Pulsar Magnetospheres and Pulsar Death

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Pulsars are rapidly spinning neutron stars whose lighthouse-like beams of radio waves sweep Earth, producing highly regular pulses with periods typically of order 1 s. Their spin periods gradually increase with time, and it was realized in 1968 that this must be due to the braking effect of a magnetic field some $10^{12}$ times stronger than that of Earth (1). The rotation of the magnetic field causes the emission of magnetic dipole radiation, which exerts a torque that slows down the neutron star’s rotation (2, 3). It was suggested in 1969 that an additional braking torque is exerted by the outflow of the relativistic particles that produce the pulsed radio emission of the pulsar (4). Now, after 37 years and the discovery of over 1500 pulsars, clear evidence for the existence and strength of this “pulsar wind” torque has finally been found in the behavior of a highly peculiar pulsar, as described by Kramer et al. (5) on page 549 of this issue. This is an important breakthrough, because it gives quantitative information on the strengths of the magnetospheric electric currents that generate the pulsar’s pulsed radiation.

Neutron stars and black holes are the most dense and compact objects known in nature, and they have the strongest gravitational fields. They are formed by the collapse of the burned-out core of a massive star, accompanied by a supernova explosion in which the envelope of the star is violently ejected. With a mass some 400,000 times that of Earth and a diameter of 20 km (smaller than Los Angeles), a neutron star is essentially a giant atomic nucleus held together by gravity. The gravitational attraction at its surface is about 11 orders of magnitude greater than on the surface of Earth. Calculations of the structure of neutron stars show that although their interior consists, in large part, of neutrons, these stars have a solid crust of a few kilometers thickness that consists of a lattice of atomic nuclei and electrons. This crust has a very high electrical conductivity that anchors the magnetic field by allowing very strong electric currents to flow in the crust. The field is expected to be mainly dipolar—like that of Earth and Jupiter—and as in these planets, it has an axis that is inclined with respect to the rotation axis (see the figure).

Putting on the brakes. The rotating magnetic field of a pulsar creates a very strong electric field that pulls charged particles out of the solid crust of the star. These particles emit gamma rays, which, in turn, interact with the magnetic field, setting in motion an avalanche of electron-positron pairs. Close to the neutron star’s polar caps, the flow of pair particles creates magnetospheric electric currents that produce the observed beams of radio waves (red). The currents and the pulsar wind of plasma (blue) flowing out from the magnetosphere along the open field lines that cross the light cylinder exert a torque on the magnetic field lines that slows down the neutron star’s rotation. This braking torque was predicted 37 years ago, and now, direct observational evidence for its existence has been found (5).

As the existence of a pulsar wind of relativistic particles flowing out into space was put forward by Goldreich and Julian (4). They calculated the strength of the electric field generated by the rotating magnetic field and found that on certain areas of the neutron star surface, this field creates a force on particles that is far stronger than the gravitational force that holds them down. Therefore, electrons can escape from these parts of the star surface and are accelerated by the electric field along the magnetic field lines, achieving a highly relativistic speed after only a few centimeters of travel. From other parts of the neutron star surface, positively charged particles (nuclei) can be drawn out, such that the magnetosphere of the neutron star is filled with an outflowing ionized plasma. As shown in the figure, this plasma can flow out into space only along open magnetic field lines, which originate in the neutron star’s polar caps around its magnetic poles, and cross the so-called light-cylinder, where the field lines would rotate with the velocity of light.

In two seminal papers (6, 7), Sturrock argued that the magnetospheric plasma must mainly consist of electrons and their anti-particles, positrons. An accelerated electric charge spontaneously emits electromagnetic radiation, and, owing to the very high energy of the electrons, this radiation will be high-energy gamma rays. (Indeed, several young pulsars have been observed to emit pulsed gamma radiation.) In a magnetic field, high-energy gamma-ray photons are spontaneously converted into electron-positron pairs by the process of pair creation. The resulting electron and positron are again accelerated in the electric field and, after a few centimeters, again produce gamma photons that produce pairs, and so on. Thus, by pulling just one electron out of the neutron star surface, a cascade of electron-positron pairs is created, which fills the magnetosphere of the neutron star with a pair plasma. (The density of this plasma is so low that an electron sel-
A Neuronal Receptor for Botulinum Toxin

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Muscle paralysis induced by botulinum toxin A is used cosmetically to eliminate wrinkles. It preferentially enters activated neurons by binding to a synaptic vesicle protein that becomes exposed after transmitter release.

Some say poison, some say “wonder drug.” Either way, the neurotoxins produced by the bacterium Clostridium botulinum have gained notoriety or fame as powerful inhibitors of neuronal synaptic transmission. Their effects range from preventing wrinkled skin to causing severe food poisoning and respiratory failure. Botulinum neurotoxins bind to the surface of nerve terminals, gain access to the cytoplasm, and block the release of neurotransmitters into the synapse. Although the mechanism by which these toxins enter neurons was worked out more than a decade ago, the receptors responsible for toxin binding and internalization have only partially been known. On page 592 of this issue, Dong et al. (1) identify SV2, a conserved membrane protein of synaptic vesicles, as the receptor for botulinum neurotoxin A.

Protein toxins are highly sophisticated weapons that bacteria use to manipulate or kill eukaryotic cells or even entire organisms with minimal effort, thus providing a source of nutrients for their survival and proliferation. Many toxins contain two polypeptide chains, referred to as A and B chains, which have distinct roles. The B chain binds to the surface of the target cell, commandeers the endocytotic pathway to facilitate internalization of the toxin, and then mediates translocation of the A chain into the cytoplasm. The A chain is an enzyme that executes the damage by modifying selected cellular target proteins or altering the amounts of intracellular signaling molecules. Consequently, signaling pathways are derailed, resulting in cell malfunction or cell death (2).

The seven botulinum neurotoxins and the