Gamma-ray bursts, evolution of massive stars and star formation at high redshifts
ASI Conference Series, 2012, Vol. 5, pp 141 – 148
Edited by S. B. Pandey, V. V. Sokolov and Yu A. Shchekinov

Observational manifestations of isolated neutron stars and their studies at the 6m telescope of SAO RAS

V. N. Komarova[1*], T. A. Fatkhullin[1], V. G. Kurt[2] and Yu. A. Shibanov[3]
[1]*Special Astrophysical Observatory RAS, Nizhnij Arkhyz, Russia*
[2]*Astro Space Center, Lebedev Physical Institute RAS, Moscow, Russia*
[3]*Ioffe Physical Technical Institute RAS, St.-Petesburg, Russia*

Abstract. Observational manifestations of isolated neutron stars and studies of these objects at the 6 m telescope are discussed. The results for PSR B0656+14, Geminga, PSR B0950+08, AXP 4U 0142+61 are presented.

Keywords : pulsars: individual: PSR B0656+14, Geminga, PSR B0950+08, 4U 0142+61, pulsar: SGR, stars: individual: RBS 1774, stars: neutron

1. Introduction

Since the discovery of GRBs their enigmatic nature prompted scientists to think of exotic objects as the GRBs' progenitors, neutron stars (NSs) being one of them. Now it is widely adopted that at least the GRBs of long duration are of extragalactic origin and have nothing in common with NSs of our Galaxy. Nevertheless the latter are still under investigation. The extreme properties of NSs (gravity, density, magnetic field) make them excellent objects to see how physics operates in unusual environments. As a NS is born in a massive star collapse it is a successor of the event which has been probably accompanied by a GRB. Thus studying the diversity of NSs may be helpful in understanding the GRB phenomenon.

Observational manifestations of NSs, being defined by the extraordinary properties of NS interior matter and physical characteristics of these objects vary greatly. Multi-wavelength observations are desired and crucial to define the origin of emission in different spectral bands; to estimate NS surface temperature; to check cooling theories; to get constraints on chemical composition and EOS; to shed light on the evolution of NSs.

*email: vkom@sao.ru

Table 1. RPPs, detected in the optical range.

Name	Ident.*	log τ yrs	d kpc	log$\dot{E}$ erg s^{-1}	B	Comments
Crab	T	3.10	2	38.65	15.25	PM, O,Sp,Pol
B1509-58	Pos,Pol	3.19	4.4	37.25	23.8	Pol
B0540-69	Pos,T	3.22	50	38.17	22.0	O, Sp, Pol
Vela	T	4.05	0.29	36.84	23.7	PM, O, Pol
B0656+14	Pos,T	5.05	0.5	34.58	25.15	PM, O, Sp
Geminga	Pos,PM	5.53	0.15	34.51	25.7	PM, O, Sp
B1055-52	Pos	5.73	1.3	34.48		U = 24.9
B1929+10	Pos	6.49	0.17	33.59	<26.2	
B0950+08	Pos	7.24	0.29	32.75	27.07	
J0108-1431	Pos	8.3	0.2			U = 26.4
J0437-4715	Pos	9.2	0.14			

* Identification of RPPs by positional coincidence (Pos), brightness variations with the pulsar period (T), polarized emission (Pol), proper motion (PM).
Comments: measured proper motion (PM), optical counterpart (O), spectral (Sp), polarimetric (Pol) observations.

Section 2 describes the variety of Isolated Neutron Stars (INSs) emphasizing on those detected in the optical domain. Most of the NSs are very faint objects and the main method of study is multicolor photometry. The results of our studies are presented in section 3.

2. The NSs variety

2.1 RPPs – Rotation-Powered Pulsars

RPPs are the most numerous class of INSs with stable radio emission due to the loss of rotational energy. They were the first to be detected and thus are the most studied. Some representatives are identified in all spectral bands. The most prominent one is the Crab nebula pulsar.

Table 1 provides some parameters of the RPPs detected in the optical domain. Along with multicolor photometric there are timing, spectral and polarimetric observations for some of the RPPs. Those studied at the 6 m telescope are given in bold.

2.2 AXPs – Anomalous X-ray Pulsars

AXPs are apparently young, of ~3-100 kyr age, NSs with strong X-ray pulsations that show a relatively stable period evolution with $\dot{P} \sim (0.05 - 4) \cdot 10^{-11} ss^{-1}$. In contrast

Table 2. Magnetars, detected in the optical range*.

Name	Age (log τ) yrs	Magnitude	d kpc	Photometry	Comments
1E 1547.0-5408	3.14	18.5	9	nIR	
SGR 1806-20	3.14	20.1	15.1	nIR	
1E 1048.1-5937	3.63	21.3	3.0	O, nIR	Pol, T
XTE J1810-197	3.75	20.8	4.0	nIR	
SGR 0501+451	4.10	19.1	5	O, nIR	
4U 0142+61	4.84	20.1	1.73	O, nIR,mIR	T
1E 2259+586	5.34	21.7	3.0	nIR,mIR	

* from Mignani (2009)

to RPPs they are not powered by rotation. The spectra are best fitted by BB+PL models: $T_{bb} \sim$ 4-7MK; $\alpha \sim$ 2.5-4; $L_x \sim 10^{34} - 10^{36}$erg/s; $B \sim 10^{14} - 10^{16}$G (derived via magneto-dipole braking). Optical counterparts are detected mostly in nIR. Some details on magnetars, detected in the optical range are given in Table 2. 4U 0142+61 has been studied at the 6 m telescope.

2.3 SGRs – Soft Gamma-ray Repeaters

SGRs have spin periods in the interval of 5-8 s with $\dot{P} \sim 10^{-10}$ss^{-1}. They appear to be associated with young (~1-10 kyr) NSs in SNRs. Quiescent spectra can be fitted by BB+PL model (T_{bb} ~5 MK, R~1 km; α=1-4); $L_x \sim 10^{34} - 10^{36}$erg/s. The energy released during the most powerful bursts is enormous ($> 10^{44}$erg for the outburst of SGR 1900+14 on August 27, 1998).

2.4 SGRs vs AXPs

Their periods are in a narrow range of 5-12 s, substantially exceeding typical periods of radio pulsars. Both types of the objects are suggested to be “magnetars”, i.e. NSs with super-strong magnetic fields. But they are strongly different in their γ-ray activity: no γ-ray emission has been detected from AXPs; while SGRs emit occasional γ-ray bursts of enormous energy, up to $10^{42} - 10^{44}$ erg.

2.5 X-ray-Dim Isolated Neutron stars – XDINs (e.g. RX J1856.5-3754)

XDINs are not associated with SNRs, they are truly isolated. There is no evidence for radio pulsations or accretion. Temperatures are lower than those in SNRs. Four of them have been detected via their periods. Very soft X-ray spectra are described

Table 3. XDINSs, detected in optical range*.

Name	Age, logτ yrs	Magnitude	d kpc	Photometry	Comments
RX J1308.6+2127	6.11	28.6^R	<1	O	
RX J0720.4-3125	6.27	26.7	0.30	nUV, O	
RX J1856.5-3754	6.60	25.7	0.14	nUV, O	Sp
RX J1605.3+3249		26.8^R	<1	O	
RBS 1774		27.2^B	0.34	O	
RX J0420.0-5022		27.5^B	0.35	O	

* from Mignani (2009)

by a blackbody (50-120 eV) with no apparent magneto-spheric contribution. High X-ray to optical ratio ($\sim 10^3 - 10^5$) is typical. Relying on low N_H derived from X-ray spectrum, they are nearby objects. Some details on XDINs, detected in the optical range are given in Table 3. The entry in bold has been studied at the 6 m telescope.

2.6 Compact Central Objects – CCOs (e.g. in CasA)

The main properties of CCOs in brief are as follows:

- unusual X-ray spectra (supposedly BB+PL);
- very high effective temperatures (~MK);
- high X-ray to optical ratio;
- no evidence for pulsations (maybe with the exception of the RCW 103 case);
- no signs of a wind as seen in young rotation-powered pulsars;
- no evidence for companion star that could be powering the X-ray emission via accretion;
- very low magnetic field.

There are also some other subclasses of NSs like Radio-Quiet INSs (RQINSs) or newly discovered Rotating RAdio Transients (RRATs).

3. Results

3.1 RPPs in optical

- PSR B0656+14
  The pulsar was studied at the 6 m telescope Koptsevich et al. (2001). The

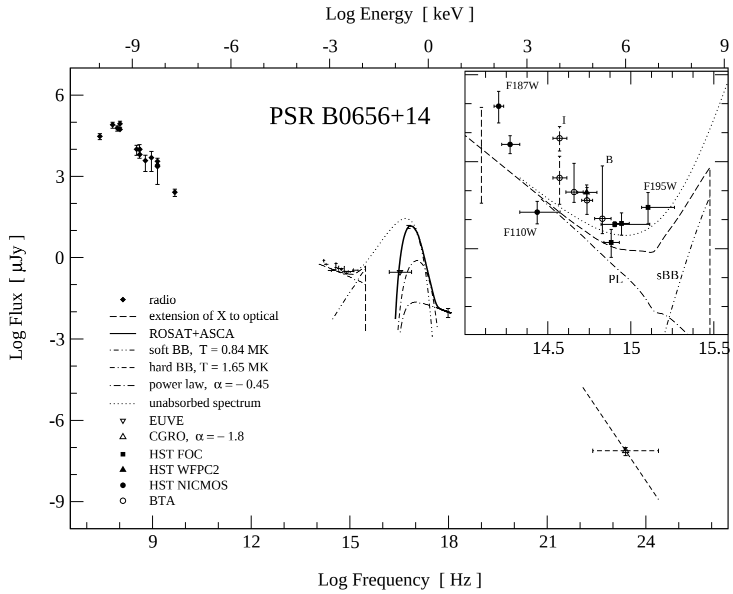

Figure 1. The multi-wavelength spectrum of PSR B0656+14.

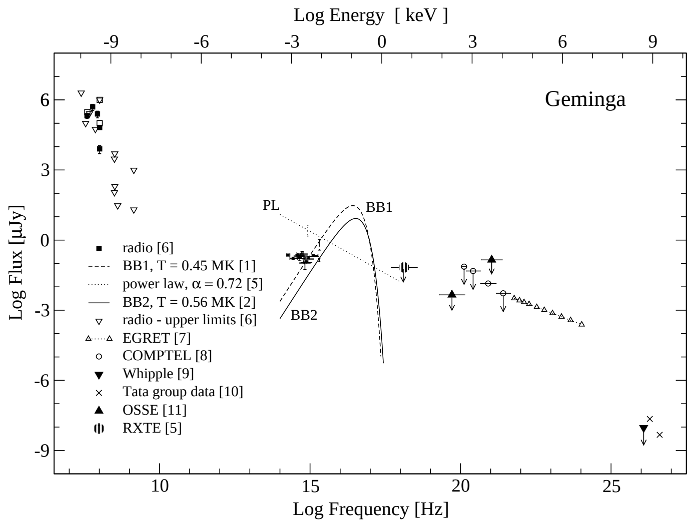

Figure 2. Geminga's multi-wavelength spectrum.

magnitudes obtained were later confirmed in observations at the Subaru telescope with higher S/N ratio: B=25.27±0.07, R_c=24.65±0.08, I_c=24.52±0.13 Shibanov et al. (2006). The UVOIR spectrum of the pulsar is a combination of thermal and non-thermal components (see Fig.1). It has a non-monotonous

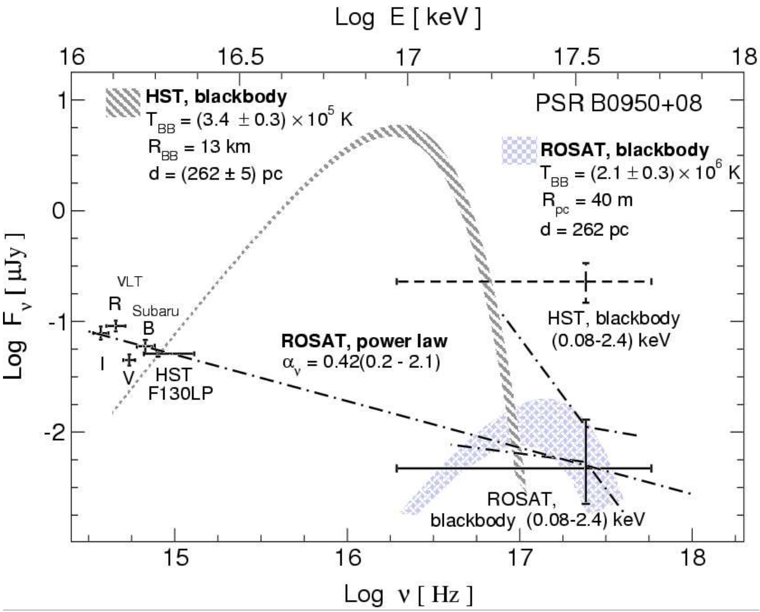

Figure 3. The multi-wavelength spectrum of PSR B0950+08.

behavior, with the excess flux in the red and IR domain. The multi-wavelength spectrum of PSR B0656+14 is given in Fig. 1.

- PSR J0633+1746 (Geminga)
  It was detected in the I-band Kurt et al. (2000, 2001). The identification was confirmed in observations at the Subaru telescope (Shibanov et al. 2006). The spectrum of Geminga's optical emission differs from the thermal one predicted by theory, has non-monotonic behavior and resembles that of PSR B0656+14 (see Fig. 2).

- PSR B0950+08
  A possible optical counterpart to the old pulsar B0950+08 was found in observations at the 6 m telescope (Kurt et al. 2000). In subsequent observations at the Subaru telescope (in B) (Zharikov et al. 2002) and VLT ESO in the UBVRI bands a faint object (e.g. B = 27.07 ± 0.16) was detected (Zharikov et al. 2004). Our studies showed that the optical counterpart to PSR B0950+08 has a flat spectrum in the wide-wavelength range $\lambda\lambda \sim 2300 - 5000$ Å and at least in the B-band it is of non-thermal nature which is unusual for rather an old pulsar (see Table 1). The multi-wavelength spectrum of PSR B0950+08 is presented in Fig.3.

3.2 AXP 4U 0142+61

The observations of the field of anomalous X-ray pulsar 4U 0142+61 in November, 2003 yielded the detection of a faint object within the Chandra error circle (Patel et al. 2003) in the R and I bands. The estimates obtained R_c=25.05±0.15 and I_c=23.9±0.45 are in agreement with those published by Hulleman et al. 2004 within the errors. It does not rule out the variability of the optical flux found earlier in IR.

3.3 RQINSs in optical: RBS1774

Two faint objects have been found in the circle of the RBS 1774 position from XMM-Newton observations (Zane et al. 2005). The faintness (B $\sim 26^{\mathrm{m}}$) and their colors ((B-V) and (V-R) are about 0.6, 0.1, 0.5 and 0.3, accordingly) do not rule out that one of them can be an optical counterpart to this INS. Another candidate of magnitude B=27.4 has been proposed lately by (Zane et al. 2008).

3.4 SGR: SWIFT J195509+261406

In multi-wavelength observations of a puzzling source, SWIFT J195509+261406, in international collaboration we detected more than 40 flaring episodes in the optical band over a time span of three days, and a faint infrared flare 11days later, after which the source returned to quiescence. The radio observations confirm a Galactic nature and establish a lower distance limit of 3.7 kpc. We suggest that SWIFT J195509+261406 could be an isolated magnetar whose bursting activity has been detected at optical wavelengths, and for which the long-term X-ray emission is short-lived. In this case, a new manifestation of magnetar activity has been recorded and we can consider SWIFT J195509+261406 to be a link between the "persistent" soft γ-ray repeaters/anomalous X-ray pulsars and dim isolated neutron stars (Castro-Tirado et al. 2008).

Acknowledgments

We are grateful to the anonymous referee for his valuable comments and corrections.

References

Castro-Tirado A. J., de Ugarte Postigo A., Gorosabel J., et al., 2008, Nature, 455, 7212, 506
Hulleman F., van Kerkwijk M. H., Kulkarni S. R., 2004, A&A, 416, 1037
Koptsevich A. B., Pavlov G. G., Zharikov S. V., et al., 2001, A&A, 370, 1004
Kurt V. G., Komarova V. N., Fatkhullin T. A., et al., BSAO, 49, 5-13
Kurt V. G., Komarova V. N., Sokolov V. V., et al., 2001, BSAO, 51, 21
Mignani R. P., 2009, in Proc. Neutron Stars and Gamma-Ray Bursts: Recent Developments and Future Directions, arXiv:0908.1010
Patel S. K., Kouveliotou C., Woods P. M., et al., 2003, ApJ, 587, 367

Shibanov Y. A., Zharikov S. V., Komarova V. N., et al., 2006, 448, 313
Zane S., Cropper M., Turolla R., et al., 2005, ApJ, 627, 397
Zane S., Mignani R. P., Turolla R., et al., 2008, ApJ, 682, 487
Zharikov S. V., Shibanov Y. A., Koptsevich A. B., et al., A&A, 2002, 394, 633
Zharikov S. V., Shibanov Y. A., Mennickent R. E., A&A, 2004, 417, 1017