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LETTER

Letter to the Editor

HST/FOC observations confirm the presence of a spectral feature in the optical spectrum of Geminga*

R.P. Mignani[1], **P.A. Caraveo**[2,3], **and G.F. Bignami**[4,5]

[1] Max-Plack-Institute für Extraterrestrische Physik, Postfach 1603 Giessenbachstrasse, D-85740 Garching, Germany (e-mail: rmignani@xray.mpe.mpg.de)
current address STECF-ESO, Karl Schwarzschild Strasse 2, D-85740 Garching, Germany
[2] Istituto di Fisica Cosmica del CNR, Via Bassini 15, I-20133 Milan, Italy (e-mail: pat@ifctr.mi.cnr.it)
[3] Istituto Astronomico, Via Lancisi 29, I-00161 Rome, Italy
[4] Agenzia Spaziale Italiana, Via di Villa Patrizi 13, I-00161 Rome, Italy (e-mail: gfb@asirom.rm.asi.it)
[5] Universitá di Pavia, Via Bassi 6, I-27100 Pavia, Italy

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Abstract. New optical and near-UV HST observations of Geminga are presented. When compared with previous ground-based and HST imaging, the data confirm and better define the presence of an emission feature centered at $\sim 6,000$Å and superimposed on the thermal continuum best fitting the extreme-UV/soft X-ray data. This feature may be interpreted in terms of cyclotron emission originated from a mixture of H/He ions in the neutron star's atmosphere. In the case of pure Hydrogen, the feature wavelength would imply a magnetic field of order $3-5\,10^{11}\,G$, consistent with the value deduced from the dynamical parameters of the pulsar. If due to cyclotron emission, the observation of this feature would represent the first case of an *in situ* measurement of the surface magnetic field of an isolated neutron star.

Key words: optical, pulsar Geminga

1. Introduction

Our understanding of the optical properties of Isolated Neutron Stars (INSs) is limited by the faintness of the vast majority of them. Indeed, only for the $m_V \sim 16.6$ Crab pulsar, acceptable, medium-resolution optical spectroscopy is available (Nasuti et al 1996). For a few more cases (PSR0540-69, PSR0833-45, PSR1509-58, PSR0656+14 and Geminga), the spectral information just relies on multicolour photometry (Nasuti et al. 1997; Mignani et al. 1998a; Pavlov et al. 1997; Bignami et al. 1996). For the rest of the optical database (PSR0950+08, PSR1929+10 and PSR1055-52), only one-or two-band detections are available (Pavlov et al. 1996; Mignani et al. 1997).

Very young objects, say up to $\tau \sim 10^4$ yrs (Crab, PSR0540-69, PSR0833-45), are characterized by flat, synchrotron-like spectra arising from energetic electron interactions in their magnetosphere (Caraveo, 1998). For the Middle-Aged ($\tau \sim 10^5\,yrs$) INSs (PSR0656+14, Geminga and PSR1055-52), also referred to as "the three musketeers" for their overall similarities (Becker & Trümper 1997), the situation is more complex and different emission processes may become relevant. For example, the non-thermal magnetospheric emission could have faded enough, at least in the optical waveband, to render visible the thermal emission from the hot neutron star surface (Mignani et al. 1998b). Its temperature, following standard cooling calculations (see e.g. Nomoto & Tsuruta 1987), could be in the $10^5 - 10^6\ K$ range, in excellent agreement with the recent X-ray findings (e.g. Becker & Trümper 1997). It is easy, then, to predict the IR-optical-UV fluxes expected along the $\sim E^2$ Rayleigh-Jeans slope of the Planck curve best fitting the X-rays, and to compare predictions with observations, where available.

2. Data overview

Among Middle-Aged INSs, Geminga is certainly the most studied (see Bignami & Caraveo 1996 and references therein). Here we review ten years of optical data which are summarized in Table 1 as well as in Fig. 1. On the basis of 3 colours only (Fig. 1a), Bignami et al. (1988) realized that the Geminga spectrum could not be fit by a simple Planck's law. The addition of the ground-based I upper limit, obtained with the NTT, and new HST colours (namely 555W, 342W and the upper limit at 675W) over the years (Fig. 1b) led Bignami et al. (1996) to propose an explanation in terms of a spectral feature superimposed to the Rayleigh-Jeans continuum of the Planckian best-fitting the ROSAT/EUVE data. Since the distance to Geminga was fixed in 157^{+59}_{-34} pc by the parallax measurement of Caraveo et al. (1996), an absolute fit to its surface thermal emission is possible. Using

Send offprint requests to: R.P. Mignani

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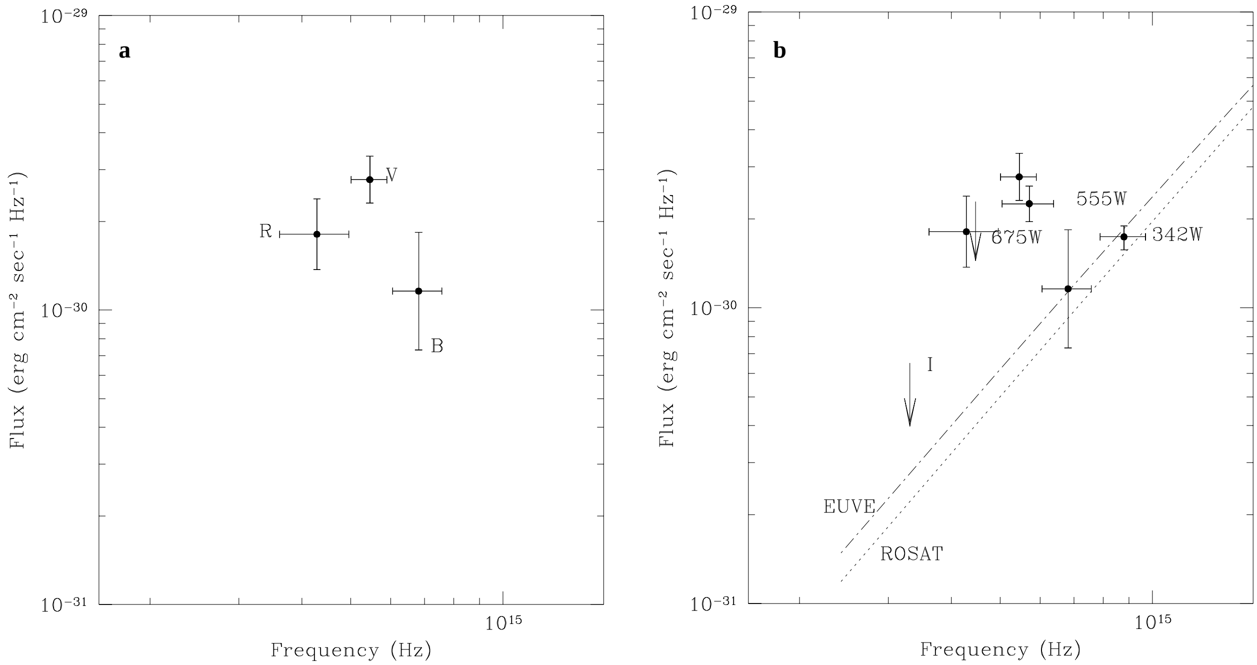

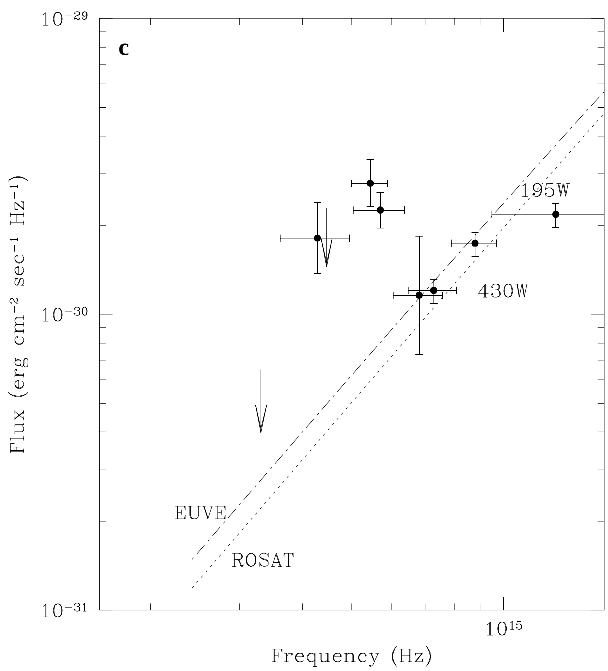

Fig. 1a–c. Ten-year evolution of the I-to-UV photometry of Geminga. **a** Situation in 1987, with 3 ground-based (CFHT, ESO 3.6m) points (R,V,B) clearly not compatible with a black-body curve (Bignami et al. 1988). **b** By the end of 1995, several points were added (see Bignami et al. 1996 where, indeed, a numerical error of a factor 4 is present in Figs. 2 and 3, where all the black-body fits should be revised downwards) both from the ground (I) and from HST (555W, 675W, 342W). **c** New HST/FOC data (430W, 195W) presented here. The lines shown represent best fit backbody curves to the ROSAT/EUVE data for an INS at d=157 pc (Caraveo et al. 1996). The two cases shown correspond to R=10 km and $T = 4.5 \times 10^5$K (ROSAT 1991 fit-dotted) and to R=15 km and T=$2.5 \times 10^5 K$ (EUVE fit-dashed). Note the absolute scale: no normalization has been performed.

the temperature $T = 4.5\ 10^5\ K$ (Halpern & Rudermann 1993), obtained with ROSAT data collected in 1991, the best fit to the B-UV flux values yields for Geminga a radius R of about 10 km, while a radius of 15 km is required if one uses the temperature best fitting the EUVE data, i.e. $2.5\ 10^5\ K$ (see Bignami et al. 1996). On the other hand, ROSAT data collected in 1993 (Halpern & Wang 1997) yield an higher best fitting temperature ($T = 5.6\ 10^5\ K$) for a somewhat lower bolometric flux. This implies, for the same Geminga distance, a smaller emitting area. However, the large errors on the spectral fit parameters make it difficult to draw firm conclusions on the effective size of the emitting area which could be anywhere from 10% to the totality of the neutron star surface.

3. New data

Additional observations of Geminga have been obtained more recently with the HST/FOC. In order to have a firm confirmation of our ground-based B measure, one observation was performed through the 430W filter ($\lambda = 3940$Å; $\Delta\lambda = 832$Å) i.e. very close to the B band. To further probe the source spectral shape, the second observation was performed through the 195W one, a wide passband UV filter ($\Delta\lambda = 946$Å) centered at $\lambda = 2110$Å. The data were collected on May 4, 1996 with total exposure times of 8200 s with filter 430W and 5100 s with filter 195W. Following the usual strategy, the observations were split in shorter exposures to allow for cosmic ray removal. The camera was operated in the nominal "F/96" mode, to which corresponds an effective focal ratio of f/151 and a field of view of 7×7 arcsec. The pixel size was thus 0.014 arcsec.

After pipeline processing, single exposures were combined and cosmic ray hits rejected by frame to frame comparisons. Average images were thus computed for each filter and smoothed over cells of 3×3 pixels using a gaussian function. In both filters, a single point source was clearly detected in the FOC field of view. Its coordinates coincide with the expected position of Geminga after correcting for the object's proper motion (Caraveo et al. 1996) at the observing epoch. Standard FOC photometry yielded magnitude values of $m_{430W} = 25.7 \pm 0.1$ and $m_{195W} = 23.9 \pm 0.1$. Conversions from magnitudes to monochromatic fluxes have been computed using the zero points provided by the HST pipeline processing. The resulting fluxes are shown in Fig. 1c, labelled with the corresponding filter names.

4. Interpretation

It is apparent that the new, more accurate, FOC 430W point confirms the B-flux obtained back in 1988 at ESO's 3.6m. At the same time, the 195W point is certainly higher than the 430W and also of the 342W one. Moreover, the V flux value was independently confirmed by repeated observations both from the ground (NTT) and from the HST (Caraveo et al. 1996). As shown in Fig. 1, our set of optical observations is self-consistent, repeatable, and robust. It must, therefore, represent a firm anchor for the spectrum of Geminga.

The points blueward of the 430W have a slope relative to each other certainly consistent with the Rayleigh Jeans E^2 slope. This is why it appears natural to regard them as the optical-UV emission from an X-ray planckian, provided, of course, that its temperature be consistent with the observed flux. This was the scenario arising from the ROSAT data published in Halpern & Ruderman (1993), where everything, i.e. X-ray temperature, neutron star dimension and distance seemed to fall in place on the optical-UV points given above. I such a scenario, Occam's razor rendered unescapable an interpretation centered on single optical-to-$\sim$ 1 keV thermal emission from a $\sim 500,000\ K$ neutron star at the Geminga distance. On top of this, the V-centered feature was interpreted as a wide cyclotron line, for want of any other possibility.

Such a simple scenario may now have to be changed if one is to accept the more recent data of Halpern & Wang (1997), who both increase the best fitting X-ray temperature and decrease the total flux and thus the fraction of the emitting surface. Accepting this new X-ray interpretation implies that the optical data can no longer be c dered as part of the same thermal emission generating the X-rays. However, we would like to underline the robustness of our repeated optical-UV data which feature error bars very much smaller than those characterizing any X-ray extrapolation.

Globally, considering the big uncertainties of the X-ray-derived parameters (to wit Halpern & Ruderman, 1993, vs. Halpern & Wang, 1997), we would still be inclined towards the simplest interpretation, i.e. to ascribe this feature to an emission line, superimposed to the E^2 Rayleigh-Jeans continuum. A fitting procedure assuming a simple Gaussian line centered at λ_c, with FWHM=$\Delta\lambda_c$, and a total energy flux F_c, yields a very good fit ($\chi^2/d.o.f. = 0.8$) to the data with the following parameters (at infinity): $\lambda_c = 5998$Å, $\Delta\lambda_c \sim 1,300$Å, $F_c \sim 4 \times 10^{-16} erg\ cm^{-2} s^{-1}$.

As mentioned in Bignami et al. (1996), the interpretation of such a feature is based on the presence of an atmosphere on Geminga, something already imagined for INSs in general, as well as explicitly for Geminga (Meyer et al 1994). For the case of an atmospheric cyclotron-emitting layer the observed $\lambda_c = 5998$Å (= 2.06 eV) implies a B field, measured at infinity, of $\sim 3.8\ 10^{11} G$ for Z/A = 1, i.e. pure H atmosphere, and correspondingly higher in the presence of He or heavier elements.

This would be the first direct magnetic field measurement for an INS. Of course, for neutron stars in binary systems, direct measures of the magnetic fields were reported by Trümper et al. (1978). In particular, our value compares favourably with the theoretical one $B \sim (P\dot{P})^{1/2}$, which for the Geminga parameters (Mattox et al. 1998) turns out to be $\sim 1.5 \times 10^{12}\ G$. The apparent huge width of the feature ($\sim 1,300$Å), or 20% considering its centre at $\sim 6,000$Å, could be accounted for by the spread of the B-field values integrated in space and time over the whole rotating NS surface.

Alternative views, including the possibility of a significanty non-thermal component, should be certaily be considered. This will be particularly true if the recent exciting result on the detection of an optical pulsation (Shearer et al. 1997a) is confirmed and the shape of the optical light curve becomes available for comparison, especially with the X-ray data.

5. Conclusions

The new data presented here, improving as they do the data given in Bignami et al. (1996), leave no room for doubt that a wide emission feature exists around $6,000$Å, superimposed on a possibly thermal continuum. The feature falls in the wavelength region expected for an atmospheric proton-cyclotron emission produced close to the surface of a magnetic neutron star. Geminga is a magnetic neutron star, to wit its periodic γ-ray emission (Mattox et al, 1998), and most probably has an atmosphere, to wit the spectral shape of its soft X-ray emission (Meyer et al 1994, Halpern & Rudermann 1993).

Not only the optical/UV data may represent, historically, the first time we actually see the surface (atmosphere) of an INS: our interpretation of the feature reported here would also imply the first direct measure of the magnetic field of an INS.

The question arises wheter to expect similar features for other INSs, as the X-ray/UV/optical data improve. If the physi-

Table 1. Summary of the I-to-UV photometry of Geminga presented in Fig. 1. Tha data have been collected over a time span of 10 yrs both from the ground (CFHT, ESO 3.6m and NTT) and from the HST. The columns list the observing dates, the telescope/detector combinations, filter names, peak wavelengths and peak widths, respectively. Three digits identify HST filters. The last two columns list the magnitude values and the corresponding fluxes, computed at the filter peak frequencies. For the V/555W filters, the quoted magnitudes correspond to the average of three, independent, exposures performed at different epochs, aimed at measuring the proper motion (Bignami et al. 1993; Mignani et al. 1994) and the parallax (Caraveo et al. 1996). The only other optical data on Geminga are the early ones of Halpern & Tytler (1988) taken through Gunn g and r filters and largely consistent with those reported above.

Date	*Telescope*	*Filter*	λ_0(Å)	$\Delta\lambda$(Å)	*mag*	*Flux* ($10^{-30}\ erg/cm^2 s\ Hz$)
Jan 94	NTT/SUSI	I[2]	9000	2400	≥ 26.4	≤ 0.64
Jan 87	CFHT	R[1]	7000	2200	25.5 $\pm$ 0.3	1.8 $\pm$ 0.5
Sep95	HST/WFPC2	675W[2]	6735	889.4	≥ 26	≤ 2.3
Jan 87, Nov 92, Jan. 94	3.6m/EFOSC-NTT/SUSI	V[1,2]	5550	890	25.4 $\pm$ 0.2	2.77 $\pm$ 0.5
Mar/Sept 94, Mar 95	HST/WFPC2	555W[2]	5252	1222.5	25.5 $\pm$ 0.15	2.25 $\pm$ 0.3
Jan 87	3.6m/EFOSC	B[1]	4400	980	26.5 $\pm$ 0.5	1.16 $\pm$ 0.6
May 96	HST/FOC	430W[3]	3940	832	25.7 $\pm$ 0.1	1.20 $\pm$ 0.1
Sep 94	HST/FOC	342W[2]	3410	702	24.9 $\pm$ 0.1	1.73 $\pm$ 0.15
May 96	HST/FOC	195W[3]	2110	946	23.9 $\pm$ 0.1	2.18 $\pm$ 0.2

[1] Bignami et al. 1988; [2] Bignami et al. 1996; [3] this work

cal assumptions mentioned above are correct, then, by and large, the answer is positive. We do expect to observe similar features on other INSs of comparable age, first of all on the other two "musketeers". However, for PSR0656+14 the photometry information available so far (Pavlov et al. 1997) shows a rather different spectral behaviour and the optical flux appears more consistent with a steep power law ($\alpha \sim 1.4$), although an additional blackbody component is present. Its optical emission would thus be the combination of both magnetospheric and thermal processes. The recent detection of optical pulsations from PSR0656+14 (Shearer et al. 1997b) seems also to support the presence of a strong magnetospheric component. For the third and oldest musketeer, our recent detection (Mignani et al. 1997) falls close enough to the Rayleigh-Jeans extrapolation of the ROSAT spectrum.

The difficulties in understanding INS physical properties have been outlined dramatically, even for the three best known cases of X-ray thermal emitters. Of them, Geminga is certainly the one with the most abundant phenomenology at yet, disentangling its thermal and non-thermal emission (i.e. distiguishing surface from magnetosphere), although well under way, will require more refined observations.

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