

GEMINGA'S TAILS : A PULSAR BOW-SHOCK PROBING THE INTERSTELLAR MEDIUM.

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We report the XMM/Newton EPIC discovery of two elongated parallel x-ray tails trailing the pulsar Geminga. They are aligned with the object's supersonic motion, extend for $\sim 2'$, have a non-thermal spectrum produced by electron-synchrotron emission in the bow shock between the pulsar wind and the surrounding medium. Electron lifetime against synchrotron cooling matches the source transit time over the x-ray features' length. Such a first X-ray detection of a pulsar bow shock (with no Ha emission) allows us to gauge the pulsar electron injection energy and the shock magnetic field, while constraining the angle of Geminga's motion and the local matter density.

The Geminga pulsar is one of the best studied isolated neutron stars⁽¹⁾. Discovered 30 years ago as a 100 MeV gamma-ray source in Gemini and later identified at x-ray and optical wavelengths, it is now known to be at a parallactic distance of ~ 160 pc⁽²⁾ and to move at 170 mas/y (equivalent to a transverse velocity of 120 km/sec) in the plane of the sky⁽³⁾. As a consequence, it

is one of a few isolated neutron stars with well-defined absolute energetics: its rotational energy loss, $\dot{E} = 3.2 \cdot 10^{34}$ erg/sec, is dominated by gamma-ray emission (10^{33} erg/sec in the tens of MeV to few GeV range for a 1 steradian beaming), implying the presence of a relativistic pulsar wind flowing out of the neutron star.

Its soft x-ray emission ($\sim 10^{31}$ erg/sec), led to Geminga's identification as a neutron star⁽⁴⁾ and yielded its pulsations at 237 msec⁽⁵⁾. The Geminga x-ray spectrum is the sum of thermal and non-thermal components⁽⁶⁾.

In order to better understand its broad band emission and modulation, as well as to ascertain the possible existence of nebular X-ray flux around this 350,000 year old pulsar, the European Photon Imaging Camera (EPIC) onboard XMM-Newton performed a 100 ksec exposure on Geminga on 4 April, 2002. While the two Metal Oxide Semiconductor (MOS) EPIC cameras were operated with the medium filter in *full frame* mode⁽⁷⁾, the pn camera was operated with the thin filter in *small window* mode to allow for the accurate timing of Geminga photons⁽⁸⁾. The data were processed with the XMM Newton Science Analysis Software (SAS version 5.3.3). After removing time intervals with high particle background and correcting for the dead time, we obtain a net exposure time of 55.0 ksec for the pn camera and 76.9 and 77.4 ksec for the MOS1 and MOS2, respectively.

Inspection of both MOS images revealed an extended x-ray feature trailing Geminga (Fig. 1 and Fig. S1) with a symmetric structure, consisting of two tails, ~ 2 arcmin long, or ~ 0.1 pc at 160 pc. Although such tails originate from, or close to, Geminga, their morphology within $1'$ from the source position cannot be studied because of Geminga's brighter emission. The tails are aligned and symmetric with respect to the pulsar proper motion vector (Fig. 1). No diffuse emission is detected in the region between the tails, both of which are $\sim 20''$ - $30''$ thick, i.e. only marginally resolved along this dimension, considering the instrument response and the limited statistics.

Both tails are highly significant, with a S/N of 13 in the energy range 0.3-5 keV. _Also the pn data

show the tails; however, owing to the *small window* operating mode, the instrument field of view is too small to allow the selection of suitable background regions, thus hampering a detailed analysis of the diffuse emission.

In what follows, we shall focus on the MOS1 and MOS2 data.

The spectrum of both tails can be described by a power law with an absorption consistent with that observed for the pulsar, $N_{\text{H}} = 1.1 \times 10^{20} \text{ cm}^{-2}$ ⁽⁶⁾, a value for which the photon index of the 450-counts tails spectrum is 1.6 ± 0.2 . The total unabsorbed flux from the region is $\sim 2.1 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$, i.e. $\sim 3\%$ of the x-ray source luminosity, or a few 10^{-6} of Geminga's rotational energy loss.

In order to ascertain possible point source contributions to the extended emissions, we have superimposed our data to the extensive multicolor image library which we have available for Geminga. The faint source 2 arcmin North West of Geminga is associated with a 11 magnitude K star, while in the area covered by our extended emission we note only the presence of a 13 mag late-type star at a position roughly coincident with the end of the southern tail and a 14 magnitude one about halfway down the tail. Even under the most favorable assumptions on the ratio between the optical and x-ray flux values for late type stars ⁽⁹⁾, such contaminating sources could yield at most 50 counts out of the 450 ascribed to the sum of the two tails, whose spectral parameters thus remain unchanged when excluding the star's potential contribution. No other point source contamination to the extended emission is apparent.

The x-ray structure around Geminga is different from x-ray structures seen around other pulsars ⁽¹⁰⁻¹²⁾. Its shape, characterized by two parallel streams with no detectable emission in between, gives the impression of the projected view, in the plane of the sky, of an empty paraboloid or cone of x-ray emission. Because similar velocity-driven, arc-shaped features have been seen in $\text{H}\alpha$ around a few pulsars ^(13,14), we have obtained a deep $\text{H}\alpha$ plate of the region, looking for a possible extended emission related to the x-ray one. The data were collected at the ESO VLT-

ANTU telescope in February 2003, for a total exposure of 5 hrs using the FORS1 instrument. In the confused interstellar medium (ISM) at these low galactic latitudes ($b=+4.2^\circ$), no organized diffuse H α emission is observed from the x-ray structure surrounding Geminga. The resulting image (fig. 2), together with the X-ray isophotes, allows us to calculate an upper limit to the H α emission of 10^{-18} erg cm $^{-2}$ arcsec $^{-2}$.

The fraction of the spin down energy channelled by Geminga into its x-ray tails is two orders of magnitude lower than the values measured for the nebulae of PSR1757-24⁽¹⁰⁾ PSR1929+10⁽¹¹⁾ and PSR B1957+20⁽¹²⁾. To date, few (if any) pulsars can rely on observing times long enough to allow for the detection of comparably faint features. In this case, the proximity of Geminga has played a crucial role, so that we are here confronted with yet another first in the phenomenology of Geminga.

The geometry of the extended emission may be modelled as a bow-shock formed at the equilibrium region between the pulsar energy loss \dot{E} and the dynamical pressure generated by its supersonic motion in the ISM. Ram pressure balance between a spherical relativistic pulsar wind and the ambient medium determines the stand-off radius R_{SO} of the bow-shock, i.e. the distance from the pulsar to the shock front:

$$\frac{\dot{E}}{4\pi R_{SO}^2 c} = \mathbf{r}_{ISM} V_{NS}^2 \quad (1)$$

where \mathbf{r}_{ISM} is the density of the interstellar medium, V_{NS} is the pulsar velocity $V_{NS}=\mathbf{mD}/\cos(i)$ (μ =proper motion, D =distance, i =inclination angle to the plane of sky, for which $i=0^\circ$), and \dot{E} is the rotational energy loss going into the relativistic wind. For simplicity, we have assumed such a wind to be spherically symmetric at the distance R_{SO} . Collimated energy outflow in the form of beams and jets complicates only slightly the geometry, but not the energetics of the problem.

The distance, proper motion and spindown energy of Geminga are known. Thus, its R_{SO} is a function of only two unknown values (the ambient medium density and i), with a negligible error dispersion on the other parameters. We calculate the expected Geminga stand-off angle ($\delta = R_{SO} \cos i/D$) as a function of the inclination angle to the plane of sky and of the ISM density (Fig S3). The stand-off angle is not resolved by EPIC, because the brightness ratio between Geminga and its extended feature is so high that we have not succeeded in subtracting the point source contribution accurately enough. The current $<5\%$ uncertainty in the knowledge of the instrument's response to a point source leaves residuals outshining the faint diffuse emission up to $40''$ from the central source. Mapping the feature close to Geminga is thus impossible: we can only set a robust upper limit of $\delta < 40''$.

Generalizing momentum balance along directions other than that of the proper motion, and assuming a spherical pulsar wind in a homogeneous ISM, the analytic solution for the axisymmetric three-dimensional shape ⁽¹⁵⁾ of the bow-shock can be described as follows

$$R_{\mathbf{J}} = \frac{R_{SO} \sqrt{3 \left(1 - \frac{\mathbf{J}}{\tan \mathbf{J}} \right)}}{\sin \mathbf{J}} \quad (2)$$

where $R_{\mathbf{J}}$ is the shock front distance as a function of the angle \mathbf{J} from the pulsar direction of motion (see inset of Fig. 4).

It is possible to fit both tails with a three-dimensional geometrical model of the Geminga bow-shock based on equation (2). In this way, we can obtain an estimate of the R_{SO} independent from all physical parameters described in equation (1). The symmetric, two-streamed feature shown in Fig. 1 is reproduced by the projection effect in the plane of the sky of such an emitting surface, assumed uniform, the edges of which show up brighter because of a limb effect.

Comparing our observations with the geometrical model computed for different values of i , we see that only bow-shocks with inclination angles to the plane of sky $i < 30^\circ$ satisfactorily describe

our data (Fig. 4). Thus Geminga travels at a relatively small angle with respect to the plane of the sky and $i < 30^\circ$ implies stand-off angle values of $\delta \sim 20'' - 30''$, corresponding to $R_{SO} \sim 6 \times 10^{16}$ cm. This set of values constrains the range for the total ambient medium density to be $0.06 < \rho_{ISM} < 0.15$ atoms/cm³. Such a range agrees with the expected value of the ISM density for the region around Geminga⁽¹⁶⁾ and constrains Geminga's Mach number to be $14 < M < 20$. More quantitative parameter fitting will have to await for higher resolution x-ray data.

The overall H α luminosity expected from a bow-shock is^(17,18) $L_{H\alpha} \sim \dot{E} \cdot V_{NS} \cdot X$, where X is the neutral H fraction. Given our H α upper limit, we deduce a neutral hydrogen fraction < 0.01 . It is plausible that such a condition be met, in the troubled ISM around Geminga, considering also the presence of the highly-ionizing γ /X-ray pulsar.

As to the physics of the tails, their hard, power-law x-ray spectrum suggests synchrotron emission of energetic electrons in a magnetic field. While energetic electrons are naturally and copiously supplied by the Geminga γ -ray pulsar, its magnetic field will have decayed to practically zero at the sub-light-year distances of interest here. An appropriate magnetic field is provided by the interstellar one compressed in the bow-shock. Because the large scale interstellar magnetic field can be assumed to be frozen to the ISM, for $M \gg 1$ and $\gamma = 5/3$, $\rho_{shock} = 4 \rho_{ISM}$ ^(19,20) implying $B_{shock} = 4B_{ISM}$, or about $\sim 10^{-5}$ G for a typical average ISM magnetic field⁽²¹⁾. Following the standard magneto-bremsstrahlung treatment, e.g.⁽²²⁾, we can estimate that the keV photons of the Geminga tails are produced by electrons up to 10^{14} eV, a value close to the energy upper limit for pulsar wind electrons in Geminga⁽²³⁾. In cooling by synchrotron photon emission, such electrons will Larmor-gyrate in the compressed bow shock field, with a radius of about 3.4×10^{16} cm. Each tail thickness is then predicted to be $\sim 6.8 \times 10^{16}$ cm, or $\sim 27''$ at the distance of Geminga, in excellent agreement with our observations (see fig. 1).

A final consideration of the emission physics and geometry supplies an independent consistency check to our model. If synchrotron emission is the major cooling process of the energetic tail

electrons, to wit their hard X-ray spectrum, one can compute the lifetime of such electrons (or, more precisely, the time it takes for them to lose half of their energy) in the bow-shock magnetic field. This turns out to be ~ 800 years. On the other hand, Geminga's proper motion (170 mas/year) allows one to compute the time taken by the pulsar and its bow shock to transit over the apparent length of the x-ray structures in the sky ($\sim 3'$ from the central source). Such a time is close to 1,000 years. Thus, Geminga's tails remain visible for a time comparable to the electron synchrotron x-ray emission life time after the pulsar passage.

The tails of Geminga, although containing only 10^{-6} of the pulsar rotational energy loss, provide a direct gauge both of the pulsar wind electron energy (10^{14} eV) and of the local interstellar magnetic field (2-3 μ G) under the simple assumptions of the synchrotron nature of the tails emission.

References and Notes

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Figure captions

Figure 1. Inner part of the GEMINGA EPIC/MOS1 and MOS2 images summed together shown after gaussian smoothing (the raw data can be seen in fig.S1). North is up, East is left. Events in the energy range 0.3- 5.0 keV are displayed. Net exposure time is ~ 77 ksec per camera. The Geminga count rates are 0.083 ± 0.001 c/sec and 0.084 ± 0.001 c/sec for the MOS1 and MOS2, respectively. Two elongated tails of diffuse emission are seen to emerge from the source, the point spread function (PSF) of which dominates the count-rate up to an angular distance of $\sim 1'$. The tails are $\sim 2'$ long and cover an area of ~ 2 square arcmin. The diffuse emission shows a remarkable symmetry with respect to the pulsar proper motion vector, marked by the arrow.

Figure 2. Deep (5 hours) VLT/FORS1 image of the Geminga field in the H α band ($\lambda = 6563$ A, $\Delta\lambda = 61$ A). North is up, East is left. The isophotes of the X-ray image are overlaid (three different steps in surface brightness level have been used: 20% -red, 50% -yellow and 100% -blue). No H α emission correlated with the X-ray tails can be seen. It is also evident that no bright

sources are present in the region covered by the tails, with the exception of the SW edge, where a 13 mag late-type star is seen. Its contribution to the X-ray emission, however, is estimated to be marginal (see text).

Figure 3. Expected stand-off angle shown as a function of ISM density and of the inclination angle of the pulsar proper motion with respect to the plane of sky ($i=0^\circ$).

The XMM images set an upper limit of $\sim 40''$ to the stand-off angle, excluding the region marked in red. The range of the stand-off angles compatible with the geometrical fits to the three-dimensional bow-shock model is shown in green (see fig. 4).

Figure 4. Comparison of our X-ray data with the three-dimensional bow-shock geometrical models. The cases for inclination angles 0° , 20° , 30° , 40° and 60° are shown. As apparent, inclination angles $i > 30^\circ$ do not fit the data. For $i < 30^\circ$, the fit constrains the stand-off angle in the range $20\text{-}30''$.

(inset). Bow-shock profile drawn from eq 2. as a function of the angle from the proper motion direction (ϑ) and shock front distance (R).

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