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Nature of “Magnetars”

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Abstract A brief review of known models for the description of Anomalous X-ray Pulsars (AXPs) and Soft Gamma-Repeaters (SGRs) is given. A new model is proposed to explain the main properties of these objects and radio pulsars with long periods on the base of the conception of drift waves in the vicinity of the light cylinder of the neutron star with the surface magnetic field $\sim 10^{12}$ G.

Key words: AXP, SGR, radio pulsars: magnetic fields – drift waves

1 INTRODUCTION

Two classes of astrophysical objects have been studied intensively during the last 10 years but their nature is unclear up to now. These are Anomalous X-ray Pulsars (AXPs) and Soft Gamma Repeaters (SGRs). It is believed usually that both classes are characterized by pulsed X-ray emission, and we can suggest that the central objects in these sources are isolated neutron stars because there is no evidence for the presence of secondary companions in all cases.

If we use the model of the magneto-dipole slowing down, then magnetic fields at the surfaces of neutron stars in AXPs and SGRs must be $10^{14} - 10^{15}$ G, two orders of magnitude higher than fields in “normal” pulsars. This was the reason why such objects were named “magnetars”. It was suggested that X-ray radiation took its energy from a magnetic reservoir. Let us consider this possibility.

The total energy of such reservoir is

$$E = \frac{B^2}{8\pi}\frac{4\pi R^3}{3} = 1.7 \times 10^{45} - 1.7 \times 10^{47}\,\mathrm{erg}, \tag{1}$$

where $R = 10\,$km is the neutron star radius. The X-ray luminosity of SGR 1806–20 is 2×10^{35} erg s^{-1}. For $E = 10^{47}$ erg this source will exist for 10^4 years only. Time of life for normal radio pulsars is $\sim 10^7$ years. So, only one magnetar must be observed among 1000 known radio pulsars. This estimate is ten times less than the observed number. Energetic difficulties become more serious if we take into account that SGR 1806–20 injects relativistic particles in the ambient SNR with the rate $\sim 10^{37}$ erg s^{-1} (Kouveliotou, Dieters & Strohmayer 1998). In this case the magnetic reservoir will be exhausted during 360 years. However the age of SGR 1806–20 is 1400 years.

To avoid this difficulty it is necessary to postulate the existence of magnetic fields $B \sim 10^{16}$ G inside a neutron star (Thompson & Duncan 1996).

It is well known that the necessary stage to generate pulsar radio emission is creation of electron-positron pairs. But a gamma-quantum in very strong magnetic fields ($B \gg 10^{12}$ G) will convert into two other gamma-quanta (Baring & Harding 1998). Therefore AXPs and SGRs must be radio quiet objects. However Shitov et al. (2000) detected radio emission from SGR 1900+14 and Malofeev & Malov (2001) registered pulsed radio signals from AXP 1E2259+586. So, there is the alternative: either we do not understand how radio pulsars radiate or magnetic fields of “magnetars” are much less than $10^{14} - 10^{15}$ G.

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The braking index n is equal to 3 for the magneto-dipole slowing down. However the data of Shitov et al. (2000) have given $n = 0.20 \pm 0.47$ for SGR 1900+14. There is the possibility to explain such value of n by the combined action of the magneto-dipole radiation and the unipolar generator induced particle ejection (Xu & Qiao 2001; Wu et al. 2003). However we cannot explain it by the magneto-dipole braking mechanism that has been used as the basic one in the “magnetar” model.

These difficulties compel some authors to use other models to explain observable properties of AXPs and SGRs.

2 OTHER MODELS

1. Paczynski (1990) and Usov (1993) proposed the model of white dwarfs with $B \sim 10^8 - 10^9$ G. But the reasonable models of white dwarfs give log $\frac{dE}{dt} \sim 36$. It is not enough to explain injection of relativistic particles in ambient SNRs. Moreover extremely short periods of white dwarfs are required.
2. Accretion (see, for example, Marsden et al. 2001). There are no any evidences of the presence of the secondary components in AXPs or SGRs in all cases. The accretion from the interstellar medium can provide luminosities $L \sim 10^{32}$ erg s^{-1}, much less than the observable ones. If the accretion occurs from a relic disk, its age turns out to be very small, and the accretion cannot explain the observed deceleration of AXPs (Li 1999).
3. Strange stars (Dar & De Rujula 2000; Usov 2001). The existence of these objects is rather problematic, and the possible models are not worked out in detail as has been done for neutron stars.
4. Precession (Shaham 1977; Sedrakian et al. 1999) can have periods of order 10 seconds, but long living free precession is doubtful realized.

Table 1 Observed Parameters of AXPs and SGRs

N	Source	$P_{\rm obs}$ (s)	$(dP/dt)_{-11}$	log $L_{\rm x}$ (erg s^{-1})	$f_{\rm pl}(\%)$	$W_x/P_{\rm obs}$
			AXP			
1	4U0142+61	8.69	0.196	34.52	~ 88	0.53
2	1E1048–5937	6.45	~ 3.81	34.53	~ 80	0.44
3	RXS1709–4009	11.00	1.86	35.83	~ 73	0.67
4	1E1841–045	11.77	4.16	35.36	100	0.64
5	1E2259+586	6.98	0.0483	35.00	~ 50	0.48
6	XTEJ1810–197	5.54	1.15	36.20	~ 70	0.41
			SGR			
1	SGR1806–20	7.48	0.083	35.30	~ 2.5	0.65
2	SGR1900+14	5.16	11	34.48	~ 5	0.38

Here $f_{\rm pl}$ is the percentage of pulsed emission, W_x is the pulse width.

3 THE DRIFT MODEL

In this report we discuss a new model for describing the “magnetar” phenomenon using usual values of magnetic fields at the surface of a neutron star $B_s \sim 10^{12}$ G (Malov et al. 2003).

Kazbegi et al. (1991) showed that besides l- and lt-waves generation of transverse electromagnetic drift waves was possible in pulsar magnetospheres with the characteristic frequency

$$\omega_0 = Re\omega = k_x u_x^b, \tag{2}$$

and the increment

$$\Gamma = Im\omega \approx \left(\frac{n_b}{n_p}\right)^{1/2} \gamma_p^{1/2} k_x \frac{u_x^b}{\gamma_b^{1/2}}\,. \tag{3}$$

Here k_x, k_φ, k_r are the components of the wave vector in the cylindrical coordinate system, u_x is the drift velocity and γ_b is the Lorentz-factor of the primary beam.

These waves cause variations of curvature of field lines

$$K \approx \frac{1 - k_\varphi r B_r / B_\varphi}{r} \,. \tag{4}$$

If $k_\varphi r \gg 1$ the change of K may be significant. As far as radiation is emitted along a tangent to the local direction of magnetic field the change of its curvature leads to the change of the radiation direction.

We can use the results of Malov & Machabeli (2002) to calculate the synchrotron luminosity

$$L = \frac{3^{1/2}\pi^{7/2}e}{32m^{1/2}c^{3/2}} \frac{I\gamma_b^{3/2} dP/dt}{P^{7/2}\gamma_p^2} \,, \tag{5}$$

the period of drift waves

$$P_{dr}^{\max} = \frac{eBP^2}{4\pi^2 mc\gamma_b} \,, \tag{6}$$

and its derivative

$$\left(\frac{dP}{dt}\right)_{dr} = eBP \frac{dP/dt}{2\pi^2 mc\gamma_b} \,. \tag{7}$$

Then we can calculate P, dP/dt and B from the system (5)–(7) (Table 2). We assume that $I = 10^{45}$ g cm^2 and $\gamma_b = 10^7$.

Table 2 Calculated Parameters of AXPs and SGRs

N	Source	P (ms)	$\frac{dP/dt}{10^{-15}}$	$\log L$ (erg s^{-1})	$\log B$ (G)	$\log(dE/dt)$ (erg s^{-1})	$\log B_s$ (G)
				AXP			
1	4U0142+61	19.81	2,23	33,91	5,70	37,06	11,60
2	1E1048–5937	87.2	2,58	33,72	4,28	37,18	12,10
3	RXS1709–4009	11.84	10	35.35	6.25	38.38	11.46
4	1E1841–045	22.41	40	34.97	5.72	38.14	11.77
5	1E2259+586	10.75	0.372	34.06	6.13	37.07	11.22
6	XTEJ1810–197	13.78	14	35.27	5.82	38.33	11.24
				SGR			
1	SGR1806–20	25.60	1.42	33.32	5.41	36.52	11.64
2	SGR1900+14	520	5545	32.34	2.63	36.19	12.79

4 QUIESCENT X-RAY EMISSION AND GAMMA-BURSTS FROM AXP AND SGR

Transitions between Landau's levels lead to the formation of spectral lines with energies

$$\begin{aligned} \varepsilon_m - \varepsilon_n &= \tfrac{p_\perp m^2 - p_\perp n^2}{2m_e} = h\nu_0 S, \\ S &= (m - n) = \pm 1, \pm 2, ... \end{aligned} \tag{8}$$

Lines corresponding to such harmonics have been detected in fact (Rea et al. 2003). They correspond to $B \sim 10^{11} - 10^{12}$ G. There are some attempts (see, for example, Zane et al. 2001) to interpret them as the absorption lines of non-relativistic protons in magnetic fields $\sim 10^{14} - 10^{15}$ G. However according to Ho et al. (2002) the vacuum polarization effect suppresses proton cyclotron lines and other spectral features due to bound species. Moreover in this case the electron cyclotron lines in the range near 1 MeV must be observed. Their detection will be the good evidence for the magnetar model. In our model such lines must be absent in spectra of AXPs and SGRs.

The frequency ν in the observer's coordinate system depends on the frequency ν_0 in the system where $V_\| = 0$,

$$\nu = \nu_0 \frac{(1 - V^2/c^2)^{1/2}}{1 - V\cos\alpha/c} \,. \tag{9}$$

Here α is the angle between the particle velocity and the line of sight.

If the Lorentz-factor of emitting particles $\gamma \gg 1$, and the angle α is small, the formula (9) can be presented in the following form:

$$\nu = \frac{2\nu_0}{1/\gamma + \alpha^2\gamma}\,. \tag{10}$$

If $\alpha^2\gamma \ll 1/\gamma$, then $\nu \approx 2\nu_0\gamma$. For $1 \lesssim \alpha^2\gamma \lesssim 10$ and $B \sim 10^{12}$ G the electron cyclotron frequency

$$\nu_0 = \frac{eB_s}{2\pi mc}\,, \tag{11}$$

is in the soft X-ray range (1–10 keV) in the observer's system. This emission can penetrate through the $e^{\pm}$ - magnetosphere and arrive to the observer. The diapason of angles α can be very wide, and the distribution function of emitting particles is not mono-energetic, therefore the resulting spectrum must be wide.

If due to any reason (for example, star-quakes) the angle α becomes very small ($\alpha^2\gamma^2 \lesssim 1$) for a short time then the frequency can achieve the high value ($\nu \sim 2\gamma\nu_0$). This frequency can find itself in the gamma-ray range. Particles with different Lorentz-factors can take part in this process, and the observed spectrum must be wide. The transformation of the power into the observer's system is described by the following formula:

$$P_\nu = P_{\nu_0}\frac{1}{1 - V\cos\alpha/c}\,. \tag{12}$$

For $\alpha \to 0$ P_ν increases drastically and becomes equal to

$$P_\nu \approx 2P_{\nu_0}\gamma^2. \tag{13}$$

So, the power in the gamma-ray range can be $2\gamma^2$ times higher than in X-ray one. If X-ray power is 10^{36} erg s^{-1}, the Lorentz-factor must be $\gamma \sim 10^4$ to provide a gamma-ray burst with the power 10^{44} erg s^{-1}. In the traditional model such energy characterizes the tail of the distribution function for the secondary particles.

AXPs and SGRs are characterized in our model by two peculiarities: i) a small angle $\beta < 10^\circ$ between magnetic and rotation axes and ii) a rotation period $P \sim 0.1$ s. About 10% of radio pulsars must have $\beta \lesssim 10^\circ$, if neutron stars are formed with an arbitrary angle β, and approximately 0.1 part of them must have $P \sim 0.1$ s. So, we can expect 1% of "magnetars" in the whole sample of radio pulsars in agreement with observations.

5 RADIO PULSARS WITH LONG PERIODS

Recently a number of radio pulsars, which must be in the radio-quiet zone was discovered. They are characterized by very long periods $P = 4.0 - 8.5$ s and high magnetic fields (up to 10^{14} G). These pulsars show apparently normal radio emission in a regime of magnetic field strength ($B_s \geq B_{cr} = 4.4 \times 10^{13}$ G) where the known models predict no emission should occur. There does not exist the model which explains the phenomenon of radio emission from all these pulsars. We believe that the observed interval between successive pulses is not equal to the rotation period, but is determined by the period of drift waves (Lomiashvili et al. 2006).

If the angle α between the line of sight and the direction of the emission cone will become less the angular width Θ of this cone the observer will see the pulse of radiation once during the period of the drift wave (see Fig. 1). If we consider these pulsars in the framework of our model, their parameters will get new 'real' values, shown in Table 3.

So, AXPs, SGRs and radio pulsars with long pulse periods have the periods of rotation from 0.1 to 1 s and magnetic field strengths $10^{11} - 10^{13}$ G, usual for normal radio pulsars. We can expect the modulation of

Table 3 Values of Pulsar Parameters

Pulsar	$P_{\rm obs}$ (s)	P (s)	$(dP/dt)_{-15}$	B_s (10^{12} G)	dE/dt(10^{32} erg s^{-1}	$\Delta\beta$(deg)	$\beta_0 \approx \delta$(deg)	Θ(deg)	W_{10}/P
PSR J2144–3933	8.5	0.85	0.048	0.2	0.032	7	7	1.5	0.1
PSR J1847–0130	6.7	1.12	210	16	61	5	5	3	0.3
PSR J1814–1744	4.0	0.50	190	6.9	300	5	5	2	0.2

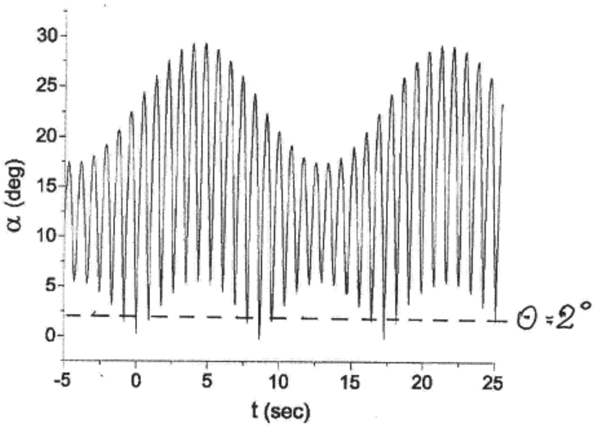

Fig. 1 The oscillating behaviour of α with time for $\Omega = 2\pi/0.85\,\mathrm{s}^{-1}, \Theta = 2^\circ$.

observed emission with the rotation period. The detection of such modulation will be the strict confirmation of our model.

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