b. We also demonstrate the retrieval framework on simulated JWST phase curve observations. We apply our new geometric framework to a joint-fit of all spectroscopic phases, assuming longitudinal molecular abundance homogeneity, resulting in an improvement in abundances precision when compared to individual phase constraints. With a 1D retrieval model on simulated HST+Spitzer data, we find strongly biased molecular abundances for CH$_4$ and CO$_2$ at most orbital phases. With 2D, the day and night profiles retrieved from WASP-43b remain consistent throughout the orbit. JWST retrievals show that a 2D model is strongly favored at all orbital phases. Based on our new 2D retrieval implementation, we provide recommendations on when 1D models are appropriate and when more complex phase geometries involving multiple TP profiles are required to obtain an unbiased view of tidally locked planetary atmospheres.

1. INTRODUCTION

Hot Jupiters have complex atmospheres; they are expected to be tidally-locked and experience large day-night temperature contrasts, along with significant variations in abundances and cloud properties (Parmentier & Crossfield 2018). Phase curve observations of tidally locked exoplanets probe the longitudinal variations in temperature, composition, and cloud properties, acting as a powerful diagnostic of energy and chemical transport (e.g., Agúndez et al. 2012; Komacek et al. 2017; Drummond et al. 2018; Steinmucke et al. 2019). Furthermore, precision abundance ratios can potentially be tied back to models of planet formation (e.g., ¨Oberg et al. 2011; Madhusudhan et al. 2014; Espinoza et al. 2017). With the promise of better precision on the horizon from future observatories such as the James Webb Space Telescope, we will be able to deepen the level of our characterization of exoplanet atmospheres. It is critical to our understanding of these worlds to assess the accuracy with which this information can be constrained by leveraging the synergies between observations and modeling efforts.

Atmospheric retrievals have emerged as a powerful tool for determining atmospheric properties such as molecular/elemental abundances, cloud properties, and thermal structures from exoplanet spectra (Madhusudhan & Seager 2009; Line et al. 2012; Lee et al. 2012; Benneke 2015; Madhusudhan 2018). Inverse modeling is driven by the data set, wavelength coverage, and observation uncertainty; just as much, retrieval-based atmospheric inference is highly model dependent, a realization that has recently received well-deserved attention. As more inverse models are developed and data diversity continues to increase, we face a growing suite of choices regarding radiative transfer, chemistry, and aerosol treatment. (Chang et al. 2019; Mollière et al. 2019; Mai & Line 2019a; Iyer & Line 2020; Barstow 2020). The specifics are ever evolving as it can be complex to pinpoint what a model may be lacking within the context of a specific data set.

A challenging aspect of retrievals is maintaining a computationally efficient forward model within common Bayesian frameworks while balancing adequately sophisticated implementation of the necessary atmospheric physics. Given the disk-integrated nature of the observed spectra, retrieval models have typically assumed 1D treatment of the temperature-pressure (TP) profile and chemistry. Yet, for instance in the case of a planet observed at quadrature, where half the dayside and half the nightside are visible, the hemispherically averaged spectrum would include contribution from contrasting hot and cool temperature-pressure (TP) profiles. Consequently, we used this case in our previous work (Feng et al. 2016) to demonstrate that a 1D retrieval model assumption affects atmospheric inference and can introduce unwanted biases. The significance of the impact depends on the type of data set and temperature contrast between the day and the night. This work found that methane is mischaracterized for simulated Hubble Space Telescope Wide Field Camera 3 (WFC3) and Spitzer Space Telescope Infrared Array Camera (IRAC) data (hereafter HST+Spitzer) - biased to a precise but inaccurate posterior distribution. Furthermore, for simulated JWST

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Obliquity of an Earth-like planet from frequency modulation of its direct imaged lightcurve: mock analysis from general circulation model simulation

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ABSTRACT

Direct-imaging techniques of exoplanets have made significant progress recently, and will eventually enable to monitor photometric and spectroscopic signals of earth-like habitable planets in the future. The presence of clouds, however, would remain as one of the most uncertain components in deciphering such direct-imaged signals of planets. We attempt to examine how the planetary obliquity produce different cloud patterns by performing a series of GCM (General Circulation Model) simulation runs using a set of parameters relevant for our Earth. Then we use the simulated photometric lightcurves to compute their frequency modulation due to the planetary spin-orbit coupling over an entire orbital period, and attempt to see to what extent one can estimate the obliquity of an Earth-twin. We find that it is possible to estimate the obliquity of an Earth-twin within the uncertainty of several degrees with a dedicated 4 m space telescope at 10 pc away from the system if the stellar flux is completely blocked. While our conclusion is based on several idealized assumptions, a frequency modulation of a directly-imaged earth-like planet offers a unique methodology to determine its obliquity.

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Velocity limits in the thermonuclear supernova ejection scenario for hypervelocity stars and the origin of US 708

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ABSTRACT

Context. Hypervelocity stars (HVS) are a class of stars moving at high enough velocities to be gravitationally unbound from the Galaxy. In recent years, ejection from a close binary system in which one of the components undergoes a thermonuclear supernova (SN) has emerged as a promising candidate production mechanism for the least massive specimens of this class. The explosion mechanisms leading to thermonuclear supernovae, which include the important Type Ia, and related subtypes, remain unclear.

Aims. This study presents a thorough theoretical analysis of candidate progenitor systems of thermonuclear SNe in the single degenerate helium donor channel, including the important Type Ia, and related subtypes, remain unclear.

Methods. Theoretical modeling of the ejection mechanism at this point in time focused heavily on the black hole connection. Theoretical modeling of the ejection mechanism at this point in time focused heavily on the black hole connection. Theoretical modeling of the ejection mechanism at this point in time focused heavily on the black hole connection.

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1. Introduction

The existence of stars moving at velocities high enough to be unbound from the Galaxy, known as hypervelocity stars (HVS), was first proposed more than three decades ago by Hills (1988). While this initial prediction was followed up by a number of theoretical studies (Hills et al. 1991), primarily based on the assumption that these objects would result from interaction of a star or binary star with a massive black hole (MBH), observational evidence was not forthcoming.

This changed with the discovery of SDSS J090745.0+024507 by Brown et al. (2005). Found in the Sloan Digital Sky Survey data set, this object, also referred to as HVS1, is likely a B-type star with a mass of about 3 M⊙ at a distance of 111 kpc from the Galactic center and a Galactic rest frame velocity of 696 km s−1 (Brown et al. 2007). This object led to a targeted search, conducted by Brown et al. (2007), which yielded nine further objects in short order, growing to 23 objects within the following decade (Brown 2015).

Theoretical modeling of the ejection mechanism at this point in time focused heavily on the black hole connection. Theoretical modeling of the ejection mechanism at this point in time focused heavily on the black hole connection. Theoretical modeling of the ejection mechanism at this point in time focused heavily on the black hole connection.
ABSTRACT

The wind driven by the intense neutrino emission from a protoneutron star (PNS) is an important site for producing nuclei heavier than the Fe group. Because of certain features in the neutrino angular distributions, the so-called fast flavor oscillations may occur very close to the PNS surface, effectively resetting the neutrino luminosities and energy spectra that drive the wind. Using the unoscillated neutrino emission characteristics from two core-collapse supernova simulations representative of relevant progenitors at the lower and higher mass end, we study the potential effects of fast flavor oscillations on neutrino-driven winds and their nucleosynthesis. We find that such oscillations can increase the total mass loss by factors up to $\sim 1.5$–1.7 and lead to significantly more proton-rich conditions. The latter effect can greatly enhance the production of $^{64}$Zn and the so-called light $p$-nuclei $^{74}$Se, $^{78}$Kr, and $^{84}$Sr. Implications for abundances in metal-poor stars, Galactic chemical evolution in general, and isotopic anomalies in meteorites are discussed.

Keywords: massive stars, core-collapse supernova, nucleosynthesis

1. INTRODUCTION

The collapse of the core of a massive star into a protoneutron star (PNS) results in profuse emission of neutrinos. Simulations have shown that these neutrinos are likely a key ingredient of the explosion mechanisms for core-collapse supernovae (CCSNe) (see e.g., Bethe 1990; Wilson & Mayle 1993; Janka et al. 2012 for reviews). Further, for both the early inner ejecta (e.g., Fröhlich et al. 2006b) and the subsequent long-term neutrino-driven wind (NDW) from the PNS (e.g., Qian & Woosley 1996; Arcones et al. 2007), neutrino interactions with the material determine the conditions governing the associated nucleosynthesis, especially the electron fraction or neutron-to-proton ratio. Such neutrino-heated ejecta is potentially a major site for producing $^{64}$Zn and the light $p$-nuclei $^{74}$Se, $^{78}$Kr, $^{84}$Sr, and $^{92}$Mo (e.g., Hoffman et al. 1996). The latter nuclei are so named because they cannot be accounted for by neutron-capture processes. Similar neutrino-driven outflows are also expected from neutron star mergers (NSMs) (e.g., Just et al. 2015; Perego et al. 2014).

Experiments with solar, atmospheric, reactor, and accelerator neutrinos have established that neutrinos oscillate among different flavors (see e.g., Tanabashi et al. 2018 for a review). Whereas the effects of neutrino oscillations on CCSN explosion and nucleosynthesis have been studied for a long time (e.g., Fuller et al. 1992; Qian et al. 1993), such effects are yet to be included self-consistently in CCSN simulations. A proper treatment is difficult partly because the regular neutrino transport changes from diffusion inside the PNS to free-streaming outside it (e.g., Richers et al. 2019). In addition, because forward scattering among neutrinos causes highly nonlinear flavor evolution of the dense neutrino gas, following such evolution is effectively a new type of neutrino transport in the flavor space (see e.g., Duan et al. 2010; Mirizzi et al. 2016 for reviews).

In this paper, we consider an interesting scenario originally suggested by Sawyer (2009), where fast oscillations in a dense neutrino gas with certain angular distributions can cause neutrinos of different flavors with different initial emission characteristics to quickly approach flavor equilibrium. Were such fast oscillations to occur near the surface of a PNS, they would effectively reset the effective luminosities and spectra for neutrino interactions outside the PNS. In addition, flavor equilibration to be obtained, there would be no need to consider further flavor evolution. Assuming the above features of fast flavor oscillations, we explore their impact on the NDWs and the associated nucleosynthesis. We find that such oscillations can increase the total mass loss by factors up to $\sim 1.5$–1.7 and lead to significantly more proton-rich conditions. The latter effect can greatly enhance...
Kinematic Structure of the Galactic Center S-cluster

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ABSTRACT

We present a detailed analysis of the kinematics of 112 stars that mostly comprise the high velocity S-cluster and orbit the super massive black hole SgrA* at the center of the Milky Way. For 39 of them orbital elements are known, for the remainder we know proper motions. The distribution of inclinations, and proper motion flight directions deviate significantly from a uniform distribution which one expects if the orientation of the orbits are random. Across the central arcseconds the S-cluster stars are arranged in two almost edge on disks that are located at a position angle approximately ±45° with respect to the Galactic plane. The angular momentum vectors for stars in each disk point in both directions, i.e. the stars in a given disk rotate in opposite ways. The poles of this structure are located only about 25° from the line of sight. This structure may be the result of a resonance process that started with the formation of the young B-dwarf stars in the cluster about 6 Myr ago. Alternatively, it indicated the presence of a disturber at a distance from the center comparable to the distance of the compact stellar association IRS13.

Keywords: Galactic Center — S-cluster — stellar dynamics

1. INTRODUCTION

The Galactic Center (GC) stellar cluster harbors a number of stellar associations with different ages and potentially different origins. The luminous 20-30M☉ O/WR-stars appear to reside in at least one single disk like structure most likely coupled to their formation process (Levin & Beloborodov 2003; Yelda et al. 2014a). Their ages have been derived as 6±2 Myr (Paumard et al. 2006). The S-cluster consisting of lighter 3.5-20M☉ stars, contains the 4 million solar mass super massive black hole (SgrA*, Gravity Collaboration et al. 2018; Parsa et al. 2017), and appears to be somewhat decoupled from the stellar disk at larger radii. Of Ks ≤18 stars that reside with separations of less than 1″ or those stars that have known semi-major axes of less than 1″ the predominant fraction are B-stars. This is especially true for the brightest of the stars (Habibi et al. 2017; Gillessen et al. 2017).

Gillessen et al. (2009) also derive the volume density distribution of the the S-cluster B-stars. They find for the 15 stars with a semi-major axes of less than 0.5″ in projection a three-dimensional power law slope of -1.1±0.3. This appears to be marginally larger than the slope derived for a more spread out cluster population of B-stars, implying that the S-stars form a distinct possibly cusp like component.

A detailed near-infrared spectroscopic study of the S-stars (Habibi et al. 2017; Martins et al. 2008; Ghez et al. 2003) shows that these stars are most likely high surface gravity (dwarf) stars The authors’ analysis reveals an effective temperature of 21000-28500 K, a rotational velocity of 60-170 km/s, and a surface gravity of log g=4.1-4.2. These properties are characteristic for stars of spectral type B0-B3V with masses between 8M☉ and 14M☉. Their age is estimated to be less than 15 Myr. For the early B dwarf (B0B2.5 V) star S2 (Martins et al. 2008) the age is estimated to be 6.6±3.4 Myr. This com-
SPATIAL VARIATION IN STRONG LINE RATIOS AND PHYSICAL CONDITIONS IN TWO STRONGLY-LENSED GALAXIES AT Z~1.4

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ABSTRACT

For studies of galaxy formation and evolution, one of the major benefits of the James Webb Space Telescope is that space-based IFUs like those on its NIRSpec and MIRI instruments will enable spatially resolved spectroscopy of distant galaxies, including spectroscopy at the scale of individual star-forming regions in galaxies that have been gravitationally lensed. In the meantime, there is only a very small subset of lensed sources where work like this is possible even with the Hubble Space Telescope’s Wide Field Camera 3 infrared channel grisms. We examine two of these sources, SDSS J1723+3411 and SDSS J2340+2947, using HST WFC3/IR grism data and supporting spatially-unresolved spectroscopy from several ground-based instruments to explore the size of spatial variations in observed strong emission line ratios like O\(_3\), R\(_2\), which are sensitive to ionization parameter and metallicity, and the Balmer decrement as an indicator of reddening. We find significant spatial variation in the reddening and the reddening-corrected O\(_3\) and R\(_2\) values which correspond to spreads of a few tenths of a dex in ionization parameter and metallicity. We also find clear evidence of a negative radial gradient in star formation in SDSS J2340+2947 and tentative evidence of one in SDSS J1723+3411 though its star formation is quite asymmetric. Finally, we find that reddening can vary enough spatially to make spatially-resolved reddening corrections necessary in order to characterize gradients in line ratios and the physical conditions inferred from them, necessitating the use of space-based IFUs for future work on larger, more statistically robust samples.

1. INTRODUCTION

Strong emission line ratios have emerged as powerful diagnostics to understand the physical conditions within distant (redshift \(z \gtrsim 1\)) galaxies, particularly the metallicity, pressure, and ionization state of the gas, and the amount of dust (e.g., Kewley & Dopita 2002, Pettini & Pagel 2004, Rigby et al. 2011, Steidel et al. 2014, Nakajima & Ouchi 2014, among many others). Most observational studies that have used these diagnostics to characterize distant galaxies have, by necessity, used the integrated light of entire galaxies to measure them. However, a spatially-integrated measurement is unlikely to fairly represent all regions within a galaxy. Distant galaxies show kiloparsec-scale structures, called “giant clumps” (e.g., Elmegreen et al. 2005, Guo et al. 2012), though recent observational and theoretical results suggest that far smaller spatial scales—tens of parsecs rather than kiloparsecs—are important for star formation in the distant universe (Johnson et al. 2017, Mandelker et al. 2013). A spatially-integrated spectrum may well be dominated by the spectrum of one bright giant clump (or a single complex of smaller clumps), if it has extreme line ratios compared to the rest of the galaxy, particularly at bluer rest wavelengths. For instance, Girard et al. (2018) find that about 40% of the star formation, as indicated by H\(_\alpha\), lies in just three clumps in a lensed galaxy at \(z = 1.6\). Moving beyond a bulk measurement of galaxy spectra to truly understand the internal physics of these sources requires spectroscopic studies with high spatial resolution.

Surveys using integral field units have characterized how strong line ratios vary spatially in nearby galaxies. Metallicity gradients, for instance, have been observed in the local universe (e.g., Belfiore et al. 2017, Poetrodjiojo et al. 2018), at low redshifts (e.g., 0.1 \(\lesssim z \lesssim 0.8\) in Carton et al. 2018), and at moderate redshifts (e.g., lensed sources at \(z = 1.49\) and 2 in Yuan et al. 2011 and Jones et al. 2010 respectively). Meanwhile, Poetrodjiojo et al. (2018) have investigated, but did not find strong evidence of, radial gradients in ionization parameter at low redshifts, though other studies such as Ellison et al. (2014) have found evidence of radial gradients in star formation rate surface densities and Dopita et al. (2014) find correlations between SFR and ionization parameter.

While spatial variation of strong line diagnostics at subgalactic scales is well-established in low-redshift galaxies, it is not yet clear how these diagnostics vary...
Comparatively little is known about atmospheric chemistry on Uranus and Neptune, because remote spectral observations of these cold, distant “Ice Giants” are challenging, and each planet has only been visited by a single spacecraft during brief flybys in the 1980s. Thermochemical equilibrium is expected to control the composition in the deeper, hotter regions of the atmosphere on both planets, but disequilibrium chemical processes such as transport-induced quenching and photochemistry alter the composition in the upper atmospheric regions that can be probed remotely. Surprising disparities in the abundance of disequilibrium chemical products between the two planets point to significant differences in atmospheric transport. The atmospheric composition of Uranus and Neptune can provide critical clues for unravelling details of planet formation and evolution, but only if it is fully understood how and why atmospheric constituents vary in a three-dimensional sense and how material coming in from outside the planet affects observed abundances. Future mission planning should take into account the key outstanding questions that remain unanswered about atmospheric chemistry on Uranus and Neptune, particularly those questions that pertain to planet formation and evolution, and those that address the complex, coupled atmospheric processes that operate on Ice Giants within our solar system and beyond.
Fast Generation of Large-Scale Structure Density Maps via Generative Adversarial Networks

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ABSTRACT

Generative Adversarial Networks (GANs) are a recent advancement in unsupervised machine learning. They are a cat-and-mouse game between two neural networks: [1] a discriminator network which learns to validate whether a sample is real or fake compared to a training set and [2] a generator network which learns to generate data that appear to belong to the training set. Both networks learn from each other until training is complete and the generator network is able to produce samples that are indistinguishable from the training set. We find that GANs are well-suited for fast generation of novel 3D density maps that are indistinguishable from those obtained from N-body simulations. In a matter of seconds, a fully trained GAN can generate thousands of density maps at different epochs in the history of the universe. These GAN-generated maps can then be used to study the evolution of large-scale structure over time.

1. INTRODUCTION

Rather than being distributed randomly throughout the universe, galaxies are found primarily within an interconnected, large-scale network of walls and filaments that stretch for 100's of Mpc (see, e.g., Giovanelli & Haynes 1991 and references therein). Between the walls and filaments lie vast, underdense regions known as cosmic voids (see, e.g., Sánchez et al. 2017). Voids are the largest structures in the universe, reaching up to $100h^{-1}$ Mpc in diameter, and they have the potential to serve as excellent laboratories for testing the popular Λ Cold Dark Matter (ΛCDM) model of structure formation. Due to their underdense nature, voids are dominated by dark energy and they are only weakly influenced by the non-linear effects of gravity. Because of this, the shapes and distributions of voids provide constraints on the dark energy equation of state, inflationary models, the sum of the neutrino masses, etc. (e.g., Li et al. 2012; Clampitt et al. 2013; Sahlén 2019).

Current observational void catalogs (e.g., Sánchez et al. 2017; Mao et al. 2017) are plagued by small number statistics due to being insufficiently deep for a complete sampling of structure on scales $\gtrsim 1$ Gpc. For example, the Dark Energy Survey (see, e.g., Flaugher 2005) found only 87 voids in their first 139 sq. degree survey (Sánchez et al. 2017). The small number of voids in the current catalogs limits our ability to place strong observational constraints on fundamental statistics such as void frequency and mean void radius. Near-future surveys from the Vera C. Rubin Observatory, as well as the Nancy Grace Roman and Euclid satellites, will result in deep maps of the universe that are able to fully sample structure on Gpc-scales.

Gigaparsec-scale simulations are necessary to determine whether or not ΛCDM can reproduce the largest structures in the universe. While Gpc-scale N-body mock catalogs do already exist (e.g., Kim et al. 2011), the largest voids are so rare that only a few dozen are found in a single Gpc-scale simulation. Such enormous simulations are computationally expensive to run, making it highly impractical to derive the statistics of the largest voids from these types of catalogs. In order to obtain a complete understanding of Gpc-scale structure in ΛCDM, a method that can quickly produce catalogs of simulated large-scale structure is required.

2. METHODS

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A possible polar origin for the FRB associated with a Galactic magnetar  

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Fast Radio Bursts (FRBs) are millisecond-long radio pulses of extragalactic origin with peak luminosities far exceeding any Milky Way source1,2. The prevalent invocation for the FRB origin1-3 involves magnetars: young, magnetically powered neutron stars with the strongest magnetic fields in the Universe4,5. A magnetar-defining signature is the emission of bright, hard X-ray bursts of sub-second duration. These occur in isolation or during a burst storm, when several hundred are observed within minutes to hours6. On April 27th 2020, the Galactic magnetar SGR J1935+2154 entered an active period, emitting hundreds of X-ray bursts in a few hours6. Remarkably, only one of these7-9 temporarily coincided with an FRB-like radio burst10-12. Here we report on the spectral and temporal analysis of 24 X-ray bursts emitted 13 hours prior to the FRB and seen simultaneously with NASA’s NICER and Fermi/GBM missions in their combined energy range. We demonstrate that the FRB-associated X-ray burst is very similar temporally, albeit strikingly different spectrally, from the 24 NICER/GBM bursts. If the FRB-associated burst were drawn from this magnetar burst population, its occurrence rate would be at most around 1 in 7000. This rarity combined with the unusual X-ray burst spectrum is perhaps indicative of an uncommon locale for the origin of the FRB-associated burst. We suggest that this unique event originated in quasi-polar open or closed magnetic field lines extending to high altitudes where radio emission can be generated, possibly from a collimated plasma flow.  

SGR J1935+2154 was discovered in 2014, when it emitted a few short, hard X-ray, magnetar-like bursts. Follow-up X-ray observations revealed the source spin period (P=3.24 s) and period derivative (dP/dt=3.24x10^-11 s/s), implying a large surface dipole magnetic field, B=2.2x10^10 G, and a spin down age, t=3.6 kyr, thus confirming its magnetar nature13. The source became active again in May 2015, May and June 201614, and December 2019. The source’s activity steadily increased with time, emitting larger numbers of bursts, brighter on average than the ones detected during the preceding activation15. On April 27th 2020, SGR J1935+2154 entered yet another active period, the most prolific so far. It comprised a long-lasting burst storm, with at least a few hundred bursts observed within a few hours16-18.  

We observed SGR J1935+2154 with the NICER X-ray Timing Instrument18 (0.2-12 keV) onboard the International Space Station on April 28, from 00:40:57 UTC until 00:59:36 UTC (~19 minutes), covering just the tail end of the storm. This NICER observation revealed ~200 bursts emitted by SGR J1935+2154, which was also visible by the Fermi Gamma-ray Burst Monitor (GBM). We identified a subset of 24 bursts simultaneously detected with NICER and GBM bursts to the high background of the latter instrument; these are the brightest among the 200 detected with NICER. Thirteen hours after the NICER observation, concurrent with a magnetar burst19-21, a Fast Radio Burst (FRB) was also detected with the CHIME22 and STARE23 radio telescopes; this FRB-contemporaneous X-ray burst was detected by the INTEGRAL24, KONUS-WIND25, and HXMT26 missions. NICER and GBM were not observing the source during the FRB time.  

We used the NICER data for a temporal analysis of the 24 X-ray bursts, as it offers a very low background compared to GBM, and hence captures the full length of each burst. The 90 ms duration27 (interval during which 90% of the burst fluence is detected) of these bursts ranged from 230 ms to about 2 seconds, with a mean of 620 ms. The burst light curves display a variety of shapes, with some exhibiting a slow rise and decay bracketing a spiky top. Regarding its duration and temporal profile, the FRB-associated X-ray burst does not stand out, compared to the 24 bursts.
Distinguishing between wet and dry atmospheres of TRAPPIST-1 e and f

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ABSTRACT

The nearby TRAPPIST-1 planetary system is an exciting target for characterizing the atmospheres of terrestrial planets. The planets e, f and g lie in the circumstellar habitable zone and could sustain liquid water on their surfaces. During the extended pre-main sequence phase of TRAPPIST-1, however, the planets may have experienced extreme water loss, leading to a desiccated mantle. The presence or absence of an ocean is challenging to determine with current and next generation telescopes. Therefore, we investigate whether indirect evidence of an ocean and/or a biosphere can be inferred from observations of the planetary atmosphere. We introduce a newly developed photochemical model for planetary atmospheres, coupled to a radiative-convective model and validate it against modern Earth, Venus and Mars. The coupled model is applied to the TRAPPIST-1 planets e and f, assuming different surface conditions and varying amounts of CO₂ in the atmosphere. As input for the model we use a constructed spectrum of TRAPPIST-1, based on near-simultaneous data from X-ray to optical wavelengths. We compute cloud-free transmission spectra of the planetary atmospheres and determine the detectability of molecular features using the Extremely Large Telescope (ELT) and the James Webb Space Telescope (JWST). We find that under certain conditions, the existence or non-existence of a biosphere and/or an ocean can be inferred by combining 30 transit observations with ELT and JWST within the K-band. A non-detection of CO could suggest the existence of an ocean, whereas significant CH₄ hints at the presence of a biosphere.

Keywords: planets and satellites: atmospheres - planets and satellites: detection - planets and satellites: individual (TRAPPIST-1) - planets and satellites: terrestrial planets

1. INTRODUCTION

The nearby TRAPPIST-1 system offers exciting new opportunities for studying the atmospheres of its seven planets with next generation telescopes such as the JWST (James Webb Space Telescope; Gardner et al. 2006; Beichman et al. 2014) or the ELT (European Large Telescope; Gilmozzi & Spyromilio 2007). Due to short orbital periods and large star-planet contrast ratios, planets orbiting such cool host stars are easier to detect and characterize via the transit method than planets orbiting hotter stars and are therefore prime targets to observe the properties of their atmospheres. On the other hand the stellar luminosity evolution of M-dwarfs is quite different to that of solar-type stars. In
Distinguishing the Rigidity Dependences of Acceleration and Transport in Solar Energetic Particles

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Abstract In solar energetic particle (SEP) events, the power-law dependence of element abundance enhancements on their mass-to-charge ratios $A/Q$ provides a new tool that measures the combined rigidity dependences from both acceleration and transport. Distinguishing these two processes can be more challenging. However, the effects of acceleration dominate when SEP events are small or when the ions even propagate scatter-free, and transport can dominate the time evolution of large events with streaming-limited intensities. Magnetic reconnection in solar jets produces positive powers of $A/Q$ from +2 to +7 and shock acceleration produces mostly negative powers from -2 to +1 in small and moderate SEP events where transport effects are minimal. This variation in the rigidity dependence of shock acceleration may reflect the non-planer structure, complexity, and time variation of coronal shocks themselves. Wave amplification by streaming protons in the largest SEP events suppresses the escape of ions with low $A/Q$, creating observed powers of $A/Q$ from +1 to +3 upstream of the accelerating shock, decreasing to small negative powers downstream.

Keywords: Solar energetic particles · Solar system abundances · Coronal mass ejections · Shock acceleration
From Cosmic Explosions to Terrestrial Fires?: A Reply

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ABSTRACT

Deschamps and Mottez (hereafter DM) argue that the Gauss-Matuyama terrestrial magnetic field reversal may have left a vanishing main dipole moment to the field for a time of order 10,000 years. They say this may have allowed an enhanced cosmic ray flux, boosting the effect we proposed in Melott and Thomas (2019). We point out that the bulk of the cosmic ray flux from a nearby supernova should be too energetic, up to a million times more energetic than the limits of deflection by the terrestrial magnetic field. In fact, only those highly energetic ones will directly reach the troposphere, relevant for cloud-to-ground lightning.

From Cosmic Explosions to Terrestrial Fires?: A Discussion. F. Deschamps and F. Mottez. J. Geology 128, online ahead of print.

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I. Introduction

WASP-121 b is a hot Jupiter that was recently found to possess rich emission (day side) and transmission (limb) spectra, suggesting of the presence of many chemical species in the atmosphere.

Aims. We survey the transmission spectrum of WASP-121 b for line-absorption by metals and molecules at high spectral resolution, and elaborate on existing interpretations of the optical transmission spectrum observed with HST/STIS.

Methods. We apply the cross-correlation technique and direct differential spectroscopy to search for sodium and other neutral and ionised atoms, TiO, VO and SH in high-resolution transit spectra obtained with the HARPS spectrograph. We inject models assuming chemical and hydrostatic equilibrium with varying temperature and composition to enable model comparison, and employ two bootstrap methods to test the robustness of our detections.

Results. We detect neutral Mg, Na, Ca, Cr, Fe, Ni and V, which we predict exists in equilibrium with a significant quantity of VO, supporting earlier observations by HST/STIS. In high-resolution transit spectra obtained with the HARPS spectrograph. We inject models assuming chemical and hydrostatic equilibrium with varying temperature and composition to enable model comparison, and employ two bootstrap methods to test the robustness of our detections.

Keywords. giant planets - spectroscopy

Context. WASP-121 b is a hot Jupiter that was recently found to possess rich emission (day side) and transmission (limb) spectra, suggesting of the presence of many chemical species in the atmosphere.
Kilonova Luminosity Function Constraints based on Zerbox Transient Facility Searches for 11 Neutron Star Mergers

Mouza AlMualla, Shaon Ghosh, Igor Andreoni, Maayane T. Soumagnac, Elena Pian, Mansi M. Kasliwal, Sara Freidberg, Avishay Gal-Yam, Reed Riddle, Siddharth Mohite, Bin-Bin Zhang

...account the online terrestrial probability for each GW trigger, we find that no more than 4.2%. If we assume that all kilonovae are brighter than −16.6 mag, is 9.7% for NSBH and 7.9% for BNS detections, assuming all kilonovae are brighter than −16.6 mag, is 9.7% for NSBH and 7.9% for BNS detections assuming flat evolution (fading by 1 mag day−1). Therefore, that all GW triggers are bonafide astrophysical events regardless of false alarm rate and that kilonovae are brighter than −16.6 mag, is 9.7% for NSBH and 7.9% for BNS detections assuming flat evolution (fading by 1 mag day−1). Therefore, we conclude that some kilonovae must have Mej < 0.03 M⊙or Xlan > 10−4 or φ >30◦to be consistent with our limits.
One of Everything: The Breakthrough Listen Exotica Catalog

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ABSTRACT

We present Breakthrough Listen’s “Exotica” Catalog as the centerpiece of our efforts to expand the diversity of targets surveyed in the Search for Extraterrestrial Intelligence (SETI). As motivation, we introduce the concept of survey breadth, the diversity of objects observed during a program. Several reasons for pursuing a broad program are given, including increasing the chance of a positive result in SETI, commensal astrophysics, and characterizing systematics. The Exotica Catalog is an 865 entry collection of 737 distinct targets intended to include “one of everything” in astronomy. It contains four samples: the Prototype sample, with an archetype of every known major type of non-transient celestial object; the Superlative sample of objects with the most extreme properties; the Anomaly sample of enigmatic targets that are in some way unexplained; and the Control sample with sources not expected to produce positive results. As far as we are aware, this is the first object list in recent times with the purpose of spanning the breadth of astrophysics. We share it with the community in hopes that it can guide treasury surveys and as a general reference work. Accompanying the catalog is extensive discussion of classification of objects and a new classification system for anomalies. We discuss how we intend to proceed with observations in the catalog, contrast it with our extant Exotica efforts, and suggest similar tactics may be applied to other programs.

Keywords: Search for extraterrestrial intelligence — Classification systems — Celestial objects catalogs — Philosophy of astronomy — Astrobiology

1. INTRODUCTION

Breakthrough Listen is a ten year program to conduct the deepest surveys for extraterrestrial intelligence (ETI) in the radio and optical domains (Worden et al. 2017). The core of the program is a deep search for artificial radio emission from over a thousand nearby stars and galaxies (Isaacson et al. 2017, hereafter I17; see also Enriquez et al. 2017; Price et al. 2020 for results), and commensal studies of a million more stars in the Galaxy (Worden et al. 2017). It joins other programs in the Search for Extraterrestrial Intelligence (SETI), most of which have also focused on nearby stars (Tarter 2001). But where should we look for ETIs? Indeed, how should we look for new phenomena of any kind?

Serendipity is a key ingredient in the discovery of most new types of phenomena and extraordinary new objects (Harwit 1981; Dick 2013; Wilkinson 2016). From...
Measuring the energy spectrum of neutral pions in ultra–high–energy proton–air interactions

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Fluctuations in the muon content of extensive air showers are anti-correlated to the fluctuations of the energy taken by the neutral pions which emerge from the first interaction of the cosmic ray in the atmosphere. We demonstrate that the high-energy tail of the neutral pion spectrum produced in the first proton-air interaction can be measured, within the uncertainties of present cosmic ray experiments, through the analysis of the probability distribution of showers over the shower muon contents.

I. INTRODUCTION

Ultra-high-energy cosmic rays (UHECRs) have long been seen as a unique opportunity to probe hadronic interaction physics at center-of-mass energies that surpass the 100 TeV center of mass scale, which is well beyond the reach of any human-made collider. Indispensable to this quest is the knowledge of the UHECRs composition, whose average mass number has been shown to be heavier than proton at the highest energies [1]. This unexpected result could be explained by phenomena in the physics of UHECR propagation and astrophysical sources that have not been accounted for [2]. Alternatively, it could be due to an incomplete description of hadronic interactions, which might hamper the interpretation of air shower data in terms of the nature of the primaries.

The description of hadronic interactions in air showers is mostly based on phenomenological models. These models are tuned to accelerator data and then extrapolated to energies and kinematic regions essential to the description of the development of the extensive air shower (EAS). In fact, there are several pieces of evidence showing that the hadronic component of the shower is poorly described. One example is the measurements of the average muon number in showers.

The combination of several experiments has shown that the muon deficit in simulations starts around $\sim 10^{16}$ eV and steadily increases up to the highest energies available $\sim 10^{20}$ eV [3]. The origin and nature of this discrepancy are still unknown. In particular, it is unclear if it is related to a poor description of low energy interactions or due to unexpected new phenomena at the highest energies.

Recently, the relative fluctuations and the event-by-event distribution of the number of muons in showers at the highest energies were measured for the first time [4]. It was also shown that the fluctuations can be traced back to fluctuations of the quantity $\alpha_1$, which is related to the first interaction of the UHECR [5]. The quantity $\alpha_1$ is defined as

$$\alpha_1 \equiv \sum_i \left( \frac{E_{i\text{had}}}{E_0} \right)^\beta,$$

where we sum over hadronically-interacting particles (basically all baryons, kaons and pions, excluding neutral pions) and where $E_{i\text{had}}/E_0$ is the fraction of the energy of the primary carried by hadron $i$. The parameter $\beta$ is set to 0.93, motivated by the dependence of the average number of muons with the primary energy in the models. In many practical cases, $\alpha_1$ can be approximated as the energy fraction carried by hadronically-interacting particles, and its complement $f_{\text{e.m.}} \simeq 1 - \alpha_1$ is the fraction of energy taken by the $\pi^0$. The detailed analysis of the probability distribution of showers over the shower muon content opens a new window of observation, which brings new information on the hadronic interactions at the start of the air shower.

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Upper boundaries of AGN regions in optical diagnostic diagrams

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ABSTRACT
The distribution of galaxies in optical diagnostic diagrams can provide information about their physical parameters when compared with ionization models under proper assumptions. By using a sample of central emitting regions from the MaNGA survey, we find evidence of the existence of upper boundaries for narrow-line regions (NLRs) of active galactic nuclei (AGN) in optical BPT diagrams, especially in the diagrams involving [S II] λλ 6716, 6731/Hα. Photoionization models can well reproduce the boundaries as a consequence of the decrease of [S II] / Hα and [O III] / Hβ ratios at very high metallicity. Whilst the exact location of the upper boundary in the [S II] BPT diagram only weakly depends on the electron density of the ionized cloud and the secondary nitrogen prescription, its dependence on the shapes of the input SEDs is much stronger. This allows us to constrain the power-law index of the AGN SED between 1 Ryd and ∼ 100 Ryd to be less than or equal to −1.40 ± 0.05. The coverage of the photoionization models in the [N II] BPT diagram has a stronger dependence on the electron density and the secondary nitrogen prescription. With the density constrained by the [S II] doublet ratio and the input SED constrained by the [S II] BPT diagram, we find that the extent of the data in the [N II] BPT diagram favors those prescriptions with high N/O ratios. Although shock-ionized cloud can produce similar line ratios as those by photoionization, the resulting shapes of the upper boundaries, if exist, would likely be different from those of a photoionizing origin.

Key words: galaxies: active – galaxies: nuclei – galaxies: Seyfert

1 INTRODUCTION

Optical diagnostic diagrams (hereafter BPT) are useful tools to discriminate different photoionization sources for galaxies when optical spectra are available (Baldwin et al. 1981; Veilleux & Osterbrock 1987). A typical BPT diagnostic sorts galaxies into three categories: H II regions, composite regions, and AGNs (for the [N II]-based BPT diagnostic, cf. Kewley et al. 2001, Kauffmann et al. 2003b), or star-forming (SF) regions, low-ionization nuclear emission-line regions (LINERs, cf. Heckman 1980) and Seyferts (for the [S II]- or [O I]-based BPT diagnostic, cf. Kewley et al. 2006). Different parts of galaxies occupy specific regions on the diagrams, with H II and SF regions lying on the lower left, Seyferts taking up the space on the upper right, LINERs occupying the lower right and composite regions sitting in the middle. By comparing observational data with the predictions from photoionization models, people have established a theoretical basis for the existence of the SF loci in optical diagnostic diagrams (e.g. Baldwin et al. 1981; Veilleux & Osterbrock 1987; Dopita et al. 2000; Kewley et al. 2001). This provides a way to put constraints on physical parameters like gas-phase metallicity or ionization parameter for SF regions (Dopita et al. 2000; Kewley & Dopita 2002). An interesting feature of the SF regions is that it has an upper boundary on all BPT diagrams. This upper boundary was both confirmed observationally by Kauffmann et al. (2003b) with SDSS data, and theoretically by Kewley et al. (2001) with modeling of extreme starburst galaxies. The commonly accepted explanation for the existence of the boundary is that the drop of electron temperature becomes more important at higher metallicity, which will subsequently lower the
Compressing combined probes: redshift weights for joint lensing and clustering analyses

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ABSTRACT
Combining different observational probes, such as galaxy clustering and weak lensing, is a promising technique for unveiling the physics of the Universe with upcoming dark energy experiments. Whilst this strategy significantly improves parameter constraints, decreasing the degeneracies of individual analyses and controlling the systematics, processing data from tens of millions of galaxies is not a trivial task. In this work we derive and test a new estimator for joint clustering and lensing data analysis, maximising the scientific return and decreasing the computational cost. Our estimator compresses the data by up-weighting the components most sensitive to the parameters of interest, with no loss of information, taking into account information from the cross-correlation between the two probes. We derive optimal redshift weights which may be applied to individual galaxies when testing a given statistic and cosmological model.

Key words: methods:statistical – large-scale structure of Universe – gravitational lensing:weak

1 INTRODUCTION
Combining different observational probes is a promising technique to unveil the physics of the Universe with upcoming dark energy experiments. First, any tensions or inconsistencies between different probes can indicate new physics or help us correct for systematic errors not controlled in an individual analysis. Second, a joint analysis significantly improves measurements of the parameters of interest, decreasing the degeneracies of an individual analysis (Bernstein 2009; Joachimi & Bridle 2010; Yoo & Seljak 2012).

The potential of these tests will be greatly enhanced by current and future cosmological surveys such as the Kilo-Degree Survey (de Jong et al. 2013), Dark Energy Survey (Abbott et al. 2018), Hyper-Suprime-Cam (HSC) lensing survey (Aihara et al. 2018), Large Synoptic Survey Telescope (Ivezić et al. 2019) and Euclid satellite for gravitational lensing (Laureijs et al. 2011), and the Dark Energy Spectroscopic Instrument (Levi et al. 2019) and 4-metre Multi-Object Spectroscopic Telescope for galaxy clustering (de Jong et al. 2012). Whilst this large volume of data represents a unique opportunity to understand the Universe, processing tens of millions of galaxies to detect the subtle signatures of new physics is not a trivial task. Developing new algorithms and strategies to analyse this data is critical to maximise the outcome of these investments.

Further, these unprecedented data volumes create another key challenge: how do we combine information from galaxies at different epochs in the evolution of the Universe? Past analyses dealt with this evolution in the data by binning galaxies in different sub-samples by epoch. However, this technique is inefficient for several reasons: it assumes no evolution within each bin, it neglects the cross-correlation between sub-samples, and it is time-consuming because we are required to repeat the same analysis for each sub-sample of galaxies. Moreover, systematic error may be imprinted by redshift evolution, if the same galaxy carries different weights toward different statistics in the joint analysis.

Rather than breaking the sample into multiple subsets, optimal weighting of the data is an alternative to this traditional approach which instead compresses the data, maintaining sensitivity to evolution in the sample. Strategies for how to compress data have gained increasing attention as a powerful method to handle “big data”, compared to brute-force data-analysis (Tegmark et al. 1997; Heavens et al. 2000). As discussed in Tegmark et al. (1997), optimal weighting based on the Karhunen-Loève approach can compress a data set with no loss of information, obtaining results with close-to-maximal accuracy. In simple words, the optimal weights identify those aspects of the data that are most sensitive to the physics we care about, and amplify them.
Three-component modelling of C-rich AGB star winds – V. Effects of frequency-dependent radiative transfer including drift

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Submitted.

ABSTRACT
Stellar winds of cool carbon stars enrich the interstellar medium with significant amounts of carbon and dust. We present a study of the influence of two-fluid flow on winds where we add descriptions of frequency-dependent radiative transfer. Our radiation hydrodynamic models in addition include stellar pulsations, grain growth and ablation, gas-to-dust drift using one mean grain size, dust extinction based on both the small particle limit and Mie scattering, and an accurate numerical scheme. We calculate models at high spatial resolution using 1024 gridpoints and solar metallicities at 319 frequencies, and we discern effects of drift by comparing drift models to non-drift models. Our results show differences of up to 1000 per cent in comparison to extant results. Mass-loss rates and wind velocities of drift models are typically, but not always, lower than in non-drift models. Differences are larger when Mie scattering is used instead of the small particle limit. Amongst other properties, the mass-loss rates of the gas and dust, dust-to-gas density ratio, and wind velocity show an exponential dependence on the dust-to-gas speed ratio. Yields of dust in the least massive winds increase by a factor four when drift is used. We find drift velocities in the range $10^{-67}$ km s$^{-1}$, which is drastically higher than in our earlier works that use grey radiative transfer. It is necessary to include an estimate of drift velocities to reproduce high yields of dust and low wind velocities.

Key words: hydrodynamics – radiative transfer – methods: numerical – stars: AGB and post-AGB – stars: carbon – stars: mass-loss

1 INTRODUCTION
Winds of AGB stars are believed to be driven by radiation pressure on dust grains, which create an outflow when they in turn drag the atmospheric gas along. These winds are relatively slow (∼10 km s$^{-1}$), but mass-loss rates can be high (∼$10^{-5}$ M$_\odot$ yr$^{-1}$) owing to high densities. The type of dust forming in AGB-star atmospheres depends on the chemical composition of the gas: oxygen-rich stars (C/O < 1) form mostly silicate-type grains (but also iron dust can form in significant quantities, see Marini et al. 2019), whilst carbon-rich stars (C/O > 1) form mainly amorphous carbon (amC) grains and smaller amounts of grains of SiC and polycyclic aromatic hydrocarbons (PAHs). The latter type of stars is usually referred to as “carbon stars” and represents evolved stars with initial masses in the range 1.5–4 M$_\odot$ that undergo so-called thermal pulses. That is, after the helium shell runs out of fuel, the star derives its energy from hydrogen burning in a thin shell; eventually, accumulated helium from the hydrogen burning ignites, causing a helium shell flash. During the thermal pulses, which last a few hundred years, material from the inner regions is mixed into the outer layers. This process is referred to as dredge-up and changes the surface composition of the star; in particular, this is how an oxygen-rich AGB star evolves into a carbon star. The amount of carbon expelled by carbon stars is significant and they may thus play role for the evolution of carbon (and carbonaceous dust) in the universe, although it cannot be ruled out that massive stars may be equally important (e.g., Gustafsson et al. 1999; Mattsson 2010). The carbon production of carbon stars is important and understanding the wind-formation mechanisms is essential to the full picture.

Radiatively accelerated dust grains exert a drag force on the gas; this drag force depends on how well grains couple to the gas, which in turn depends on the radiation flux, the density and temperature of the gas, as well as the extinction.
You Can Always Get What You Want: The Impact of Prior Assumptions on Interpreting GW190412

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ABSTRACT

GW190412 is the first observation of a black hole binary with definitively unequal masses. GW190412’s mass asymmetry, along with the measured positive effective inspiral spin, allowed for inference of a component black hole spin: the primary black hole in the system was found to have a dimensionless spin magnitude between 0.17 and 0.59 (90% credible range). We investigate how the choice of priors for the spin magnitudes and tilts of the component black holes affect the robustness of parameter estimates for GW190412, and report Bayes factors across a suite of prior assumptions. Depending on the waveform family used to describe the signal, we find either marginal to moderate (2:1–7:1) or strong (≥20:1) support for the primary black hole being spinning compared to cases where only the secondary is allowed to have spin. We show how these choices influence parameter estimates, and find the asymmetric masses and positive effective inspiral spin of GW190412 to be qualitatively, but not quantitatively, robust to prior assumptions. Our results highlight the importance of both considering astrophysically-motivated or population-based priors in interpreting observations, and considering their relative support from the data.

1. INTRODUCTION

GW190412 (Abbott et al. 2020) was the first reported observation of a binary black hole (BBH) from the third observing run (O3) of the Advanced LIGO (Aasi et al. 2015) and Advanced Virgo (Acernese et al. 2015) detector network. GW190412’s source is the first system to have definitively unequal masses (cf. Abbott et al. 2019a), with the primary black hole (BH) being ∼30 M⊙ and the secondary BH being ∼8 M⊙. In addition to unveiling emission from higher-order multipoles (HMs), this asymmetry allowed for enhanced constraints on the intrinsic and extrinsic parameters of the BBH system.

The spins of compact binary components are difficult to measure from gravitational-wave (GW) signals (Poisson & Will 1995; Vitale et al. 2014; Pürrer et al. 2016; Abbott et al. 2016a). Typically, spin constraints are presented in terms of mass-weighted combinations of the two component spins: the effective inspiral spin

$$\chi_{\text{eff}} = \frac{m_1 \chi_1 \cos \theta_1 + m_2 \chi_2 \cos \theta_2}{m_1 + m_2},$$  (1)

where $m_1 \geq m_2$ are the component masses, $\chi_i$ are the dimensionless spin magnitudes, and $\theta_i$ are the angles between the spins and the Newtonian orbital angular momentum $\vec{L}$, encodes information about the spin components aligned with the orbital angular momentum (Damour 2001; Racine 2008; Santamaría et al. 2010; Ajith et al. 2011), whereas in-plane spins are characterized by the effective precession spin (Schmidt et al. 2015)

$$\chi_{p} = \max \left\{ \chi_1 \sin \theta_1, \frac{q(4q + 3)}{4 + 3q} \chi_2 \sin \theta_2 \right\}. $$  (2)

The LIGO Scientific & Virgo Collaboration (LVC) reported an effective spin for GW190412 of $\chi_{\text{eff}} = 0.25^{+0.08}_{-0.11}$ (median and 90% credible interval; Abbott et al. 2020). Since $\chi_{\text{eff}}$ is positive and constrained away from zero, at least one of the BHs in the GW190412 system had a spin direction in the same hemisphere as $\vec{L}$ during the GW inspiral. GW190412 also exhibited marginal hints of orbital precession, which is consistent with at least one of the BH spins being non-zero.

A BBH with $\chi_{\text{eff}} > 0$ has been observed before in GW151226 (Abbott et al. 2016b; Miller et al. 2020), and potentially in GW1702729 (Abbott et al. 2019a; Chatzi-
Recurrent Neutrino Emission from Supermassive Black Hole Mergers

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The recent detection of possible neutrino emission from the blazar TXS 0506+056 was the first high-energy neutrino associated with an astrophysical source, making this special type of active galaxies promising neutrino emitters. The fact that two distinct episodes of neutrino emission were detected with a separation of around 3 years suggests that emission could be periodic. Periodic emission is expected from supermassive binary black hole systems due to jet precession close to the binary’s merger. Here we show that if TXS 0506+056 is a binary source then the next neutrino flare could occur before the end of 2021. We derive the binary properties that would lead to the detection of gravitational waves from this system by LISA. Our results for the first time quantify the time scale of these correlations for the example of TXS 0506+056, providing clear predictions for both the neutrino and gravitational-wave signatures of such sources.

INTRODUCTION

With the first detections of astrophysical high-energy neutrinos [1, 2] and gravitational waves [3], the era of multi-messenger astronomy has begun, enabling the exploration of the Universe in a whole new manner. We have learned from gravitational-wave observations that there exists a significant population of stellar-mass binary black holes with properties we only begin to understand [4, 5]. Neutron star mergers can now be investigated using a combination of gravitational waves and the broad photon spectrum from radio up to GeV gamma-rays, in the future possibly adding TeV gamma-rays and neutrinos [6–12]. We have learned from neutrino observations that the high-energy events are of extragalactic origin given the lack of clustering of events in the Galactic plane [13, 14]. The detection of a possible correlation of a gamma-ray flare from the blazar TXS 0506+056 with a high-energy neutrino in September 2017 is a first hint that active galaxies may produce a significant fraction of the observed flux of cosmic high-energy neutrinos [15]. A dedicated search for further neutrino flares from TXS 0506+056 in the past revealed a 3.5σ evidence for a long-duration (110±35 days) flare of TeV neutrinos around 2.8 years prior to the 2017 measurement [16]. No gamma-ray flare occurred during that time, which makes the modeling of the multi-messenger data challenging [17], although not impossible [18]. Several ideas of how to produce these multi-messenger signatures have been presented, see e.g. [19–21].

Transient blazar flares may be produced in the wake of galactic mergers when two supermassive black holes (SMBHs) inspiral towards each other. The black holes on close orbits reorient their spin in this inspiral phase. Spin precession due to relativistic effects in turn can result in precessing relativistic outflows that periodically change the direction of high-energy radiation [22]. This scenario leads to the prediction of a population of blazars that are currently in such a state. The first potential hints of such signatures have been identified by Kun et al. [23]. Recent observations of periodicity at radio wavelengths also point toward a precessing jet scenario [24].

In this Letter, we examine the observational consequences of transient blazar flares could arise from jet precession in supermassive binary black holes (SMBBHs) close to merger. In particular, we examine the possible time structure of high-energy neutrino emission from blazars due to jet precession, focusing on TXS 0506+056. Considering this scenario we predict the time of the next neutrino flare from TXS 0506+056 and the expected time of the corresponding SMBBH merger. We discuss the possibility of detecting this merger through gravitational waves using the Laser-interferometer Space Antenna (LISA) in the next decade: LISA will be the first gravitational wave detector in space, consisting of three spacecrafts that are positioned in an equilateral triangle. The gravitational frequency range probed by LISA is in the 0.1 mHz to 1 Hz range and well-suited for the detection of supermassive black hole mergers. The launch of LISA is scheduled in the early 2030s. Here, we discuss the parameter range for which gravitational waves from TXS 0506+056 occur in the time frame of the lifetime of LISA.
It has to be cool: on supergiant progenitors of binary black hole mergers from common-envelope evolution

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ABSTRACT

Common-envelope (CE) evolution in massive binary systems is thought to be one of the most promising channels for the formation of compact binary mergers. In the case of merging binary black holes (BBHs), the essential CE phase takes place at a stage when the first BH is already formed and the companion star expands as a supergiant. We study which BH binaries with supergiant companions will evolve through and potentially survive a CE phase. To this end, we compute envelope binding energies from detailed massive stellar models at different evolutionary stages and metallicities. We make multiple physically extreme choices of assumptions that favor easier CE ejection as well as account for recent advancements in mass transfer stability criteria.

We find that even with the most optimistic assumptions, a successful CE ejection in BH binaries is only possible if the donor is a massive convective-envelope giant, i.e. a red supergiant (RSG). The same is true for neutron star binaries with massive companions. In other words, pre-CE progenitors of BBH mergers are BH binaries with RSG companions. We find that due to its influence on the radial expansion of massive giants, metallicity has an indirect but a very strong effect on the chemical profile, density structure, and the binding energies of RSG envelopes. Our results suggest that merger rates from population synthesis models could be severely overestimated, especially at low metallicity. Additionally, the lack of observed RSGs with luminosities above log(L/L⊙) ≈ 5.6–5.8, corresponding to stars with M ≳ 40 M⊙, puts into question the viability of the CE channel for the formation of the most massive BBH mergers. Either such RSGs elude detection due to very short lifetimes, or they do not exist and the CE channel can only produce BBH systems with masses ≤ 50 M⊙. Finally, we discuss an alternative CE scenario, in which a partial envelope ejection is followed by a phase of possibly long and stable mass transfer.

Key words. stars: binaries: general – stars: black holes – stars: neutron – stars: massive – gravitational waves

1. Introduction

Since the discovery of the first gravitational wave signal from a binary black hole (BBH) coalescence by the Advanced LIGO Interferometer in September 2015 (GW150914, Abbott et al. 2016), the LIGO/Virgo Collaboration has reported the detection of nine further BBH mergers by the end of its second observing run O2 (Abbott et al. 2019). The third observing run O3 has recently been concluded and a larger number of publicly issued alerts is an indication that a few tens additional detections of BBH mergers are on the way. With the growing population of BBHs, the discussion on possible formation scenarios of compact binary mergers is as lively as ever. A large number of channels have been put forth, especially in the case of BBHs. These include but are not limited to the formation from isolated binaries through common envelope (CE) evolution (Belczynski et al. 2016; Eldridge & Stanway 2016; Klencki et al. 2018; Mapelli & Giacobbo 2018; Kruckow et al. 2018) or in chemically homogeneous evolution regime (Mandel & de Mink 2016; de Mink & Mandel 2016; Marchant et al. 2016), dynamical formation in globular clusters (Rodriguez et al. 2016; Askar et al. 2017; Samsing 2018), in nuclear clusters (Arca-Sedda & Gualandris 2018; Fragione & Kocsis 2019), or in disks of active galactic nuclei (Antonini & Rasio 2016; Stone et al. 2017; McKernan et al. 2018), as well as formation channels involving triple (Antonini et al. 2017) or quadruple stellar systems (Fragione et al. 2019). So far, it has not been possible to distinguish between various channels based on the gravitational wave information alone. In particular, the promising method of distinguishing between dynamical and isolated binary formation based on the BBH spin-orbit misalignment distribution (Farr et al. 2017; 2018) is hindered by our lack of knowledge of the natal black hole (BH) spins (Belczynski et al. 2017; Baver et al. 2019). As a result, the contribution of various channels to the entire population of BBH mergers is usually estimated on theoretical grounds (Abadie et al. 2010; Barack et al. 2019). The CE evolution channel is sometimes considered to be especially promising thanks to its potential to produce a relatively high merger rate of BBHs compared to other channels, although any rate prediction from theoretical population models are highly uncertain.

The essential stage in the CE evolution channel is a dynamically unstable phase of mass transfer that leads to a rapid spiral-in of the companion object inside the shared envelope originating from the giant donor star (Paczynski 1976; Webbink 1984; Iben & Livio 1993; Podsiański 2001; Ivanova et al. 2013b). The drag force is thought to cause a dramatic shrinkage of the binary separation and the dissipated orbital energy to lead to an ejection of the CE (under the right circumstances). The huge range in both timescales and length scales involved in this complex process makes hydrodynamic simulations challenging (eg. Ricker & Taam 2012; Passy et al. 2012; Nandez & Ivanova 2016;