Part 5
High-Energy Observations

https://doi.org/10.1017/S025292110005987X Published online by Cambridge University Press

Pulsar Astronomy — 2000 and Beyond
ASP Conference Series, Vol. 202, 2000
M. Kramer, N. Wex, and R. Wielebinski, eds.

X-ray emission characteristics of pulsars and their nebulae

Werner Becker
Max-Planck-Institut für extraterrestrische Physik, Giessenbachstrasse 1, Postfach 1603, 85740 Garching, Germany

Abstract. Recent X-ray observatories like ROSAT, ASCA, RXTE, BeppoSAX and Chandra have achieved important progress in neutron star and pulsar astronomy. The identification of Geminga as a rotation-powered pulsar, the discovery of X-ray emission from millisecond pulsars and the identification of cooling neutron stars are only few of the fascinating results. In the following I will give a brief review on the X-ray emission properties of rotation-powered pulsars and their wind nebulae.

1. Emission properties

To get into the X-ray emission properties of the detected pulsars, we group the whole sample into five classes, according to their spin-down age $\tau = P/2\dot{P}$.

1.1. The Crab-like pulsars

It is well established that in the young *rotation-powered* pulsars with ages $\leq$ 2000 years magnetospheric emission dominates. In the case of the Crab pulsar, for example, at least $\sim 75\%$ of the total soft X-ray flux is magnetospheric emission characterized by a power-law spectrum and sharp pulses. Thermal cooling radiation from the Crab pulsar surface is buried by the intense emission from the pulsar's synchrotron nebula. An upper limit for the unpulsed flux within the 0.1-2.4 keV range, deduced from the DC level of the soft X-ray pulse profile, was taken by Becker & Aschenbach (1995) as an upper limit for the thermal flux from the young neutron star. Knowing the Crab pulsar's surface temperature allows a comparison with theoretical predications at an early time in the neutron star's thermal evolution. A temperature of less than 2×10^6 K (3σ) was found to be marginally consistent with standard cooling models.

The ROSAT HRI data taken from the Crab nebula have been used to improve our understanding of this object in many aspects. In a long term study of the Crab nebula using ROSAT HRI data, spanning a period of more than 6 years, Greiveldinger & Aschenbach (1999) have shown that the X-ray intensity of the synchrotron nebula varies on time scales of years by about 20%. The intensity variations are found to be confined to rather large ($\sim$ 25" $\times$ 25") and well defined regions in the torus and may point towards a decrease in the relativistic wind's bulk motion. Using the instruments aboard *Chandra* it will be easy to further investigate this long term variations. First images taken with the HETG aboard *Chandra* provided already spectacular details on the nebula structure, its torus and the jet-like feature associated with the pulsar-wind outflow. To demonstrate the recent progress in X-ray astronomy, images from the Crab pulsar and plerion as seen by Chandra's HETG and the ROSAT HRI are shown in Figure 1.

1.2. The Vela-type pulsars

Different from the Crab-like pulsars are rotation-powered pulsars in the age bracket $\sim 10^4 - 10^5$ years (e.g. the Vela-pulsar, PSR B1706-44, B1046-58, B1800-21, B1823-13, B1951+32 and J1105-6107). They exhibit strong steady emission from a pulsar-powered synchrotron nebula (mostly unresolved) combined with a small pulsed contribution of magnetospheric or thermal origin dominating the emission in the range $\sim 0.1 - 0.5$ keV (Becker & Trümper 1996). X-ray pulses are only detected for the Vela pulsar (Ögelman, Finley & Zimmerman 1993). The other Vela-type pulsars are more distant and suffer from photoelectric absorption which prevents the detection of their soft pulses in the presence of the dominant nebula emission. This interpretation is also true for PSR 1951+32 in CTB 80. A report of a $\sim 2\sigma$ signal by Safi-Harb, Ögelman & Finley (1995) could not be established in a deep ROSAT HRI observation and more recently by observations using the Rossi Timing explorer. The pulsed fraction upper limit deduced from the ROSAT HRI data is about 9%.

Apart from the Vela pulsar itself there is no spectral information for this sources below 0.5 keV, which means that their black-body component is invisible because of photoelectric absorption. The spatial structure of the Vela pulsar/nebula has been resolved recently with the ROSAT HRI (cf. Fig.1).

1.3. The cooling neutron stars

These are the three middle aged pulsars Geminga, PSR 0656+14 and 1055-52. The soft X-ray emission properties of these pulsars are characterized by a dichotomy, i.e. the spectra are best described by a two-component model in which the soft emission is represented by a black-body spectrum and the hard component either by a thermal spectrum or by a power-law. The existence of two spectral components is also confirmed by phase-resolved analysis. All three pulsars show a phase shift of $\sim 100°$ and a change in the pulsed fraction from $\sim 10 - 30\%$ below a transition point of $0.5 - 0.6$ keV, rising up to $\sim 20 - 65\%$ above. The X-ray pulse profiles for both the soft and the hard components are found to be sinusoidal.

The soft thermal emission is assigned to be cooling emission from the neutron star's surface. The modulation of this emission can be explained by non-uniformities in the surface temperature due to the presence of a strong magnetic field which gives rise to an anisotropic heat flow in the neutron star's outer layers. The radius of the emitting area obtained by using $R_{bb} = d/T^2\sqrt{f_{bol}/\sigma}$, in which f_{bol} and T denotes the fitted bolometric flux and temperature of the pulsar's soft component and σ the Stefan-Boltzmann constant, are found to be in the range $\sim 7 - 30$ km.

Based on ROSAT data, the hard spectral components of these pulsars can be interpreted as magnetospheric emission or thermal radiation from polar hot spots. Because of bandwidth limitations it is not possible to discriminate between these possibilities. But ASCA observations have shown recently that the hard component of Geminga is characterized by a power-law implying a magne-

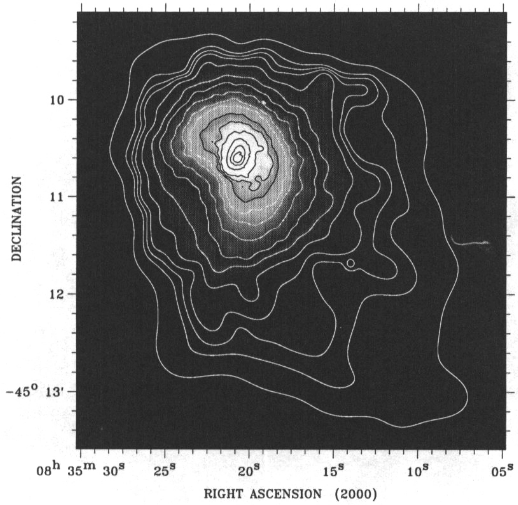

Figure 1. Vela pulsar and plerion as observed with the ROSAT HRI. All HRI data taken between May 1994 and June 1996 (corresponding to a total exposure time of 210 ksec) have been merged together to produce the image. The structure, shape and size of the nebula is different from what is observed from the Crab and PSR 1509-58. The nebula luminosity is 0.04% (0.1-2.4 keV) of the pulsar's spin-down energy whereas for the Crab nebula it is $\sim$ 5% and for the nebula around PSR 1509-58 it is $\sim$ 1% (in the same energy band).

tospheric origin (Halpern & Wang 1997). Similar results have been reported for 1055-52 (Wang et al. 1998) and PSR 0656+14 (Greiveldinger et al. 1996), although in the latter case the limited photon statistics prevents a clear distinction between a thermal and non-thermal origin of the harder emission.

The existence of X-ray bright pulsar-wind nebula as a common feature surrounding rotation-powered pulsars was recently reported on the basis of ASCA observations (Kawai & Tamura 1996). Indeed, the ASCA data taken from PSR 0656+14, 1055-52 and Geminga (as well as from some more pulsars) show a faint diffuse and a somewhat clumpy emission around these pulsars, interpreted as a result of an interaction from a pulsar wind outflow with the surrounding interstellar matter (Kawai & Tamura 1996; Shibata et al. 1997). The ROSAT (and if available the BeppoSAX) data of these sources were re-analyzed recently by Becker et al. (1999) with the aim to search for faint point sources, which – due to the wide ASCA point-spread function of about 3 arcmin (FWHM) – could result in such a pattern of diffuse emission and knots in the ASCA data. At least for Geminga, PSR 0656+14 and PSR 1055-52 faint X-ray counterparts where found in the ROSAT data which correspond well with the diffuse structure and knots seen in the ASCA data. Becker et al. (1999) therefore conclude

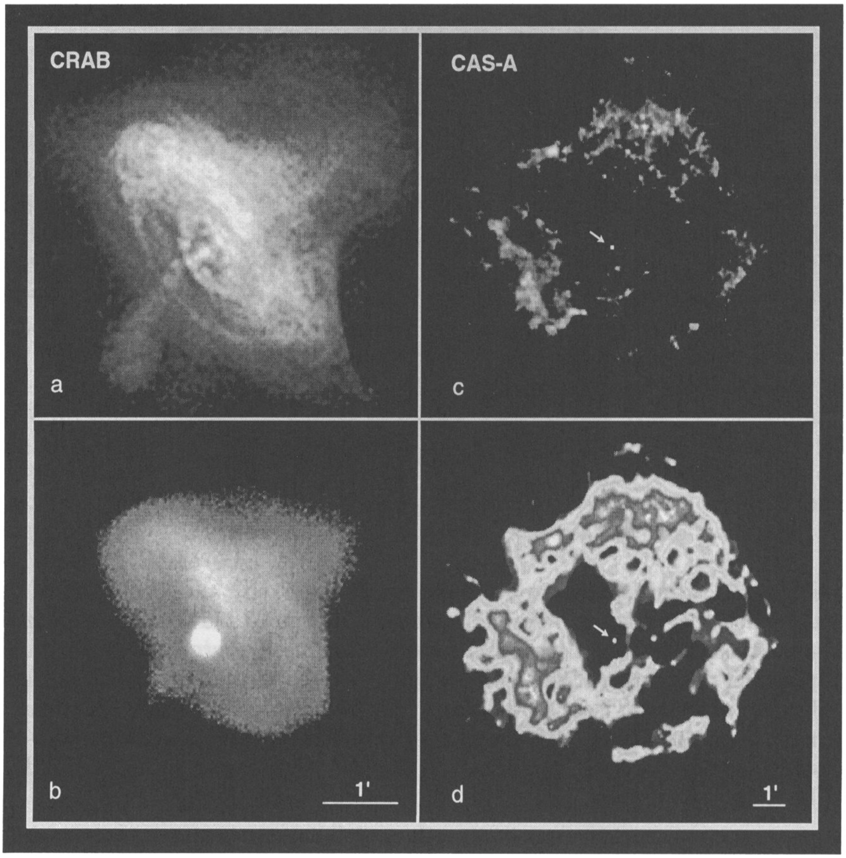

Figure 2. The Crab as observed with the HETG abord Chandra (**a.**) and the ROSAT HRI (**b.**). Image (**c.**) shows another recent discovery made by Chandra: the point source close to the geometrical center of CAS-A, a 320 year young supernova remnant. The corresponding ROSAT HRI image is shown in (**d.**). Although the central point source was already detected in deep ROSAT HRI observations, only the unprecedent high spatial resolution provided by Chandra allowed to identify the emission as being from a young neutron star or a black hole. Spectral analysis using the Chandra ACIS data shows that a power-law (non-thermal) spectrum implies a slope which is steeper and a luminosity which is lower than those found in other young (i.e. Crab-like) pulsars. Spectral fits using thermal spectra result in a too high temperature and a too small emitting area than expected for cooling radiation from a hot young neutron star. Assuming that the point source is a young neutron star and the emission is thermal and comes from the whole surface, an upper limit on the surface temperature is $\sim 2.5 \times 10^6$ K. A search for radio emission from the point source at 21 cm using the 100 meter dish at Effelsberg did not detected pulsed radio emission from the position of the X-ray point source. The problem in searching for faint pulsed radio emission from a young pulsar in CAS-A is that the supernova remnant itself is a very bright radio source, i.e. burying any faint emission from a young pulsar.

https://doi.org/10.1017/S025292110005987X Published online by Cambridge University Press

that the X-ray knots seen around these pulsars in the ASCA data are unlikely to be associated with the pulsars and are unrelated background objects.

1.4. Pulsars old and close in space

Besides the young pulsars and those whose surface cooling is visible in the X-ray wave band, X-ray emission is detected from three other pulsars: PSR B1929+10, B0950+08 and B0823+26. All are characterized by a spin-down age of $\sim 0.2 - 3 \times 10^7$ years and a close distance of $\sim 0.12 - 0.38$ kpc. Pulsed X-ray emission, however, could only be detected from PSR B1929+10 (Yancopoulos, Hamilton & Helfand 1994). Its X-ray pulse profile is very broad with a single pulse stretching across almost the entire phase cycle. Spectral information is only available for B1929+10. Its soft X-ray spectrum can be equally well fitted with a power-law of photon-index ~ 2 and a black-body spectrum. A faint synchrotron tail which is oriented along the pulsar's proper motion direction was found in the ROSAT PSPC data by Wang, Li & Begelman (1993).

1.5. The millisecond pulsars

ROSAT, with a significantly higher sensitivity compared with previous X-ray satellites allowed for the first time to detect X-ray emission from objects as faint as millisecond pulsars. However, although eleven of the 35 detected rotation-powered pulsars belong to the small group of millisecond pulsars, the origin of the detected X-ray emission for most of them is not yet known Six of the eleven ms-pulsars (PSR B1957+20, J1012+5307, B0751+18, J1744-1134, J1024-0719 and J0030+0451) are identified in X-rays only by their positional coincidence with the radio pulsar, and in view of the low number of detected counts do not provide much more than a rough flux estimate. These objects are so faint that the sensitivity of Chandra and XMM is needed to detect enough photons required for a detailed spectral and temporal study in the soft and hard band beyond 2 keV. More detailed results are found for the other five ms-pulsars which all provide important empirical information on the pulsar's X-ray emission mechanisms. A recent review on the X-ray emission properties of millisecond pulsars, which summarizes the current emission properties and observational status is given by Becker & Trümper (1999) and Becker (2001).

2. Summary

The current findings of the pulsar's emission properties show that young pulsars with ages of less than $\sim$ 2000 years appear Crab-like (i.e. bright synchrotron nebula, sharp X-ray pulses with high pulsed fraction) whereas $\sim 10^4 - 10^5$ year old pulsars resemble more the emission properties observed for the Vela pulsar (i.e. X-ray emission beyond 0.5 keV dominated by the emission from the pulsar-driven synchrotron nebula, soft pulses only observable from the Vela-pulsar). However, although these emission properties are found to fit very well for the rotation-powered pulsars (i.e. the radio pulsars) it is quit evident that they are not representative for the whole sample of young neutron stars which exist in our Galaxy. Topics which are discussed in the literature in respect to this are soft gamma-ray repeaters and anomalous X-ray pulsars (see Mereghetti 2000 for a recent review).

The middle aged pulsars (i.e. the cooling neutron stars) show emission properties which are found to be described by a dichotomy (i.e. two spectral components, soft component is of thermal origin and in agreement with being a relic of the stars heat content during its creation, hard component of non-thermal origin released from within the coo-rotating magnetosphere, transition point at about 0.5-0.6 keV). Pulsar wind nebulae as they have been proposed to exist by ASCA observations are found to be unresolved and unrelated background objects (Becker et al. 1999).

The X-ray emission observed from millisecond pulsars is likely to be dominated by non-thermal processes. This, at least, is observed for PSR 1821-24, PSR 1937+21 and PSR J0218+4232 for which power-law spectra have been measured by ASCA, RXTE or SAX. For the other millisecond pulsars the existing data do not allow to unambiguously identify the emission process. Two of the eleven detected millisecond pulsars are found to show diffuse extended X-ray emission: PSR 1821-24 in M28 and PSR J0218+4232. Whereas for PSR 1821-24 the extended emission possibly comes from unresolved globular cluster sources the faint diffuse emission found around PSR J0218+4232 might be plerionic.

References

Becker, W., Aschenbach, B. 1995, in *The Lives of Neutron Stars*, eds A. Alpar, U. Kilizóglu & J. van Paradijs, Kluwer Academic Publishers, p.47

Becker, W., Trümper, J. 1996, A&AS, 120, C69

Becker, W., Trümper, J. 1999, A&A, 341, 803

Becker, W., Kawai, N., Brinkmann, W., Mignani, R. 1999, A&A, 352, 532

Becker, W., 2001, in *X-ray Astronomy '99: Stellar Endpoints, AGN & the Diffuse X-ray Background*, eds N.White et al, to appear in Astrophysical Letters & Communications

Greiveldinger, C., Aschenbach, B. 1999, ApJ, 510, 305

Greiveldinger, C., Camerini, U., Markwardt, C.B., Ögelman, H., Safi-Harb, S., Finley, J.P., Tsuruta, S., Shibata, S., Sugawara, T., Sano, S., Tukahara, M. 1996, ApJ, 465, L35

Halpern, J.P., Wang, F.Y.-H. 1997, ApJ, 477, 905

Kawai, N., Tamura, K. 1996, in *IAU Colloquium 160*, eds S.Johnston, M.A.Walker and M.Bailes, p367

Kawai N., Saito Y. 1999, 3rd INTEGRAL Workshop "The Extreme Universe", Sept. 1998, Taormina, Italy, in press

Mereghetti, S. 2000, NATO ASI 1999, Kluwer Academic Publisher, in press, a preprint is available from *astro-ph/9911252*

Ögelman, H., Finley, J.P., Zimmerman, H.U. 1993, Nature, 361, 136

Safi-Harb, S., Ögelman, H., Finley, J.P. 1995, ApJ, 439, 722

Shibata S., Sugawara, T., Gunji, S. et al.: 1997, ApJ, 483, 843.

Wang F.Y.-H., Ruderman M., Halpern J.P., Zhu T. 1998, ApJ, 498, 373

Wang, Z.R., Li, Z.Y., Begelman, M.C. 1993, Nature, 364, 127

Yancopoulos, S., Hamilton, T.T., Helfand, D.J. 1994, ApJ, 429, 832