ANOMALOUS PULSARS AND OTHER RADIO QUIET NEUTRON STARS IN SUPERNOVA REMNANTS

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ABSTRACT. The "Anomalous X–ray Pulsars" (AXP) are a small (but quickly increasing) group of pulsars characterized by periods of several seconds (5 to 12 s) and by the absence of massive companion stars. It is unclear whether they are accreting from very low mass companions or consist of isolated neutron stars. Two of them are associated with supernova remnants. Other supernova remnants contain X–ray point sources that, despite their lack of pulsations, share some of the properties of the AXP, and might be related objects. Recent discoveries of pulsations in Soft Gamma-ray Repeaters might support the magnetar interpretation of AXP.

1. Introduction

The "Anomalous X–ray Pulsars" (AXP) were initially recognized as a class based on their narrow distribution of spin periods, compared to the much broader one (0.069 - $\sim$1500 s) observed in High Mass X–ray Binary (HMXRB) pulsars (Mereghetti & Stella 1995). However, an X–ray pulsar cannot be classified as an AXP based only on the value of its period. There are a few other characteristic properties that distinguish AXP from the more common HMXRB pulsars :

a) no identified optical counterparts, with upper limits excluding the presence of normal massive companions, like OB (super)giants and/or Be stars

b) very soft X–ray spectra (characteristic temperature $\lesssim$ 1 keV and/or power-law photon index $\gtrsim$ 3)

c) relatively low and steady X–ray luminosity ($\sim 10^{35}$-10^{36} erg s^{-1})

d) relatively stable spin period evolution, with long term spin-down trend

e) a few of them are associated with supernova remnants.

While there are several HMXRB pulsars with periods similar to those of the AXP (e.g., 2S 1553–542, Cen X-3, GS 0834–430), all the known pulsars with the properties (a) and (b) have periods in the narrow $\sim$6-12 s range. In practice, AXP can be defined as "pulsars with a very soft spectrum, that are neither HMXRB nor rotationally powered neutron stars like the Crab and Vela pulsar, and have luminosity $\sim 10^{35}$-10^{36} erg s^{-1}". It is remarkable that all the objects satisfying this definition, that are known up to now, have similar periods and (when measured) a spin-down. It is unclear whether this narrow period distribution is a mere selection effect, a chance result due to the statistics of small numbers, or a real effect related to the particular characteristics and evolution of these objects. Table 1 lists the current sample of AXP, together with a few other possibly related objects discussed below. For recent reviews on the properties of AXP see Mereghetti, Israel & Stella (1998b) and Mereghetti, Stella & Israel (1998).

2. AXP and other classes of sources

2.1. AXP and Supernova Remnants

Only two AXP are almost certainly associated with supernova remnants: 1E 2259+586 and 1E 1841–045. They are located very close to the center of the radio shells of the SNR CTB 109 and Kes 73, respectively. Non-thermal diffuse emission with a radius of 2-3 arcmin, interpreted as either a small synchrotron nebula or a dust scattering halo, has been discovered around 1E 2259+586 (Rho & Petre 1997). The diffuse flux is about 10-20% of that from the point source, still greater than the rotational energy loss of $\sim 10^{32}$ erg s^{-1} that could provide a neutron star with the P and $\dot{P}$ values of 1E 2259+586. Kes 73 has a center-filled X–ray morphology, due to the SNR thermal emission, that has so far prevented the detection of a similar nebula around 1E 1841–045 .

AX J1845.0-0300 is located at only ~20 arcmin from the supernova remnant Kes 75 (Torii et al. 1998), however an association between the two objects can be ruled out since Kes 75 has a radio and X–ray plerionic component indicating the presence of a different, energetic pulsar at its center. There is no evidence of SNR for the other AXP, but diffuse radio/X–ray emission has not been searched with the same sensitivity in all the sources. In conclusion, though some of the sources within SNR discussed in section 2.3 might be AXP, it seems that AXP are not necessarily associated with SNR.

2.2. AXP and Soft Gamma-ray Repeaters

Based on some analogies between the famous March 5th, 1979 event and 1E 2259+586 (similar periods, association with SNR) Thompson & Duncan (1996) suggested a possible connection between Soft Gamma-ray Repeaters (SGR) and AXP. They showed that their "magnetar" model, originally developed to explain the phenomenon of Soft Gamma-ray Repeaters (Duncan & Thompson 1992), could also explain the persistent X–ray emission from AXP.

The discovery of a periodicity at 7.5 s and a spin down of 2.6 10^{-3} s yr^{-1} in SGR 1806–20 (Kouveliotou et al. 1998a), as well as the recent report of a period of 5.16 s (Hurley et al. 1998) and $\dot{P} = 6\ 10^{-11}$ s s^{-1} (Kouveliotou et al. 1998b) in SGR 1900+14, has further supported a possible relationship between SGR and AXP. Contrary to AXP, the persistent X–ray counterpart of SGR 1806–20 has a hard power law spectra. This might be due, however, to the presence of the synchrotron nebula. The high spectral and angular resolution provided by AXAF and XMM will allow to obtain better information on the (pulsed) emission from the X–ray counterparts of SGR.

2.3. AXP and radio-quiet Isolated Neutron Stars

The three supernova remnants G296.5+10, Puppis A and RCW 103 contain unresolved X–ray sources that are considered strong neutron star candidates (see, e.g., Caraveo, Bignami & Truemper 1996). In the lack of periodic pulsations and radio emission, this interpretation is based on the location of these sources close to the geometrical center of shell SNR, coupled with their very high X–ray to optical flux ratio, similar to what is observed, e.g., in the Vela pulsar or in Geminga. These sources have soft spectra, with characteristic blackbody temperatures kT $\lesssim$ 1 keV like those of the AXP, and similar, or slightly smaller, X–ray luminosities. Though they are believed to be cooling, isolated neutron stars, at least in the case of 1E 1614-5055 in RCW 103 this seems to be contradicted by the recently reported evidence for flux variability (Petre, Gotthelf & Hwang 1998). More sensitive searches for periodicities in these sources might reveal other AXP.

The two ROSAT sources RX J0720.4-3125 (Haberl et al. 1997) and RX J1856.5–3754 (Walter et al. 1996) have been proposed as old neutron stars powered by accretion from the interstellar medium. The spin period of RX J0720.4-3125 is in the AXP range, but its luminosity is 2-3 orders of magnitude smaller (if this source is really as close as $\sim$ 100 pc, as implied by its very low interstellar absorption). Also these sources have soft blackbody-like spectra, but their temperatures are lower than those of AXP.

2.4. AXP and Low Mass X–ray Binaries

The known pulsars in LMXRB are also listed in Table 1. They form a very heterogeneous sample for what concerns X–ray spectral/variability properties, companion stars and evolutionary histories. They are clearly different from the AXP, although 4U 1626–67 was originally considered by Mereghetti & Stella (1995). An interesting connection between some of the LMXRB pulsars (4U 1626–67 and HD 49798) and the AXP was suggested by Ghosh, Angelini & White (1997), who proposed similar origins from common-envelope evolution of HMXRB. According to these authors, neutron stars in close HMXRB undergo complete spiral-in during a common envelope phase, producing Thorne-Zytkow objects, and, subsequently, AXP consisting of solitary neutron stars surrounded by an accretion disk. On the other hand, in relatively wide HMXRB, the spiral-in releases enough orbital energy to eject the envelope of the massive companion, resulting in the formation of a neutron star plus helium star binary, like e.g. 4U 1626–67.

3. AXP Models

The absence of a massive companion and the presence of a neutron star are observationally well established, but the mechanism responsible for the observed X–ray luminosity is unclear. Binary models have the advantage of naturally providing accretion as a source of energy. However, the absence of orbital motion signatures, such as periodic delays in the pulse arrival times or a periodic modulation of the flux, has also led to interpretations based on single stars.

3.1. Binary Models

These models are constrained by the optical/IR limits on the AXP counterparts and by the absence of orbital Doppler modulations of the pulses. The former allow to exclude bright massive companions, while the latter are now beginning to exclude also main sequence stars for large regions of the orbital parameter space. The most sensitive searches for orbital Doppler shifts have been obtained with the RXTE satellite. The resulting upper limits on the projected X–ray semiaxis $a_x \sin i$ are $\sim$30 and $\sim$60 light-ms (for orbital periods between few minutes and one day), respectively, for 1E 2259+586 and 1E 1048.1-5937 (Mereghetti, Israel & Stella 1998a). Except for the unlikely possibility that these systems are seen face-on, main sequence companions can be ruled out. Helium burning stars with M $\lesssim 0.8\ M_{\odot}$ cannot be excluded, but the accretion rate resulting from Roche lobe overflow would produce a much greater luminosity than the observed one. A possibility is that the He companion underfill its Roche lobe and a smaller accretion rate be provided by a stellar wind. White dwarf companion stars are compatible with the $a_x \sin i$ limits and yield consistent values of accretion. For example, a white dwarf with mass of $\sim 0.02\ M_{\odot}$ and $P_{orb} \sim 30$ min would give the $\dot{M}$ of a few $\times 10^{-11}\ M_{\odot}$ yr^{-1} required by the observed luminosity of 1E 2259+586.

3.2. Accreting Isolated Neutron Stars

In general, models involving accretion from the interstellar medium (ISM) have problems in providing the required luminosity under typical ISM parameters and neutron star velocities (unless the compact object lies in a molecular cloud). van Paradijs et al. (1995) proposed a more efficient scenario, in which isolated neutron stars are fed from residual accretion disks formed after complete spiral-in during a common envelope evolutionary phase of a HMXRB. This idea has been further developed by Ghosh et al. (1997), who interpreted the two component spectra observed in most AXP as evidence for two distinct accretion flows: a high-angular momentum component from the accretion disk, responsible for the power-law emission and the long term spin-down, and a spherically symmetric, low-angular momentum component, giving rise to the blackbody emission from a large fraction of the neutron star surface.

3.3. Magnetars

Models based on strongly magnetized (B$\sim 10^{14}$–10^{15} G) neutron stars, or "magnetars", have been developed to explain the peculiar properties of SGR (Duncan & Thompson 1992; Thompson & Duncan 1996). If one assumes that the almost steady spin-down at $\sim$ (0.5–50) $\times 10^{-12}$ s s^{-1} observed in AXP is determined by magnetic dipole radiation losses, values of B $\gtrsim 10^{14}$ G are obtained, suggesting that also the X–ray emission from these objects could be powered by magnetic field decay. For most AXP, only few and sparse period measurements exist, and the observed spin-down irregularities can easily be reproduced in the magnetar scenario by invoking a few glitches. This interpretation, if confirmed by more observational evidence, is certainly exciting and rich of implications for the overall statistics of high magnetic field neutron stars. Alternatively, the presence of slowly rotating AXP in relatively young SNR would imply that a significant number of neutron stars are born with periods above several seconds. Important tests of the magnetar wrt accretion interpretations could be derived from detailed observations of correlated $\dot{P}$ and luminosity variations over different time scales.

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Anomalous X–ray Pulsars (AXP)					
source	P (sec)	kT (keV)	SNR	comments	ref.
1E 1048.1–5937	6.45	0.64	–	BB+Pow.Law spectrum	S86,O98
AX J1845.0–0300	6.97	0.7	–		T98
1E 2259+586	6.98	0.44	CTB 109	BB+Pow.Law spectrum	F81, P98
4U 0142+61	8.69	0.39	–	BB+Pow.Law spectrum	W87, I94
1RXSJ170849–40091	11.00	0.41	–	BB+ Pow.Law spectrum?	S97
1E 1841–045	11.77	–	Kes 73		V97
Soft Gamma-ray Repeaters (SGR)					
	P (sec)		SNR		
SGR 1806–20	7.48		G10.0–0.3	pow.law $\alpha_{ph} \sim 2.2$	S94,K98
SGR 0526–66	8.1		N49	March 5, 1979 in LMC	M79
SGR 1900+14	5.16		G42.8+0.6 ?		H96,H98
(candidate) Radio-Quiet Neutron Stars					
	P (sec)	kT (keV)	SNR		
1E 1207–5209	–	0.25	G296.5+10		M96
1E 1614–5055	–	0.6	RCW 103	time variable	G97
1E 0820–4247	–	0.3	Puppis A		P96
RX J0720.4–3125	8.39	0.08	–		H97
RX J1856.5–3754	–	0.06	–		W96
Low Mass X–ray Binary (LMXRB) pulsars					
	P (sec)	Companion	P_{orb}		
SAX J1808.4–3658	0.0025	Main seq. M $\lesssim 0.1\ M_\odot$	2.01 hrs	transient, Type I bursts	W98
GRO J1744–28	0.467	red giant ? M $\sim 0.25\ M_\odot$?	11.8 days	Type II bursts	F96
Her X-1	1.24	A9-B $\sim 2\ M_\odot$	1.7 days		N89
4U 1626–67	7.66	He star?	42 min		M81,N89
HD 49798	13.2	O6 subdwarf	1.55 days	white dwarf?	I97
GX 1+4	120.	M6 giant	?		N89

Table 1 - AXP and related objects