Pulsar Astronomy: the HST Contribution

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Abstract

HST observations have contributed significantly to our knowledge on the behaviour of Isolated Neutron Stars (INSs) as optical emitters. First, HST has been instrumental both to discover new optical counterparts (PSR B1055-52, PSR B1929+10, PSR B0950+08) and to confirm proposed identifications (PSR B0656+14). Second, HST multicolor photometry provided useful information to characterize the optical emission mechanism(s) at work in middle-aged INSs like PSR B0656+14 and Geminga. Last, but not least, the superior angular resolution of the HST allowed both to perform a very accurate morphological study of the plerionic environments of young pulsars (e.g. the Crab and PSR B0540-69) and to perform very accurate astrometric measurements yielding proper motions (Crab, Vela, Geminga, PSR B0656+14) and parallaxes (Geminga).

1 Introduction

Although conspicuous INSs such as the Crab and Vela pulsars have been observed from the very beginning of the mission, HST started to play a key role on the study of the optical behaviour of these faint targets after the first refurbishing mission in 1993. The study did not proceed systematically, e.g. from the brighter to the dimmer, but rather following a random walk dictated by the allocation of observing time. Table 1 lists all the INSs (be they bona fide pulsars or radio-silent neutron stars) observed so far by the HST.

Although their number is limited, the objects in Table 1 sample 10 magnitudes in brightness and 4 decades in age, going from the youngest pulsars, such as the Crab and PSR B0540-69, to rather old ones, such as PSR B0950+08.

All INSs, but the Crab, are faint. All challenging, sometimes plainly impossible to observe from the ground. This was the case of PSR B1055-52 (Mignani et al. 1997\textsuperscript{7}) which, together with PSR B1929+10 and PSR B0950+08 (Pavlov et al. 1996\textsuperscript{10}) have been seen only with the HST using the FOC and the U filter. To the score of HST identifications we can add the INS candidate RXJ 1856-3754 (Walter & Matthews 1997\textsuperscript{14}).

2 The Data

Over the years, HST has collected light curves, for the Crab (Percival et al. 1993\textsuperscript{13}) and PSR B0540-69 (Boyd et al. 1995\textsuperscript{8}), spectra, for the same two objects (Gull et al. 1998\textsuperscript{11}; Hill et al. 1997\textsuperscript{5}), and images in different filters for all of them. The major results obtained by HST in pulsar astronomy have been reviewed by Mignani et al. (2000)\textsuperscript{[8]}. The observational efforts pursued by different groups with the imaging instruments on board HST are summarized in Table 2, where, for sake of clarity, the spectral coverage provided by HST has been roughly divided in two infrared channels (IR and I), four optical ones (R,V,B,U)- plus narrow bands (NB)- and one ultraviolet. In Table 2, NICMOS, WFPC2, and FOC observations are indicated. If an observation has been done more than once, the number in parenthesis gives the number of repetitions.

Table 2 shows quite eloquently that not all the entries in Table 1 received the same amount of observing time: it is worth noticing that, apart from the "dancing Crab", the objects with the highest number of observations is the rather dim Geminga, followed by PSR B0656+14, to show that objects fainter than V≈25 were not discriminated in this study. The amount of information contained in this comprehensive list has been used:

- to measure pulsars’ proper motions and parallactic displacements,
- to study plerion phenomenology
- to assess the spectral distribution of objects too faint for spectroscopy

The major achievements are summarized in the next sections.
### Table 1: \( \dagger \) determined from HST parallax; \( \ddagger \) determined from radio parallax. Isolated Neutron Stars observed so far by the HST. Two more objects (PSR B1509-58 and RXJ0720-3125) with a proposed optical ID have been studied from the ground only. The table lists the neutron stars' ID (first column), their spin-down age (column two), their rotational energy loss in erg/s (column three), their nominal radio distance in kpc (column four) and their magnitude in the V band, unless otherwise indicated (column five). Horizontal lines separate decades of pulsar spin-down age.

| ID       | Log(yr) | Log(dE/dt) | D(kpc) | mag |
|----------|---------|------------|--------|-----|
| Crab     | 3.1     | 38.6       | 2.0    | 16.6|
| B0540-69 | 3.2     | 38.2       | 55     | 22.5|
| Vela     | 4.1     | 36.8       | 0.5    | 23.6|
| B0656+14 | 5.0     | 34.6       | 0.76   | 25.0|
| Geminga  | 5.5     | 34.5       | 0.16(\dagger) | 25.5|
| B1055-52 | 5.7     | 34.5       | 1.5    | 24.9(U) |
| B1929+10 | 6.5     | 33.6       | 0.17(\ddagger) | 25.7(U) |
| B0950+08 | 7.2     | 32.7       | 0.28(\ddagger) | 27.1(U) |

### Radio-silent INSs

| RXJ 1856-3754 |
|---------------|
| \(< 0.13\)    |
| 25.6          |

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### Table 2: Summary of the multicolor photometry of INSs obtained by the HST. Objects are separated as in Table 1. \emph{Italic} indicates the pulsars first observed with the HST and the detections wavebands.

| ID       | IR | I   | R   | V   | B   | U   | UV  | NB          |
|----------|----|-----|-----|-----|-----|-----|-----|-------------|
| Crab     |    | WFPC2 |     |     |     |     |     | 547M (several) |
| B0540-69 |    | WFPC2 |     |     |     |     |     | 656N, 658N |
| Vela     |    | NICMOS | WFPC2 |     | FOC |     |     | FOC         |
| B0656+14 |    | NICMOS | WFPC2 | FOC | FOC |     |     | FOC         |
| Geminga  |    | NICMOS | WFPC2 | FOC | FOC |     |     | FOC         |
| B1055-52 |    | NICMOS | WFPC2(4) |     |     |     |     | FOC         |
| B1929+10 |    |       | FOC |     |     |     |     | FOC         |
| B0950+08 |    |       |     |     |     |     |     | FOC         |
| RXJ 1856-3754 | | WFPC2(2) | WFPC2 | WFPC2(2) |     |     |     |             |

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**Figure 1:** Optical flux distribution of PSRB0656+14 (left) and Geminga (right) as obtained (see Koptsevich et al. 2000) from the combination of ground-based and HST photometry (three digits labels). While the two objects belong to the same class of middle-aged pulsars with similar energetics, their optical properties appear different. Dotted lines represent the extrapolation of the soft X-ray black-body emission measured by ROSAT.
3 High Resolution Imaging

3.1 INS astrometry.

For all the pulsars observed more than once, namely the Crab, Vela, PSR B0656+14 and Geminga, a proper motion has been measured, yielding also new and independent measurements of the objects’ transverse velocities. This topic is reviewed in these proceedings by Mignani et al. Sometimes, the accurate determination of the proper motion has been a by-product of a sequence of observations aimed at the measurement of the object’s parallactic displacement and hence its distance (see also De Luca et al., these proceedings). This has been done for Geminga (Caraveo et al. 1996[3]) and is currently underway for the Vela pulsar. Determining the distance to a pulsar allows the assessment of the absolute optical luminosity which, compared with the overall energy loss dE/dt, yields the efficiency to convert rotational energy loss into optical emission, an important parameter in pulsar modelling.

3.2 Morphology studies

HST imaging of Crab, Vela and PSR B0540-69 allows one to trace the relativistic pulsar wind and to better study the plerion phenomenology. Moreover, with the proper motion vectors clearly aligned with the axes of symmetry of the Crab and Vela plerions, proper motions, or rather the mechanisms responsible for them, seem to play a role in shaping the inner remnants (see Mignani et al., these proceedings, and Pavlov et al. 2000[12]). Comparisons between HST frames and recently obtained Chandra high resolution images open new avenues to study the multiwavelength behaviour of young energetic plerions. The case of PSR B0540-69 is discussed in an accompanying paper by Caraveo et al.

3.3 Multicolor Imaging

HST multicolor imaging appears to be the next best thing to a spectrum for studying the spectral shape of faint objects and discriminating between thermal emission from the INS surface and non thermal magnetospheric one.

Two classical examples are

- PSR B0656+14, where Pavlov et al. (1997)[1] have shown a composite spectral shape featuring both a thermal and non-thermal components (see Fig.1, left panel)

- Geminga, for which Bignami et al. (1996)[4] and Mignani et al. (1998)[5] have provided the evidence of a cyclotron spectral feature on top of a thermal continuum (see Fig.1, right panel). If correct, the cyclotron identification (discussed also by Jacchia et al. 1999[6]) of the feature would provide the first in situ measurement of the magnetic field of an isolated neutron star.

4 Conclusions.

All in all, the study of INSs, in spite of their faintness, has yielded a wealth of interesting results definitely worth the time and efforts devoted to them. New identifications have been secured while new insights have been achieved for pulsars already identified.

Of course, a lot remains to be done. Young pulsars are definitely promising targets, thus we should concentrate on newly discovered young objects, such as the 16 msec one in the LMC. Here the timing capability of the STIS, so far poorly exploited, should be fully used.

Radio quiet candidate neutron stars are also promising, although admittedly demanding, targets.

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