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Letter to the Editor

Detection of an X-ray pulsed signal from the supernova remnant N157B in the Large Magellanic Cloud

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Abstract. The supernova remnant N157B was in the field of view during an observation of the LMC with the BeppoSAX satellite. A signal with a 16 ms periodicity was detected in the MECS data. The pulse profile is characterized by a single narrow peak with a flux of $(5.1 \pm 1.1) \times 10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. In this paper the dynamical state of the plerion–shell system is discussed, and inferences are drawn on the optical luminosity of the pulsar and the plerion.

Key words: stars – stars: neutron – pulsars: individual – X-rays: stars

1. Introduction

N157B (NGC 2060, SNR 0539–69.1) is a supernova remnant in the Large Magellanic Cloud located very near the giant HII complex 30 Doradus. The age of the remnant has been estimated as $\sim 5 \times 10^3$ yr (Wang & Gotthelf 1998). The radio image shows that N157B has a bright Crab-like core and a fainter component with an extent of about 22×17 pc (Dickel et al. 1994). Such objects are generally considered to be powered by the spinning down of a pulsar, but no evidence of a point–like radio source within N157B was found. No polarized radio emission has been detected either (Dickel et al. 1994), while from a Crab–type SNR a uniform polarization is expected. The X-ray spectrum of N157B, well described by a power law with an energy slope ~ 1.5 (Wang & Gotthelf 1998) and without line features, is distinctly different from those typical of shell remnants; instead, it is much more similar to Crab–like ones, which are characterized by energy slopes ~ 1.0. The image in hard X rays, finally, matches well the radio plerion. Recently an RXTE observation has allowed the discovery of a pulsed signal with a period of 16.114712 $\pm$ 0.000003 ms (Marshall et al. 1998a, Marshall et al. 1998b). A $\dot{P}$ value of $(5.124 \pm 0.003) \times 10^{-14}\,\mathrm{s\,s^{-1}}$ has been derived using RXTE and previous ASCA observations. In this paper we present the results of the BeppoSAX observation, and in particular we present the timing and spectral analysis and discuss the spectral results of the pulsed and unpulsed emission.

2. Observation and data reduction

The LMC field around PSR B0540–69 was observed with the Narrow Field Instruments on board the BeppoSAX satellite (Boella et al. 1997a) during the Science Verification Phase on October 25–26, 1996. The supernova remnant N157B was in the FOV with an off-axis angle of $\sim 16'$. In our analysis we used only the two instruments in the focal plane of the X-ray concentrators: the LECS, operating in the 0.13–10 keV energy range (Parmar et al. 1997), and the MECS operating in the 1.5–10 keV range (Boella et al. 1997b). Both are imaging instruments with FOV radius of $20'$ and $28'$, respectively. The total observation length T was 71379 s, but the net exposure times were 19042 s for the LECS and 46742 s for the MECS. In the timing and spectral analysis we considered only the events selected within a circular region centered on the source with a radius of $4'$. The local background for LECS and MECS has been measured in a region of the image far from any field sources, and compared with the background of archival blank fields. The MECS local background spectrum can be well represented by the blank field increased by a factor 16%. The LECS local background presents features at low energies that are not in the blank sky observations, therefore the local background has been used. The detected source events were 255 and 1773 for LECS and MECS, respectively. LECS and MECS response matrices at the correct off-axis position were used.

3. Timing and spectral analysis

The arrival times of the LECS and MECS selected events were converted to the Solar System Baricentric Frame, using the BARICONV code[1] and the coordinates derived from the X-ray image α(2000.0)=$05^h37^m36.7^s$, δ(2000.0)=$-69°09'41.3''$. The Z^2 test (Buccheri & de Jager 1989) on the first two harmonics was applied to search for a periodic signal. The searching

[1] see http://www.sdc.asi.it/software/saxdas/baryconv.html

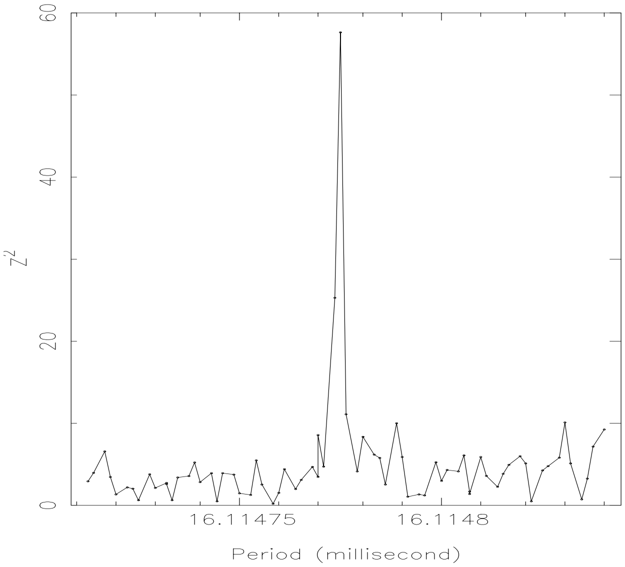

Fig. 1. Z^2 periodogram for the first two harmonics in the interval 16.11470 – 16.11485 for the MECS selected events.

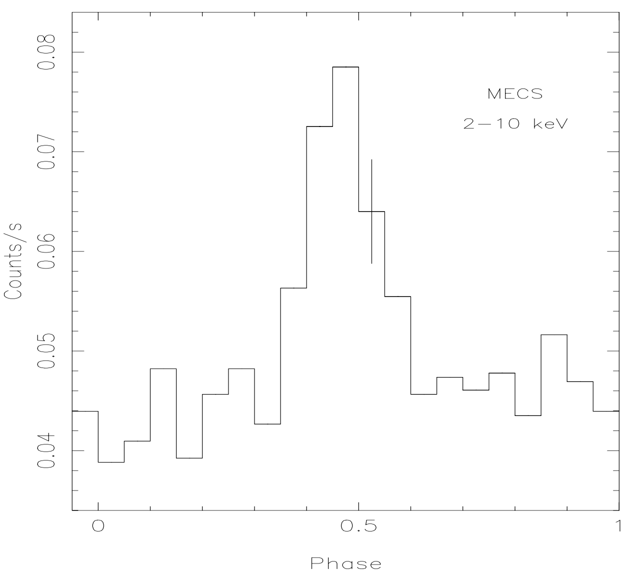

Fig. 2. The folded pulse profile of the 16 ms pulsar in N157B in 2–10 keV MECS energy range.

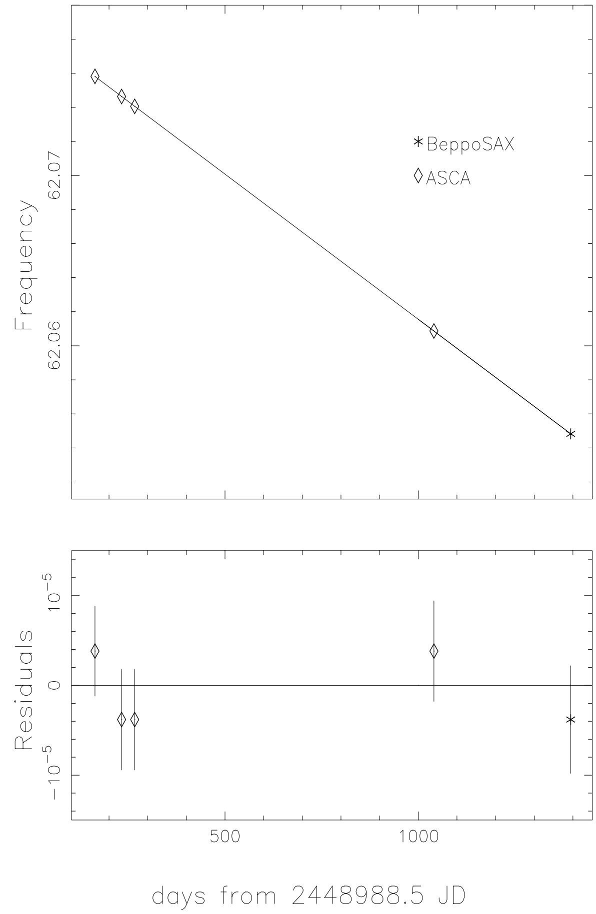

Fig. 3. Historic plot of the pulsar frequency from the first ASCA observation to the BeppoSAX observation (top). Residuals of the fit (bottom).

interval was centered on the period value predicted at the BeppoSAX observation epoch, extrapolated from the RXTE value of October 12, 1996, using the period derivative of Marshall et al. (1998a, 1998b). This derivative was also used in the evaluation of the phase of each event. The resulting Z^2 periodogram for the MECS data is shown in Fig. 1. The period value at the folding reference epoch (JD=2445038.500) is P=16.114775 $\pm$ 0.000002 ms, in agreement with the RXTE extrapolation within the reported uncertainty. Our error on the period is estimated from the frequency resolution, equal to $1/2T$.

Fig. 2 shows the pulse shape resulting from the folding of the MECS events (2–10 keV) with a phase resolution of 20 bins (0.8 ms): it is characterized by a single peak with a duty cycle at the zero level of about 0.25.

We checked also the long term behaviour of this new fast pulsar using several ASCA archival observations. For each of them we perfomed an accurate frequency evaluation using the same Z^2 method and including the first derivative. A historic plot of the pulsar frequency from June 1993 to October 1996 is presented in Fig. 3: a parabolic fit to these data does not give any appreciable second derivative and indicates a constant $\dot{P}$ = (5.124 $\pm$ 0.003) $\times$ 10^{-14} s s^{-1}. A longer time baseline is then necessary to measure $\ddot{P}$ and to compute the braking index. No significant feature at the period value determined from the MECS was found in the LECS periodogram. This is not surprising since the total number of LECS events is only 19% of MECS, with a higher background.

We determined the spectrum of the plerion component in the phase intervals 0.0-0.35 plus 0.6-1.0, both in the MECS and LECS light curves. The background was evaluated as described before, and subtracted. A fit with a simple power law plus low energy absorption gives an acceptable χ^2 but an N_H (1.71 $\pm$ 0.07) $\times$ 10^{21} cm^{-2}, well below the value derived from measurements of the optical extinction in the region (Wang & Gotthelf

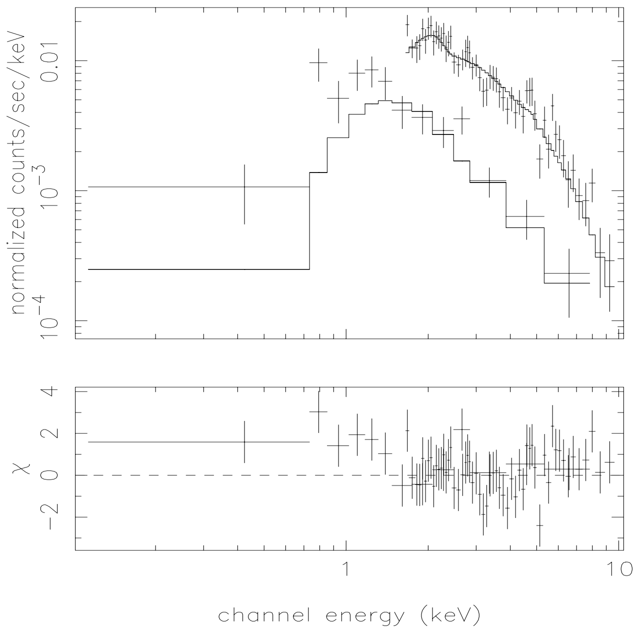

Fig. 4. Nebular spectrum and best fit model (top) and residuals of the fit (bottom).

1998). With N_H frozen to 7.0 × 10^{21} cm^{-2} we obtained a residual below 1 keV as shown in Fig. 4. This excess, as suggested by Wang and Gotthelf, could be due to a contribution from the hot gas of 30 Doradus. The fit in the energy range 2–10 keV gives a photon index 2.63 ± 0.09. The flux in the same range is (3.9 ± 0.1) × 10^{-12} erg s^{-1} cm^{-2} and the luminosity, for an estimated distance of 47 kpc, is 1.0×10^{36} erg s^{-1}.

A satisfactory evaluation of the spectral distribution of the pulsed signal is not straightforward because of the poor statistics and the large relative errors; these are due to the subtraction of the high off–pulse level, consisting of the local background from the 30 Doradus complex and the plerion emission. We then fitted the pulsed MECS spectrum, taken in the phase interval 0.35–0.6 and background subtracted, with a sum of two power laws: one representing the nebular spectrum and the other the pulsed spectrum only. The parameters of the former were kept frozen to the above values. The photon index of the pulsed signal was found to be 1.1 ± 0.4: it is flatter than the Crab pulsar, even if it could still be compatible (at 1.5 standard deviations) because of the large uncertainty. We tried also to fit a black body model, and estimated a temperature of 2.0 ± 0.5 keV, which again implies a very flat spectrum in our energy range. The average pulsed flux in the energy band 2–10 keV is equal to (5.1 ± 1.1) × 10^{-13} erg cm^{-2} s^{-1}, corresponding to a luminosity of 1.3 × 10^{35} erg s^{-1}.

4. Discussion

It is interesting to compare the properties of this new plerion–pulsar association with the Crab Nebula, which is the prototype of the class. The basic parameters are the rotational energy loss rate $\dot{E} = 4.8 \times 10^{38}$ erg s^{-1}, the surface magnetic field $B_s = 3.2 \times 10^{19} (P\dot{P})^{0.5}$ = 9.2×10^{11} G, the braking age $t = 1.6 \times 10^{11}$ s, and the light cylinder radius $r = 7.7 \times 10^7$ cm, to be compared with 4.5 × 10^{38} erg s^{-1}, 3.8×10^{12} G, 3.9×10^{10} s and 1.6× 10^8 cm for the Crab pulsar respectively. The near coincidence between the braking age of the new pulsar and the age deduced for N157B (Wang & Gotthelf 1998) is an indication that the period at present is substantially longer than at birth. From the theory of pulsar driven SNRs (e.g. Bandiera, Pacini, & Salvati 1984), and assuming equipartition at injection between electrons and magnetic field, one finds the energy content and the pressure of the plerion in N157B: $W = 0.5\, k\dot{E}t = k\, 3.8 \times 10^{49}$ erg, $p = k\, 6.0 \times 10^{-9}$ dyne cm^{-2}. The form factor k depends on the history of the system, and for a braked pulsar is a factor of several. This pressure is larger than the central pressure of a Sedov bubble with the parameters appropriate to N157B, $p \sim 2 \times 10^{-9}$ dyne cm^{-2}, unless the ISM is made of "cloudlets" according to the scenario of White & Long (1991): the cloudlets evaporate behind the shock, and raise the density near the center of the remnant. In this way also the central pressure may be raised, by even more than an order of magnitude. An independent clue in favour of a clumped medium comes from the kinematics of the pattern of H_α features, that is expanding with a typical velocity of only 200 km s^{-1} (Chu et al. 1992): these features are likely denser clouds, that have not been effectively accelerated by the SNR blast wave. We note in passing that the sound speed just outside the plerion is 3000 km s^{-1} in the Sedov case, while in the White & Long cases that we have considered is anyway comparable with the pulsar velocity (1000 km s^{-1} as suggested by Wang & Gotthelf 1998): thus a strong bow shock would never be generated.

The strong pressure which we infer implies a plerion magnetic field $B \sim 1 \times 10^{-3}$ G, and a synchrotron break frequency $\nu_b \sim 20$ GHz; a second intrinsic break must be present in order to match the X-ray data. Interpolation between the radio point (with a spectral index 0.15, Filipović et al. 1998) and our X-ray point provides the broad band spectrum of the plerion: the total luminosity is 8%$\dot{E}$, and the optical surface brightness 24.8 m_V arcsec^{-2}, including an absorption of $A_V = 1$; the detection of such weak brightnesses is further hampered by the diffuse nebular emission which covers the region, at the outskirts of 30 Doradus.

As for the emission of the pulsar, we stress the extreme hardness of the X-ray spectrum. If one were to extrapolate it to higher energies, a 100% efficiency (assuming a fan beam) would be reached at ~ 10 MeV. If instead one considers the measured fan beam efficiency of similar young pulsars, e.g. PSR 0531+21, PSR 0833–45, and PSR 1509–58, one finds values ranging between 0.1% and 1%; such values imply a break in the spectrum just above the MECS range, at a luminosity $L \approx 10^{36}$ erg s^{-1}. If above the break $L_\nu \nu$ remains approximately constant, in the EGRET range the new pulsar would contribute about 10% of the total LMC luminosity (Sreekumar et al. 1992). We recall that at 16 arcmin there is the other young pulsar–plerion association PSR 0540-69, and that it is not unreasonable that a few such sources could contribute a substantial fraction of the total LMC luminosity in the EGRET range.

We can guess the optical magnitude of the pulsar by scaling the Crab pulsar optical luminosity as if it was marginally synchrotron self absorbed (see e.g. Pacini & Salvati 1987); the magnetic field at the light cylinder radius is equal in the two sources, but the radiating surface here is a factor of four smaller, so that, including absorption, $m_V \sim 24.6$. Extrapolating the X-ray spectrum to the optical region is very likely meaningless, as it would be to extrapolate to low energies the soft γ-ray spectrum of the Vela pulsar: below the dominant γ-ray component, several different secondary components are present in the pulsed spectrum, each produced by a different mechanism, and the assumption of a "simple" spectral shape is seen to be true only in the Crab pulsar.

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