XMM-Observations of Pulsars: A study of thermal- vs. non-thermal emission

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ABSTRACT

Recent X-ray observatories like ROSAT and ASCA have achieved important progress in neutron star and pulsar astronomy. The identification of Geminga, 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 we will give a brief review on the X-ray emission properties of rotation-powered pulsars and outline briefly the prospects expected from a mission like XMM and AXAF for neutron star astronomy.

1. Why are neutron stars targets for X-ray observatories ?

Neutron stars are among the most fascinating astronomical objects in the universe. Born in the imploding core of a supernova, they provide a unique class of stellar objects with properties that make them nearly ideal probes for investigating a wide variety of physical problems.

A primary goal to study rotation-powered pulsars at X-ray energies is to search for thermal X-ray emission from cooling neutron stars. The close link between the thermal evolution of neutron stars and the physical characteristics of neutron star material at super-nuclear densities provides an important clue to the empirical study of matter at extreme energies and super-nuclear densities. Comparing measured neutron star temperatures with the theoretical predictions based on different equations of state thus provides the empirical basis essential for the verification of neutron star models and cooling theories.

Another point of interest is the physical mechanism operating in the pulsar magnetosphere to produce the intense, broad-band beamed radiation. It is well known that the radio emission of pulsars is due to coherent processes, and coherent curvature radiation has been identified as the most promising mechanism (see Michel 1991 and references therein). On the other hand, the optical, X-ray and gamma-ray emission observed in pulsars must be incoherent. Therefore, the fluxes in these energy bands are directly proportional to the densities of the radiating high energy electrons in the acceleration regions, no matter what radiation process (synchrotron radiation, cyclotron radiation or inverse Compton effects) is at work. High energy observations thus should provide the key for an understanding of the pulsars' emission mechanisms.

2. What is known on the pulsars' X-ray emission properties ?

Studying neutron stars with ROSAT and ASCA for more than eight years has increased the number of X-ray detected pulsars to 34[1] by now. Although this is less than $\sim 5\%$ of the known radio-pulsar population, the detected objects cover a wide range of ages, magnetic field strength and spin periods. The observed X-radiation can be attributed to various thermal an non-thermal emission processes, including

- Non-thermal emission from relativistic particles accelerated in the pulsar magnetosphere. The emission is characterized by a power-law spectrum and sharp X-ray pulses.
- Extended emission from a pulsar driven synchrotron nebula and emission from a relativistic pulsar wind interacting with the interstellar matter.
- Photospheric emission from the hot surface of a cooling neutron star. In this case a modified black-body spectrum and smooth, low amplitude variations with rotational phase are expected.
- Thermal emission from the neutron star's polar caps which are heated by the bombardment of relativistic particles streaming back to the surface from the pulsar magnetosphere.

Investigating the observed X-ray emission properties it is instructive to group the whole sample of detected objects according to their spin-down age.

Young pulsars like the ~ 1000 year old Crab pulsar emit sharp X-ray pulses with a fraction of pulsed photons up to 75%. The X-ray emission of these objects is connected with the acceleration of charged particles in the pulsar magnetosphere. No thermal X-ray emission from the surface of these young neutron stars could be detected by ROSAT. The intense X-ray emission from synchrotron nebula surrounding the young pulsars buries the thermal cooling emission (Harnden & Seward 1984; Becker & Aschenbach 1993).

The Vela pulsar, which has a characteristic age of about thirty-thousand years, is located in the center of the Vela supernova remnant. Its characteristic pulsar radiation is observed in the radio, optical, X- and gamma-ray domain. With ROSAT it became possible to show that its X-ray emission consists of two different components: a pulsed soft component likely emitted by the 1.5 million degree hot neutron star surface and dominating the emission in the soft band (0.1-0.6 keV), and a somewhat harder and steady component, emitted from the pulsar driven synchrotron nebula (Ögelman et al. 1993). The modulation of the neutron stars cooling emission is explained by non-uniformities in the surface temperature distribution due to the presence of the strong magnetic field which gives rise to an anisotropic heat flow in the neutron star's outer layers. A second supernova remnant, Puppis-A is located behind the Vela supernova remnant and stronger

[1] For a tabulated summary of the X-ray detected rotation-powered pulsars, their X-ray luminosities and parameters see http://www.xray.mpe.mpg.de/~web/bt97_update.html

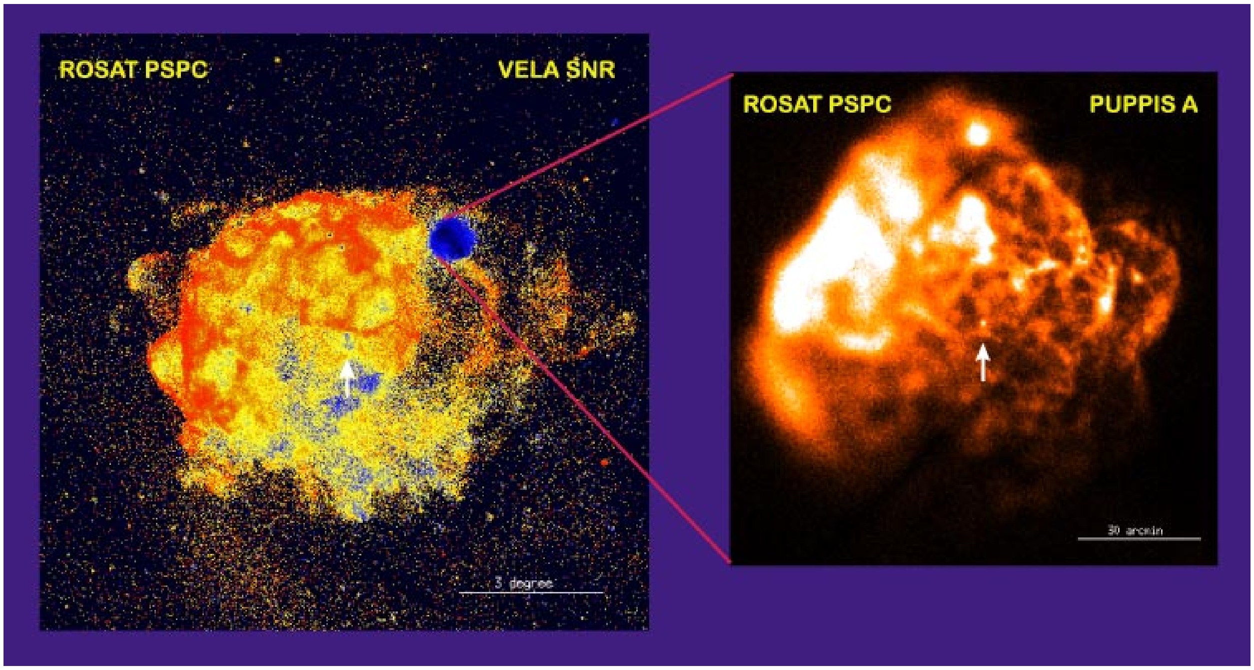

Fig. 1.— **a.)** False-color representation of the Vela supernova remnant (curtesy of B. Aschenbach). The red color represents the soft emission (0.1-0.6 keV) and the blue color the emission within 0.6-2.0 keV. The location of the Vela pulsar is represented by an arrow. Its X-ray emission below 2 keV is dominated by the intense emission from the pulsar's synchrotron nebula. Cooling emission from the young neutron star is only visible below ≈ 0.5 keV. **b.)** The SNR Puppis-A is located in the north-west of the Vela remnant. A zoomed image of Puppis-A (curtesy B. Aschenbach) is given in the right image. The arrow indicates the point source RX 0820+42 which is regarded to be very good candidate for a young neutron star.

absorbed than Vela. The faint point source RX J0820+42 in the center of the remnant is a very good candidate for a young neutron star showing photospheric emission at a temperature of ~ 1.5 million degree (Zavlin, Trümper & Pavlov 1999). It has been found recently that its emission is modulated with a period of 75.3 ms. At the same time the period derivative could be determind. The corresponding age and magnetic field is 8.0×10^3 years and 3.4×10^{12} Gaus, respectively (Pavlov, Zavlin & Trümper 1998).

Middle aged neutron stars which are hundred thousand to million years old show soft modulated X-ray emission with a pulsed fraction of typically 15-30% (Ögelman 1993). Their X-ray emission is found to be of thermal origin and being a relic of the initial heat content from the neutron star birth. The bolometric luminosities and luminosity upper limits deduced from the ROSAT data are found to be in good agreement with the predictions of standard cooling models for young neutron stars (Crab, PSR 1509-58, Vela), neutron star candidates in supernova remnants (RCW 103, 1E1207-51, Puppis-A) as well as for the middle aged pulsars Geminga, PSR 1055-52 and

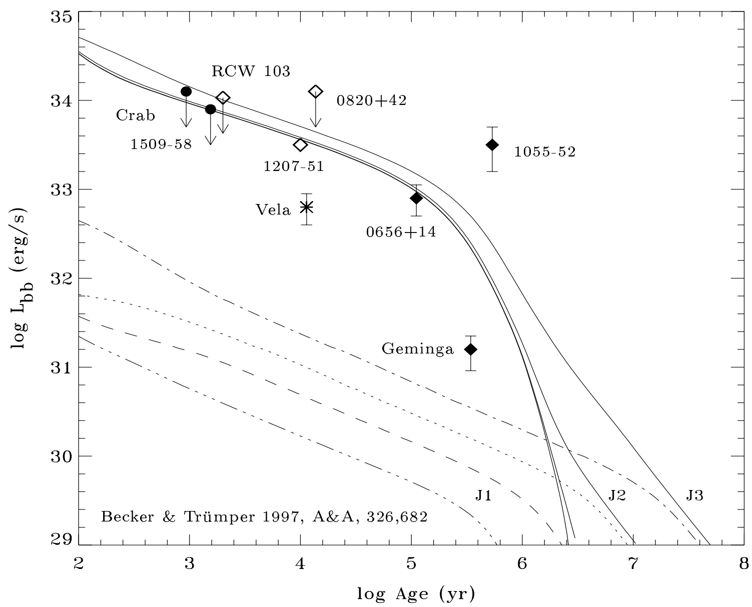

Fig. 2.— Empirically derived bolometric luminosities and predicted cooling curves for a neutron star with a realistic equation of state (cf. Becker & Trümper, 1997). Solid lines represent the standard cooling, dashed and dotted lines the so called fast cooling models. The latter are predicted by assuming an enhanced neutrino cooling in the first $\sim 10^5$ years in the neutron stars' live.

PSR 0656+14. The latter have been identified to be archetypal cooling neutron stars (see Becker & Trümper 1997 and references there in). The pulsars belonging to the class of middle aged neutron stars also show another somewhat harder emission component which is associated with non-thermal emission from the neutron star magnetosphere (Becker & Trümper 1997).

Millisecond pulsars are believed to represent an end-point in the evolution of accretion-powered neutron stars. They are distinguished by their small spin periods of less than 20 ms, a relatively weak magnetic field of $10^8 - 10^9$ Gauss and a very old characteristic age of several billions of years. More than $\sim 75\%$ of the known disk millisecond pulsars are in binaries with a compact companion star, compared with the $\sim 1\%$ of binary pulsars found in the general population. This gives support to the idea that their fast rotation has been acquired by angular momentum transfer during a past mass accretion phase.

X-ray emission from millisecond pulsars was first discovered by ROSAT (Becker & Trümper 1993)[2]. However, although ten of the 34 detected rotation-powered pulsars belong to the small

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[2]A recent review on the X-ray emission properties of millisecond pulsars which summarizes the current emission properties and observational status in a much wider and more complete way than here possible is given by Becker & Trümper (1998). A preprint can be obtained from /astro-ph/9806381

group of millisecond pulsars the origin of the detected X-ray emission is still unknown for most of them. Five of the ten ms-pulsars are identified only by their positional coincidence with the radio pulsar, and in view of the low number of detected photons do not provide much more than a rough flux estimate. These objects are so faint that the sensitivity of XMM is needed to detect enough photons required for a detailed spectral and temporal study in the soft and hard band beyond 2 keV. Somewhat more detailed results are found for the other five ms-pulsars for which X-ray pulsations could be detected. Their X-ray spectra suggests that most of their X-rays are emitted by non-thermal emission processes. An interpretation in terms of magnetospheric emission is further supported by the similarity of the pulse profiles observed in the radio and X-ray domain. Another indication for a non-thermal origin of the X-rays comes from a correlation between the pulsar's rotational energy loss and their observed X-ray luminosities. The X-ray luminosity correlates over a wide range remarkably well with the spin-down energy leaving only little room for intrinsic fluctuation in the X-ray efficiency (Becker & Trümper 1997). The millisecond pulsars are found to have the same X-ray efficiency as the $1 - 2 \times 10^3$ year young Crab type pulsars. Because the X-ray emission from young pulsars is known to be of non-thermal origin, the close correlation suggest that this is also true for the millisecond pulsars.

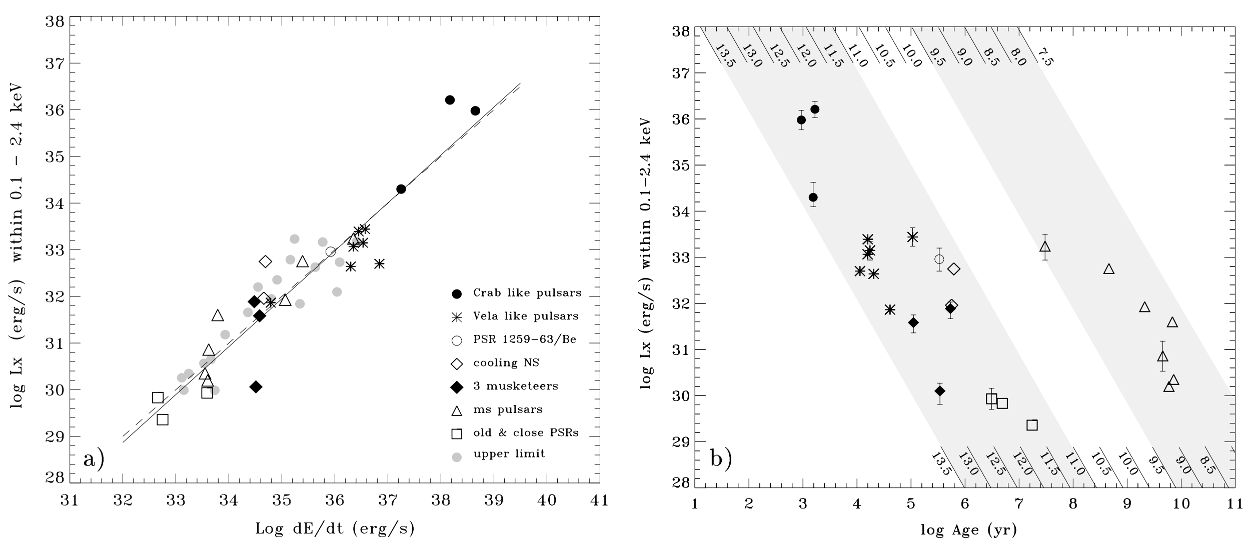

Fig. 3.— X-ray luminosities of the ROSAT detected rotation-powered pulsars vs. the pulsars' spin-down energy $\dot{E}$ (left) and characteristic age (right). We note that the thermal spectral components have been subtracted. Although field pulsars and millisecond pulsars form well-separated populations they have the same X-ray efficiency (cf. Becker & Trümper 1997 and discussion there in). The surprisingly close correlation between L_x and $\dot{E}$ strongly suggests that the bulk of the observed X-rays is emitted at the expense of rotational energy, as it is observed for the radio and gamma-ray emission.

3. Prospects: What is possible with XMM and AXAF ?

The next generation of X-ray satellites XMM and AXAF is expected to have a strong impact on our understanding of the neutron stars X-ray emission mechanism. With XMM, for example, we will be able to set much stronger constraints to the neutron star's surface temperature and to better discriminate between different cooling models than with ROSAT or ASCA. Further, it will be possible for the first time to observe characteristic spectral features which are predicted by neutron star's photospheric models taking into account realistic opacities. The cooling neutron stars can be studied in the hard band beyond 2 keV and neutron star candidates – so far identified only by their point-source like appearance somewhere close to the center of a supernova remnant – can be studied in detail by their spectral and temporal emission properties.

Pulse-phase resolved spectral analysis will be possible with XMM due to its large collecting powered coupled with the temporal and spectral resolution of the EPIC-PN camera. The GPS navigation system will provide a clock accuracy sufficient to allow pulse arrival time measurements even for millisecond pulsars. XMM and AXAF will allow to detect X-ray emission from much more rotation-powered pulsars than it was possible with the current X-ray observatories. Especially with XMM we will have for the first time an X-ray satellite sensitive enough to study the faint old and millisecond pulsars in detail and to identify the nature of their X-ray emission even in the hard band beyond 2 keV.

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