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Gamma-ray astronomy / Astronomie des rayons gamma

Gamma-ray pulsars: A gold mine

Les pulsars γ : Une mine d'or

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ABSTRACT

The most energetic neutron stars, powered by their rotation, are capable of producing pulsed radiation from the radio up to γ rays with nearly TeV energies. These pulsars are part of the universe of energetic and powerful particle accelerators, using their uniquely fast rotation and formidable magnetic fields to accelerate particles to ultra-relativistic speed. The extreme properties of these stars provide an excellent testing ground, beyond Earth experience, for nuclear, gravitational, and quantum-electrodynamical physics. A wealth of γ-ray pulsars has recently been discovered with the Fermi Gamma-Ray Space Telescope. The energetic γ rays enable us to probe the magnetospheres of neutron stars and particle acceleration in this exotic environment. We review the latest developments in this field, beginning with a brief overview of the properties and mysteries of rotation-powered pulsars, and then discussing γ-ray observations and magnetospheric models in more detail.

RÉSUMÉ

Les étoiles à neutrons les plus puissantes, qui tirent leur énergie de leur rotation, sont capables d'émettre des impulsions lumineuses des ondes radio jusqu'aux rayons γ, d'énergies proches du TeV. Ces pulsars font partie des puissants accélérateurs de particules de l'Univers, profitant de leur rotation unique et de leur formidable champ magnétique pour accélérer des particules jusqu'à des vitesses ultra-relativistes. Les propriétés extrêmes de ces étoiles permettent de tester la physique nucléaire, la gravitation et l'électrodynamique quantique dans des conditions inaccessibles sur Terre. Le télescope gamma spatial *Fermi* vient de révéler un riche échantillon de pulsars γ. Leur rayonnement γ énergétique permet de sonder la magnétosphère des étoiles à neutrons et d'étudier l'accélération de particules dans cet environnement exotique. Nous présentons les derniers développements de ce domaine, en commençant par une rapide revue des propriétés et mystères soulevés par ces pulsars, puis en détaillant plus avant les observations γ et les modèles magnétosphériques.

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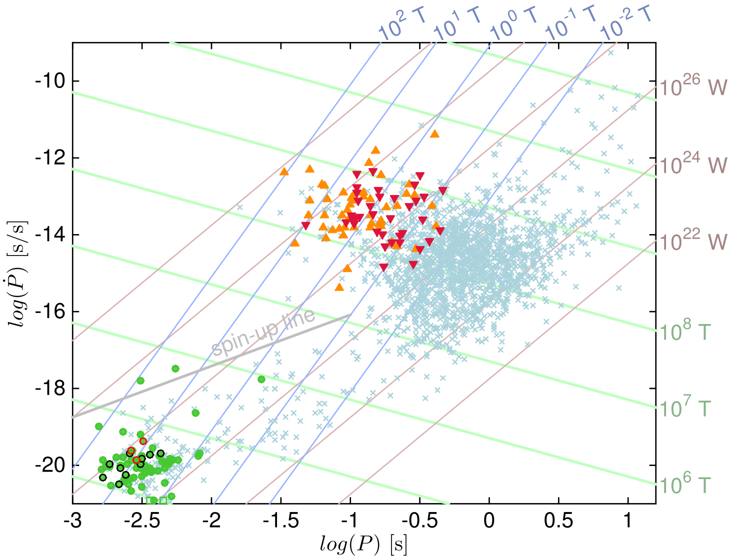

Fig. 1. (Color online.) Distribution in period (P) and period time derivative ($\dot{P}$) of γ-ray pulsars [1] and radio pulsars [2] with 53 radio-loud and γ-loud young pulsars (orange upward triangles), 37 radio-faint and γ-loud young pulsars (red downward triangles), 71 radio-loud and γ-loud millisecond pulsars (green filled circles, circled in black and red when in black-widow and redback systems, respectively), and 2256 other radio pulsars (light blue). Recently discovered millisecond pulsars, with no $\dot{P}$ measurement yet, are plotted as squares at $\dot{P}$ near 10^{-21}. Lines of constant spin-down power (brown) and polar magnetic field strength (green) are given for a magnetic dipole in vacuum and a stellar moment of inertia of 1.4×10^{38} kg·m^{-2} applicable to a 1.4-solar-mass neutron star with a 12-km radius [3]. Lines of constant magnetic field strength at the light cylinder radius are shown in blue. The gray line marks the spin-up rate expected from mass transfer at the Eddington rate from a stellar companion in a binary system (see equation (1)).

1. Neutron stars, pulsars, and their puzzles

A neutron star is an extreme object in many regards. It is a compact, rapidly spinning, highly magnetized star, formed from the core of a massive star which runs out of nuclear power and collapses under its own gravity, while the outer stellar layers rebound and explode into a supernova. By conservation of angular momentum, the collapsed neutron star ends up spinning at the mind-boggling rate of tens of revolutions per second (see Fig. 1). With the equivalent of 1 to 2 solar masses compressed in a sphere the size of a city, with 10 to 14 km radii [4–6], these objects provide a unique test-ground to study ultra-dense matter. To put these numbers into perspective, imagine a pinhead filled with 200,000 tons of matter, crushed near the surface by a gravitational force 1.3×10^{11} times larger than on Earth.

The magnetic field, entrained and amplified (and partly generated?) in the birth collapse, is also beyond terrestrial measure. Assuming magnetic dipole radiation, we infer polar strengths of 10^8 to 10^{11} T, which correspond to the strongest magnetic fields in the known universe (see Fig. 1). In comparison we measure ~ 60 µT near the Earth poles and can briefly reach 10^3 T in terrestrial laboratories. The rotation of the magnetic field, anchored in the star and inclined at an angle α_B to the spin axis (see Fig. 2), induces a net radial Poynting flux which carries energy away from the star at the expense of its rotational energy. The young neutron stars thus slow down over a few 10^8 years, from initial spin periods P of 30–100 ms and rotational powers $\dot{E}_{\rm rot}$ of 10^{30-32} W, down to periods of order 1 s and to powers as low as 10^{22-24} W (see Fig. 1). In comparison, the total radiation yield from the Sun represents 3.8×10^{26} W. In the course of their evolution, some neutron stars born in binary systems may spin up by accreting angular momentum from a low-mass star companion, if the geometry of the mass transfer is favorable. In Fig. 1, these recycled pulsars "drift" below the maximum spin-up line, up to periods of a few milliseconds, hence their name of millisecond pulsars (MSP) and their large rotational powers of 10^{26-30} W despite their few billion years of age. They have low magnetic fields of 10^{4-6} T.

The interior structure of a neutron star defies our understanding of the states of matter at different depths (from the solid ionic crust to neutron matter, to hyperon-dominated matter, condensed mesons, or strange quarks) and of the coupling of the magnetic flux tubes (generated by superconducting protons) with the numerous rotational vortices of the neutron superfluid. The moment of inertia also serves to test gravity theories beyond General Relativity. Mass-radius measurements and observations of the rotational properties and starquake 'glitches', and of the thermal emission and long-term stellar cooling, provide complementary constraints on these questions. A few results are discussed in Section 4.3 and we point the reader to [7] for further literature.

Neutron stars have been dubbed pulsars when found to emit pulses of radiation in the radio in 1967 [8], in the optical and X rays in 1969 [9–11], and in γ rays in the early 1970s [12]. Pulses of short duration and stable frequency were rapidly explained as rotating light beams sweeping past the Earth at the angular velocity, $\Omega = 2\pi/P$, of the star: only dense stars such as neutron stars could spin fast enough to match the observed frequencies [13]. Since then, over 2400 pulsars have been discovered across the sky at different wavelengths (see Fig. 1). The narrow, lighthouse-like, beams that were first