

Part 4

Optical Observations

A Sociological Study of the Optically Emitting Isolated Neutron Stars

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Abstract.

Although less than 1 % of all radio pulsars are detected at optical wavelengths, their optical emission can yield a wealth of information that is either very difficult or plainly impossible to obtain at other wavelengths.

1. Introduction

The sample of the optically emitting Isolated Neutron Stars (INS) is not a rapidly growing one. In spite of non negligible observational efforts, no new objects have been positively detected in the last few years. The last *new* identification dates back to 1997 when HST resolved the counterpart of PSR B1055-52 (Mignani et al., 1997).

Studying the optical behaviour of INSs is certainly a challenging task. There are neither routine nor serendipitous discovery such as in radio and, at least up to a point, in X-rays, where a numerous community has ample access to observing facilities.

At variance with radio and X-ray wavelengths, in the optical domain there are no instruments dedicated to the study of INS. Moreover, the tiny kernel left by a SN explosion is, by and large, not perceived as a potentially interesting object by the community of the optical astronomers.

2. INS Sociology

All astronomical objects score differently along the electromagnetic spectrum, but INSs seem to be a rather extreme case. Very prominent in the radio domain, they undergo a minimum in the optical while the rise again in X-rays, only to reach another maximum in high-energy gamma-rays.

Neutron stars are not glamorous optical emitters: they tend to be faint, point-like sources with flat spectra (when at all measured) and no lines. But these balls of iron, ideal for studying physics under extreme conditions, have fostered more Nobel prizes than any other celestial object. However, with their ultra-thin atmosphere, they are hardly considered stars any more. Lacking prominent lines, they defy the traditional tools of the optical trade and would rather require ad hoc, unconventional approaches to unveil their peculiarities such as, e.g. the behaviour of elongated atoms. Moreover, their study calls for the most powerful

optical telescopes, whose observing time is very much in demand for other hot topics in astronomy. Thus, Isolated Neutron Stars get, at best, few percent of the precious observing time of a big optical telescope, to be compared with a significant fraction of the observing time (if not the totality) of a radio one and a 10-20 % in X-rays. No wonder the family of X-ray emitting neutron stars is more numerous than that of the optical ones. (see e.g. Becker and Trümper, 1997)

Table 1 presents a summary of the data available on INs with an optical identification either secured on the basis of timing or proper motion (PM) or proposed on the basis of positional coincidence (Pos). The grand total remains 9 and recent efforts on PSR 1706-44 (Mignani et al, 1999) and on the newly discovered 16 msec pulsar, PSR 0537-6910 (Mignani et al, 2000), have not yet yielded positive identifications. Quite a lot of work went also into the timing of PSR0656+14 and Geminga (Shearer et al 1997,1998) but the low S/N of the ground based data has severely hampered the statistical significance of the results gathered so far.

Table 1. Summary of optical observations available for all the INs identified so far

<i>PULSAR</i>	<i>V mag</i>	<i>Timing</i>	<i>Pol</i>	<i>Photometry</i>	<i>ID</i>
CRAB	16.6	Ground, HST	Y	J to U,spectrum	Timing
PSR0540-69	22.4	Ground, HST	Y	I,R,V,B,U,spectrum	Timing
PSR1509-58	22.0	negative	(1)	R,V,B	Pos
VELA	23.6	Ground	-	R,V,B,U	Timing
GEMINGA	25.5	Ground? (2)	-	I,R,V,B,spectrum(3) 555,432,342,190	PM
PSR0656+14	25.1	Ground? (2)	-	I,R,V,B, 555,130L	Pos PM(4)
PSR1055-52	24.9		-	<i>342</i> (5)	Pos
PSR0950+08	27.1		-	<i>130L</i> (5)	Pos
PSR1929+10	25.7		-	<i>130L,342</i> (5)	Pos

- (1) see Wagner, these Proceedings
- (2) tentative results to be confirmed (Shearer et al., 1997,1998)
- (3) very low S/N
- (4) tentative result (Mignani et al, 1997) to be confirmed through HST
- (5) the magnitude of these objects refers to the filter in italic

The optical behaviour of INs is composite, ranging from non-thermal emission for the younger objects (Crab, PSR 0540-69, Vela and , possibly, PSR 1509-58), to mostly thermal, for the remaining, older, ones. Caraveo (1998) and Mignani (1998) have comprehensively reviewed the subject.

Now we want to tackle the problem from a different point of view : sociology vs. physics and astronomy.

Table 1 shows that the optically identified NSs are few and generally faint. Are

these unfavourable characteristics enough to explain the very limited interest (or lack thereof) enjoyed by INS in the optical domain?

2.1. Does the appeal of a class of celestial sources depend upon their number?

High energy gamma-ray astronomy offers an interesting example. While the bona fide NSs detected as gamma-ray sources are seven (Thompson et al, 1997), the high energy Astronomy community considers neutron stars amongst the most interesting objects in the sky and finds it perfectly sound to devote quite a lot of observing time (and effort) to their quest.

A different example, in the optical domain, could be that of gravitational lensing systems, which attracted, quite correctly, an enormous interest when numbering in the few. The same is true also for the MACHO events.

2.2. ...or their brightness?

The sky is full of faint targets which get their share of astronomical attention, irrespective of their consistency as a class. In fact, ever since Galileo, in astronomy the faintest objects, the ones at the limits of every telescope, are always the newest and most exciting.

Optically identified INSSs are comparable both in number and in brightness to the optically identified GRBs, to mention a very recent hot topic. However, GRBs do have lines and thus the classical astronomical tools can be immediately applied to them, making it worthwhile to obtain spectra of 26 mv objects.

An inspection to Table 1 shows that faintness is not even a limitation for neutron stars. The best studied neutron star is certainly Geminga, which is also one of the very faintest, while comparatively little has been done on the Crab, by far the brightest NS, and the only accessible also to small telescopes.

3. The brightest and the dimmest

Here we shall use Crab and Geminga as test cases to show that the understanding of a NS behaviour depends more on the interest it arises in the community than on anything else.

3.1. Crab

Soon after the discovery of the pulsating star, a rough evaluation of its spectrum, proper motion and secular decrease were announced (see Nasuti et al, 1996 for a complete list of the references). The proper motion was eventually nailed down in 1977 (Wyckoff and Murray, 1977) but nothing was done to obtain a decent spectrum of an easy target nor to better assess its secular decrease.

While the Crab was extensively, and wrongly, used as a textbook example of the multiwavelength behaviour of INSSs, two signatures of the emitting mechanism(s), namely the pulsar spectrum and the decrease of its total brightness, were totally neglected, in spite of their potential interest for the understanding of the physics of the Crab pulsar. A reasonable spectrum was eventually obtained by Nasuti et al.(1996), showing a real flat power law continuum. Does this measurement exhaust the interest in the spectral behaviour of the Crab?

Crab is certainly the only NS bright enough to allow a higher resolution spectral study, with the aim of looking for something unique to the special physics of the pulsar and its surroundings.

On the contrary, obtaining high resolution pictures of the Crab Nebula and its pulsar is a rewarding exercise. This led to a series of HST pictures which have been recently used also to measure anew the pulsar proper motion (Caraveo and Mignani, 1999), suggesting a possible link between the pulsar proper motion and the X-ray jet structure. While the study of the interaction of the pulsar with the nearby medium has been extensively carried out, the precise photometry of the pulsar was never pursued. This has left the pulsar secular decrease as an open issue of the physics of the Crab (see Nasuti et al, 1996 for a complete discussion).

3.2. Geminga

The long chase for Geminga has been reviewed by Bignami and Caraveo (1996 and references therein) from its discovery, back in 1973 by NASA's SAS II, to the HST era. The milestones in the Geminga chase have been

-1981: confirmation and positioning by COS-B

-1983: discovery of a possible X-ray counterpart by the Einstein Observatory

-1987: pinpointing of its possible optical counterpart, dubbed G"

-1992: discovery of the 237 msec periodicity in X-rays, followed by similar results in the γ -ray domain, thus linking the X and γ -ray sources (ROSAT and EGRET)

-1993: measurement of the proper motion of G", thus proving its INS origin

-1996: improvement of the γ -ray light curve when taking into account the proper motion (Mattox et al.1996), thus linking G" to the source of γ -rays.

After the HST first refurbishment mission, in 1993, Geminga has been extensively imaged: first, to measure the source parallactic displacement (Caraveo et al. 1996), then to collect multiband photometry data. These HST observations, confirming and refining difficult measurements with ground-based instruments, have resulted in the spectral distribution of Fig.1(Mignani et al, 1998). A broad feature, centered at $\lambda = 5998\text{\AA}$ and with a width of $1,300\text{\AA}$, appears superimposed to the Rayleigh-Jeans continuum, as extrapolated from the soft X-rays.

If interpreted as an ion-cyclotron emission, this implies, for a pure H atmosphere a B field of $3.8 \cdot 10^{11}G$ (or $7.6 \cdot 10^{11}G$ in the case of He, see Jacchia et al, 1999) not too far from to the value of $1.5 \cdot 10^{12}$ obtained, theoretically, using Geminga's period and period derivative.

This is the first time that the magnetic field of an INS is directly measured.

Moreover, the phenomenology of the source at high energies has been considerably enriched, owing to the very precise positioning of the optical counterpart. The possibility to link HST data to the Hipparcos reference frame yielded the position of Geminga to an accuracy of 0.040 arcsec, a value unheard of for the optical position of a pulsar, or of any object this faint (Caraveo et al, 1998). This positional accuracy has allowed to phase together data collected over more than 20 years by SAS-2, COS-B and EGRET (Mattox et al, 1998). The many "firsts" of Geminga have been summarized by Bignami (1998).

Quite surprisingly, some of the key parameters of Geminga are now known with an accuracy better than that available for the Crab pulsar. This is due in part

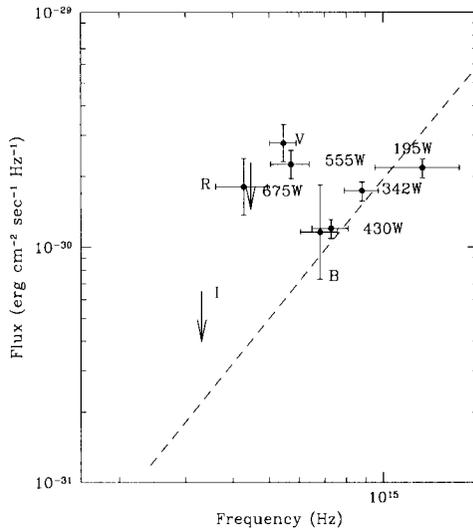


Figure 1. Multiband photometry of Geminga. Three digits identify WFPC2/FOC imaging filters. The dashed line represents the optical extrapolation of the blackbody best-fitting the ROSAT data. For the best fitting temperature of $5.77 \cdot 10^5 K$, and the measured distance of 157 pc, the emitting radius is $R = 10 km$.

to the remarkable stability of this object, which rendered possible to phase together such a long time span of γ -ray data, in part to the continuous attention this object has been receiving by the astronomical community at large.

3.3. Geminga-like sources

The identification of Geminga as a radio quiet INS broadened considerably the framework of the multiwavelengths study of NSs, establishing a promising yet elusive template: the Geminga-like objects. A Geminga-like source should be bright in γ ray, conspicuous in X-rays, faint in the optical, null in radio. How many Gemingas are hidden in the third EGRET catalogue (Hartman et al., 1999)? The only way to tell is to start a chase on promising sources, possibly at middle galactic latitudes, to avoid far away objects, preferably in non crowded regions. Imaging X-ray instruments, good resolution and high throughput are mandatory to play the game with a reasonable efficiency. The ESA XMM telescope, with its EPIC cameras, could play a significant role on this, as Einstein did for Geminga, 20 years ago.

Caraveo, Bignami and Trümper (1997) have further elaborated on this idea applying the template to unidentified X-ray sources and recognizing a handful of radio quiet INS candidates.

Once again the numbers are small, but they are going to grow rapidly. On XMM, EPIC will certainly provide plenty of serendipitous sources awaiting an identification.

4. Making Neutron Stars Optically Appealing

So far, the studies of the optical behaviour of NS have been carried out mostly by "amateur" optical astronomers. Indeed, those who develop a taste for the optical observations of Isolated Neutron Stars usually stumble into optical astronomy as a part of their multiwavelength approach aimed at the understanding of these fascinating objects.

Will it be possible to render the topic more appealing to the optical community, showing that NS are not just curious objects?

Will the optical Time Allocation Committees become more generous and invest observing time on the subject?

Will the community be able (or willing) to develop the needed tools?

Instruments devoted to timing are, of course, important, but timing, is just but one aspect of a multi-facet problem. We have to apply all the tools of classical optical astronomy and possibly develop new ones. The case of Geminga shows that endurance pays but the process needs to be accelerated.

References

- Becker, W. & Trümper, J. 1997 *A&A*, 326, 682
 Bignami, G.F. & Caraveo, P.A. 1996 *ARA&A*, 34, 331
 Bignami, G.F. 1998 *Advances in Space Research*, 21, 243
 Caraveo, P.A. et al. 1996 *ApJ*, 461, L91
 Caraveo, P.A., Bignami, G.F. & Trümper 1997
 Caraveo, P.A. et al. 1998 *A&A*, 329, L1
 Caraveo, P.A. 1998 *Advances in Space Research*, 21, 187
 Caraveo, P.A. & Mignani, R. 1999, *A&A*, 344, 367
 Hartman, R.C. et al. 1999 *ApJS*, 123, 79
 Jacchia A. et al. 1999 *A&A*, 347, 494
 Mattox, J.R., Halpern J.P. & Caraveo, P.A. *A&AS*, 120C, 77
 Mattox, J.R., Halpern J.P. & Caraveo, P.A. *ApJ*, 493, 891
 Mignani, R., Caraveo, P.A. & Bignami, G.F. 1997a, *ApJ*, 474, L51
 Mignani, R., Caraveo, P.A. & Bignami, G.F. 1997b, *The Messenger*, 87, 43
 Mignani, R., Caraveo, P.A. & Bignami, G.F. 1998, *A&A*, 332, L37
 Mignani, R. 1998, in "Neutron Stars and Pulsars: Thirty Years after the Discovery" Eds. N. Shibasaki et al, Universal Academic Press 335
 Mignani, R., Caraveo, P.A. & Bignami, G.F. 1999, *A&A*, 343, L5
 Mignani, R. et al 2000, *A&A*, in press
 Nasuti F.P. et al 1996, *A&A*, 314, 849
 Shearer A. et al. 1997, *ApJ*, 487, L181
 Shearer A. et al. 1998, *A&A*, 335, L21
 Thompson, D.J. et al. 1997 *Proc. of the Fourth Compton Symposium*, eds. Dermer C.D. et al. *AIP Conference Proceedings*, 410, 39
 Wyckoff, S. & Murray, C.A. 1977, *MNRAS*, 180, 717