Pulsars

Polarized γ-rays from Vela

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INCREASINGLY sophisticated observations of pulsars over the past two decades have led convincingly to the conclusion that pulsars are magnetized neutron stars. But despite the wealth of detail accumulated, there is still no comprehensive model of the pulsation mechanism, because of the lack of knowledge of the configuration of the magnetic field and particle flux. Now, P.A. Caraveo *et al.* (*Astrophys. J.*, in the press) report that the flux of 100-MeV γ-rays from the Vela pulsar are polarized. This result is of great significance because of the close link between photon polarization and the ordering of the source. These new observations open the way to a better understanding of pulsar physics.

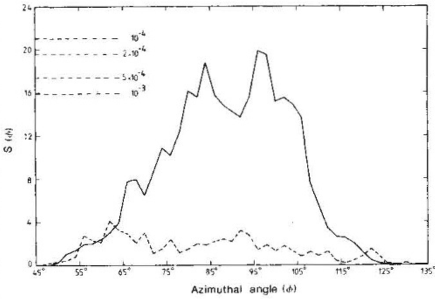
Because the wavelength of γ-rays is so short (about 10^{-14} m at 100 MeV), classical wave techniques cannot be used to measure their polarization. The kinematics of the particles produced by the interactions of γ-ray photons (Compton scattering and 'pair production') can be used, however. The emerging particles (electrons or electron–positron pairs) have azimuthal distributions related to the plane of the electric vector (polarization) of the incident γ-ray.

The means of studying γ-ray polarization by the pair-production process ($\gamma \rightarrow e^{+} + e^{-}$) in spark chambers was recently described by A.A. Koslenkov and I.G. Mitrofanov (*Sov. Astr.* **29**, 591–593; 1985), who based their work on the basic theory developed by L.C. Maximon and H. Olsen (*Phys. Rev.* **126**, 310–319; 1962). The azimuthal distribution of the planes containing the electron–positron pairs is related to the direction of the electric vector of the incident, linearly polarized γ-rays. This is seen as a broad quadrupolar modulation of the distribution of produced pairs about the azimuthal angle ϕ relative to the incident photons and provides a means of investigating the degree of polarization of incident γ-ray fluxes.

As well as the intrinsic, azimuthal spread, two other effects broaden the distribution further. First, pair production is a three-body process that occurs in the presence of a nucleus which recoils, introducing an unknown perturbation. Second, the electron and positron are Coulomb-scattered as they emerge from the conversion material of the spark-chamber plates. The net result is a reduction in the depth of modulation.

Caraveo *et al.* apply this theory to data previously obtained at the European Cos-B satellite γ-ray telescope. The spark chamber within the instrument identifies the trajectories of the two materialized electrons in some detail, so that a three-dimensional reconstruction of individual events is possible. Only γ-ray events that have clearly defined tracks of the two electrons in the form of an inverted V are analysed. A Monte-Carlo simulation of the Cos-B configuration shows that the signal from completely polarized flux would be modulated by about 20 per cent, and that at least 2,000 events would be required to give a statistically meaningful result.

Emission from the Vela pulsar, which was chosen because it has provided more suitable and pulsed γ-ray events (2,526) than any other source detected by Cos-B, is strongly linearly polarized (see figure). Two further tests confirm this result. First, the azimuthal modulation is only apparent if the data are transformed from the coordinates of the spin-stabilized satellite to the 'despun' coordinates of the source. Second, γ-rays from the Cygnus region of the sky, of similar statistical quality, show no polarization, which is as expected, given the extended nature of the source.



The azimuthal modulation of the plane containing the electron–positron pairs derived from 2,526 pulsed Vela γ-rays that materialize in the Cos-B spark chamber (solid curve). The dashed curve applies to 3,109 photons from the Cygnus region used as a comparison. S is the deviation function as defined in Caraveo *et al.* Overall chance occurrence probability levels are shown as derived from Monte-Carlo simulations.

Thus Vela seems to be a strongly polarized source and, by implication, it is a naked neutron star. It is probable that the polarized γ-rays are emitted by either curvature or synchrotron radiation. Also the γ-ray source must be sufficiently close to the neutron star for the magnetic field to be well ordered, but not so close that photons are lost by pair creation as they traverse suitably intense magnetospheric field lines.

The polarized photons are strongly correlated with the Vela pulsar rotation. The broad spread (30°) in the azimuthal distribution, however, precludes the possibility of identifying any relation between the phase of the pulsar and a swing in the direction of polarization of the γ-rays (as found in radio signals). But the degree of polarization does seem to vary throughout the pulse cycle, and this may help to elucidate the geometrical configuration of the pulsar. Separate analyses of the two main pulses, the interpulse region, and the background (emission in the period between the secondary and primary pulses) show that the interpulse is almost completely polarized, whereas the two pulses are, at best, only weakly polarized and the background is completely isotropic.

This result is compatible with the geometrical model proposed by F.G. Smith (*Mon. Not. R. astr. Soc.* **219**, 729–736; 1986) to explain all the emission (radio to γ-ray) of the Crab and Vela pulsars for which the interpulse emission is derived from curvature radiation in a fan beam. The lack of polarization in the first pulse is probably related to curvature radiation from the polar region, which is rotated by 360° (and thus smeared) with respect to the line-of-sight.

A similar analysis of γ-rays from the Crab (1,533 suitable events) and Geminga (1,204 suitable events) failed to produce a significant result. Clearly the poor statistical quality, combined with instrumental effects that give a low depth of modulation, renders a meaningful result unlikely. In the case of the Crab, any polarization is further stifled because half of the γ-rays emission is unpulsed and must originate from the Nebula or from a region that is not ordered by the magnetic field of the neutron star. It is a pity that there is no definitive result for Geminga. A positive detection of linear γ-ray polarization would confirm the compact nature of this object, which, because of the implied magnetic field, could then be identified as a neutron star rather than, say, a black hole.

The Cos-B investigation institutes a useful technique for the study of neutron stars and other objects. The close connection between the polarization of γ-rays and their parent particles and fields gives observers an undistorted view of the source configuration. Cos-B is hampered by poor statistics and a design not intended for polarization studies. Forthcoming telescopes, COMPTEL and EGRET, with improved data collection, and GRASP (γ-ray spectroscopy and positioning), with built-in polarimetry capability, will allow routine, accurate measurements of γ-ray polarization. □

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