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Soft gamma repeaters/anomalous X-ray pulsars – are they magnetars?†

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The observational properties of Soft Gamma Repeaters and Anomalous X-ray Pulsars (SGR/AXP) indicate the necessity of an energy source different from the rotational energy of a neutron star. The model, where the source of the energy is connected with a magnetic field dissipation in a highly magnetized neutron star (magnetar) is analyzed. Some observational inconsistencies are indicated for this interpretation. The alternative energy source, connected with the nuclear energy of superheavy nuclei stored in the nonequilibrium layer of low mass neutron star is discussed.

Keywords: Stars: neutron; gamma-ray burst: general; nuclear reactions

1 Introduction

Neutron stars (NS) are the result of a collapse. Conservation of the magnetic flux gives an estimation of NS magnetic field as $B_{\rm ns} = B_{\rm s}(R_{\rm s}/R_{\rm ns})^2$, $B_{\rm s} = 10$–100 Gs, at $R \sim (3$–$10)\ R_\odot$, $R_{\rm ns} = 10$ km, $B_{\rm ns} = 4 \cdot 10^{11}$–$5 \cdot 10^{13}$ Gs [23].

Estimation of the NS magnetic field is obtained in radio pulsars by measurements of their rotational period and its time derivative, in the model of a dipole radiation, or pulsar wind model, as (E, I, and Ω are NS rotational energy, moment of inertia, and rotational angular velocity, respectively):

$$E_{\rm rot} = 0.5 I\Omega^2, \quad \dot{E}_{\rm rot} = AB^2\Omega^4, \quad B = IP\dot{P}/4A\pi^2, \quad A = R^6/6c^3, \qquad (1)$$

B is NS surface dipole magnetic field at its magnetic pole. Timing observations of single radiopulsars (the rapidly rotating ones connected with young supernovae remnants are marked by star) give the following estimation $B_{\rm ns} = 2 \cdot 10^{11}$–$5 \cdot 10^{13}$ Gs [39] (see Fig. 1).

†The extended version of the talk given on Ioffe Workshop on GRBs and other transients: twenty years of Konus–Wind Experiment. In memory of E.P. Mazets

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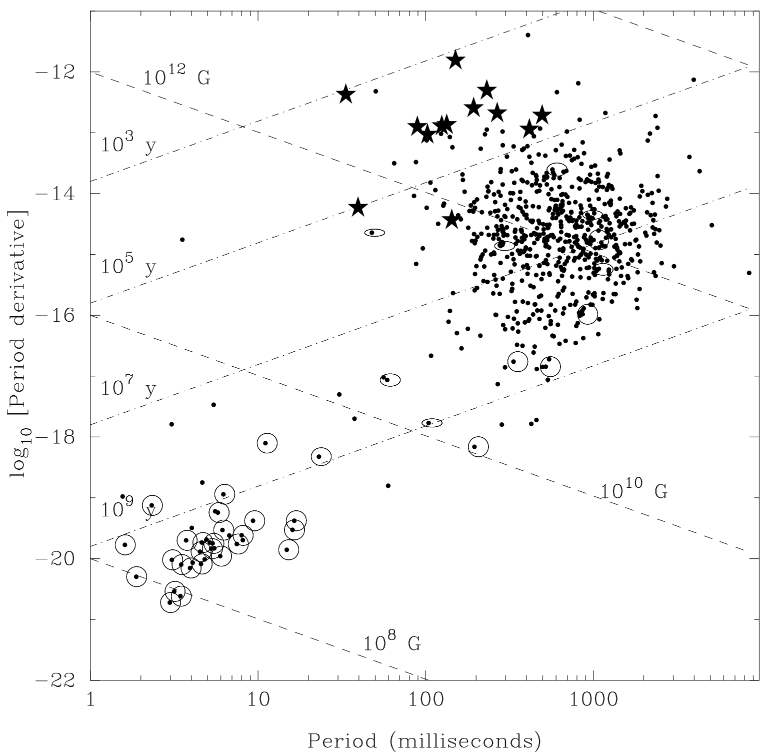

Figure 1 P–$\dot{P}$ diagram for radiopulsars. Pulsars in binary systems with low-eccentricity orbits are encircled, and in high-eccentricity orbits are marked with ellipses. Stars show pulsars suspected to be connected with supernova remnants (from [39]).

The pulsars with a small magnetic field in the left lower angle in Fig. 1 decrease their magnetic field during recycling by accretion in a close binary (see [8]).

SGR are single neutron stars with periods 2–8 seconds. They produce "giant bursts", when their luminosity L in the peak increases 5–6 orders of magnitude. Having a slow rotation and small rotational energy, their observed average luminosity exceeds rotational loss of energy by more than 10 times and orders of magnitude during the giant outbursts.

It was suggested in [19] that the source of energy is their huge magnetic field, 2 or 3 orders of magnitude larger than the average field in radiopulsars. Such objects were called magnetars.

2 SGR, giant bursts, and short GRB

The first two Soft Gamma Repeaters (SGR) had been discovered by KONUS group in 1979. The first one, FXP 0520-66, was discovered after the famous giant 5 March 1979 burst [42, 43, 24], see also [45]. In another source B1900+14 only small recurrent bursts had been observed [41]. Now these sources are known under the names SGR

0520-66 and SGR 1900+14 respectively. The third SGR 1806-20 was identified as a repetitive source in [37, 38]. The first detection of this source as GRB070179 was reported in [44], and it was indicated in [45] that this source, having an unusually soft spectrum, can belong to a separate class of repetitive GRB, similar to FXP0520-66 and B1900+14. This suggestion was completely confirmed. The fourth known SRG1627-41, showing a giant burst, was discovered in 1998 almost simultaneously on BATSE [34] and BeppoSAX [20]. The giant bursts had been observed in 4 sources.

2.1 SGR0526-66

It was discovered due to a giant burst of 5 March 1979, projected to the edge of the SNR N49 in LMC, and described in [42, 43, 24, 45]. Accepting the distance 55 kpc to LMC, the peak luminosity in the region $E_\gamma > 30$ keV was $L_{\rm p} \geq 3.6 \times 10^{45}$ ergs/s, the total energy release in the peak $Q_{\rm p} \geq 1.6 \times 10^{44}$ ergs, in the subsequent tail $Q_{\rm t} = 3.6 \times 10^{44}$ ergs. The short recurrent bursts have peak luminosities in this region $L_{\rm p}^{\rm rec} = 3 \times 10^{41} - 3 \times 10^{42}$ ergs/s, and energy release $Q^{\rm rec} = 5 \times 10^{40} - 7 \times 10^{42}$ ergs. The tail was observed about 3 minutes and had regular pulsations with the period $P \approx 8$ s. There was not a chance to measure $\dot{P}$ in this object.

2.2 SGR1900+14

Detailed observations of this source are described in [47, 48, 36, 59]. The giant burst was observed 27 August, 1998. The source lies close to the less than 10^4 year old SNR G42.8+0.6 situated at a distance of ∼10 kpc. Pulsations had been observed in the giant burst, as well as in the X-ray emission observed in this source in quiescence by RXTE and ASCA. $\dot{P}$ was measured, being strongly variable. Accepting the distance

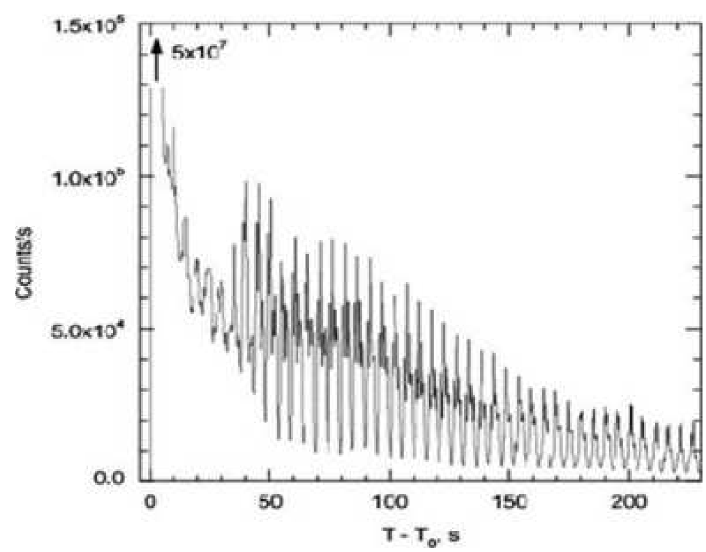

Figure 2 The giant 1998 August 27 outburst of the soft gamma repeater SGR1900+14. Intensity of the $E > 15$ keV radiation is presented, from [48].

10 kpc, this source had in the region $E_\gamma > 15$ keV: $L_\mathrm{p} > 3.7 \times 10^{44}$ ergs/s, $Q_\mathrm{p} > 6.8 \times 10^{43}$ ergs, $Q_\mathrm{t} = 5.2 \times 10^{43}$ ergs, $L_\mathrm{p}^\mathrm{rec} = 2 \times 10^{40} - 4 \times 10^{41}$ ergs/s, $Q^\mathrm{rec} = 2 \times 10^{39} - 6 \times 10^{41}$ ergs, $P = 5.16$ s, $\dot{P} = 5 \times 10^{-11} - 1.5 \times 10^{-10}$ s/s. This source was discovered at frequency 111 MHz as a faint, $L_\mathrm{r}^\mathrm{max} = 50$ mJy, radiopulsar [56] with the same P and variable $\dot{P}$ good corresponding to X-ray and gamma-ray observations. These values of P and average $\dot{P}$ correspond to the rate of a loss of rotational energy $\dot{E}_\mathrm{rot} = 3.5 \times 10^{34}$ ergs/s, and magnetic field $B = 8 \times 10^{14}$ Gs. The age of the pulsar estimated as $\tau_\mathrm{p} = P/2\dot{P} = 700$ years is much less than the estimated age of the nearby SNR. Note that the X-ray luminosity of this object $L_\mathrm{x} = 2 \times 10^{35} - 2 \times 10^{36}$ ergs/s is much higher than the rate of a loss of rotational energy, which means that rotation cannot be a source of energy in these objects. It was suggested that the main source of energy comes from a magnetic field annihilation, and such objects had been called magnetars [18]. The light curve of the giant burst is given in Fig. 2.

2.3 SGR1806-20

The giant burst from this source was observed in December 27, 2004 [54, 49, 21]. Recurrent bursts had been studied in [35, 28]. Connection with the Galactic radio SNR G10.0-03 was found. The source has a small but significant displacement from that of the non-thermal core of this SNR. The distance to SNR is estimated as 14.5 kpc. The X-ray source observed by ASCA and RXTE in this object shows regular pulsations with a period $P = 7.47$ s, and average $\dot{P} = 8.3 \times 10^{-11}$ s/s. As in the previous case, it leads to the pulsar age $\tau_\mathrm{p} \sim 1500$ years, much smaller than the age of SNR estimated by 10^4 years. These values of P and $\dot{P}$ correspond to $B = 8 \times 10^{14}$ Gs. $\dot{P}$ is not constant, uniform set of observations by RXTE gave much smaller and

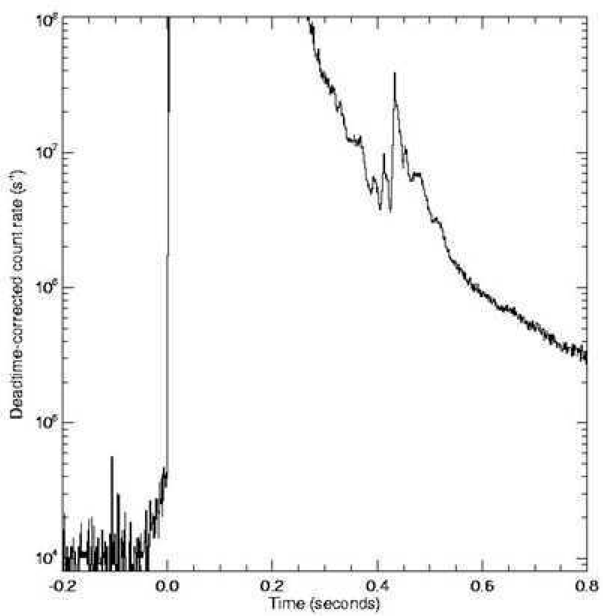

Figure 3 SWIFT light curve of 27 December, 2004 giant burst in SGR1806, from [54].

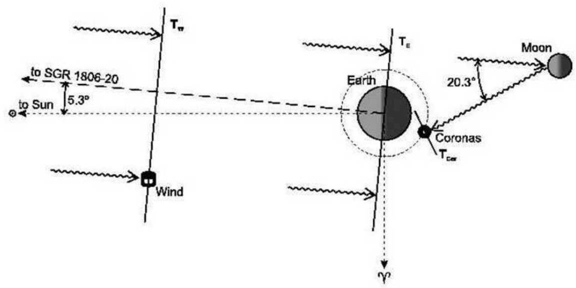

Figure 4 The position of satellites Wind and Coronas-F relative to the Earth and Moon during the outburst, from [49, 21].

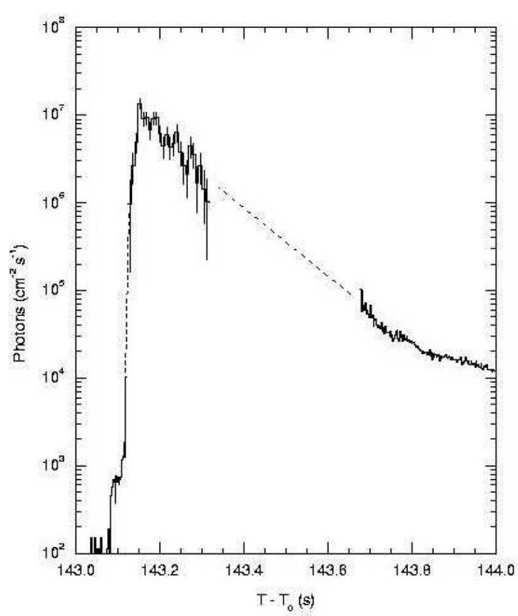

Figure 5 Reconstructed time history of the initial pulse. The upper part of the graph is derived from Helicon data while the lower part represents the Konus–Wind data. The dashed lines indicate intervals where the outburst intensity still saturates the Konus–Wind detector, but is not high enough to be seen by the Helicon, from [49, 21].

less definite value $\dot{P} = 2.8(1.4) \times 10^{-11}$ s/s, the value in brackets gives 1σ error. The peak luminosity in the burst reaches $L_{\rm p}^{\rm rec} \sim 10^{41}$ ergs/s in the region 25–60 keV, the X-ray luminosity in 2–10 keV band is $L_{\rm x} \approx 2 \times 10^{35}$ ergs/s is also much higher than the rate of the loss of rotational energy (for average $\dot{P}$) $\dot{E}_{\rm rot} \approx 10^{33}$ ergs/s.

The burst of December 27, 2004 in SGR 1806-20 was the greatest flare, ∼100 times brighter than ever. It was detected by many satellites: Swift (see Fig. 3), RHESSI, Konus–Wind, Coronas-F, Integral, HEND and others.

Very strong luminosity of this outburst permitted us to observe the signal reflected from the moon by the HELICON instrument onboard Coronas-F. The positions of Wind and Coronas-F relative to the Earth and Moon during the outburst are given in Fig. 4; the reconstructed full light curve of the outburst, in Fig. 5 (from [49, 21]).

2.4 SRG1627-41

Here the giant burst was observed 18 June 1998, in addition to numerous soft recurrent bursts. Its position coincides with the SNR G337.0-0.1, assuming 5.8 kpc distance. Some evidences were obtained for a possible periodicity of 6.7 s, but the giant burst does not show any periodic signal [46], contrary to three other giant bursts in SGR. The following characteristics had been observed with a time resolution 2 ms at photon energy $E_\gamma > 15$ keV: $L_\mathrm{p} \sim 8 \times 10^{43}$ ergs/s, $Q_\mathrm{p} \sim 3 \times 10^{42}$ ergs, no tail of the giant burst had been observed. $L_\mathrm{p}^\mathrm{rec} = 4 \times 10^{40} - 4 \times 10^{41}$ ergs/s, $Q^\mathrm{rec} = 10^{39} - 3 \times 10^{40}$ ergs. Periodicity in this source is not certain, so there is no $\dot{P}$.

2.5 SRG giant bursts in other galaxies

The similarity between giant bursts in SGR, and short GRB was noticed in [48, 5]. The experiment KONUS–WIND had observed two short GRBs, interpreted as giant bursts of SGR. The first one, GRB070201, was observed in M31 (Andromeda), 1 February, 2007. The energy of the burst is equal to $1 \cdot 10^{45}$ erg, consistent with giant bursts of other SGR [50]. The second short burst, GRB051103, was observed in the galaxy M81, 3 November 2005. The energy of the burst is equal to $7 \cdot 10^{46}$ erg [25, 22].

3 Estimations of the magnetic fields in SGR/AXP

Despite the fact that rotation energy losses are much smaller than the observed luminosity, for estimation of the magnetic field strength in these objects used the same procedure as in radio pulsars, based on measurements of P and $\dot{P}$, and using (1). The first measurements have been done for SGR 1900+14, in different epochs by measurements of satellites RXTE and ASCA [36], presented in Figs. 6–8.

The pulse shape is changing from one epoch to another, inducing errors in finding derivative of the period. The big jump in $\dot{P}$ visible in Fig. 8 looks surprising for

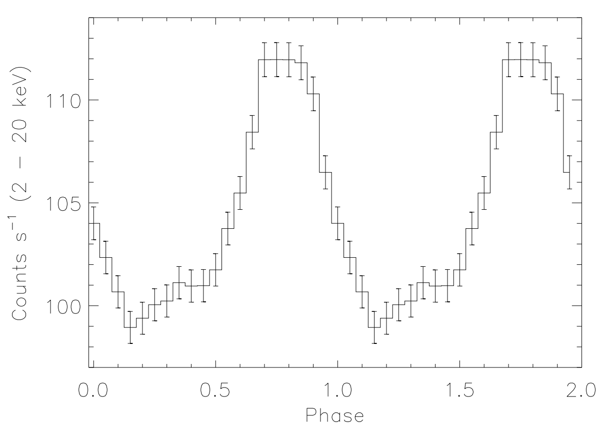

Figure 6 The epoch folded pulse profile of SGR 1900+14 (2–20 keV) for the May 1998 RXTE observations (from [36]).

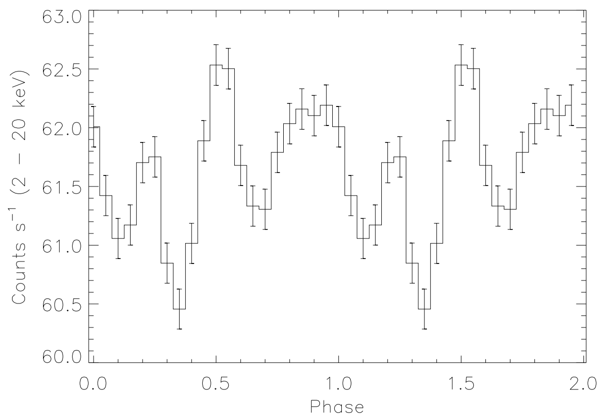

Figure 7 The epoch folded pulse profile of SGR 1900+14 (2–20 keV) for the August 28, 1998 RXTE observation. The plot is exhibiting two phase cycles, from [36].

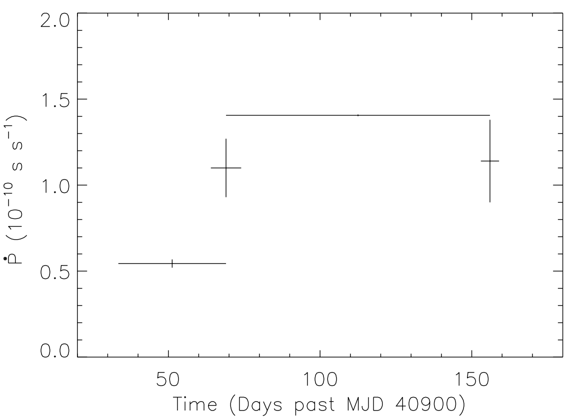

Figure 8 The evolution of "period derivative" versus time since the first period measurement of SGR 1900+14 with ASCA in [29]. The time is given in Modified Julian Days (MJDs) (from [36]).

magnetic dipole losses, because it needs a considerable jump in the magnetic field strength prohibited by self induction effects. Contrarily, in the model of pulsar wind rotational energy losses it looks quite reasonable that these losses strongly increase during the giant burst, when the $\dot{P}$ jump was observed.

Further evidence in favour of the magnetar magnetic field was connected with the absorption lines in the spectrum of SGR 1806-20, observed by RXTE in November 1996 [30]. The main line corresponds to magnetic field $(5–7)\cdot 10^{11}$ Gs, when interpreted as an electron cyclotron line. In order to preserve the magnetar model, the authors [30] suggested that this line is connected with the proton motion, increasing the magnetic field estimation almost 2000 times. It is connected, however, with a drastic, $\sim 4\cdot 10^6$, decrease in the absorption cross-section, compared to the electron cyclotron line. Therefore, if this cyclotron line is real, its connection with the proton is very improbable.

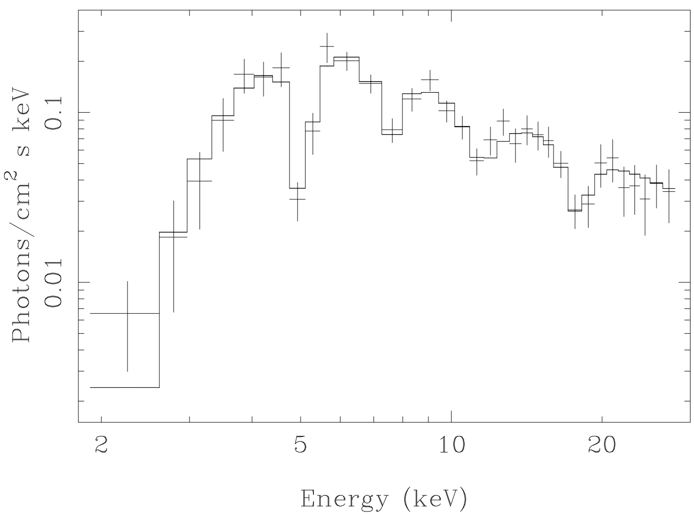

Figure 9 SGR 1806-20 spectrum and best-fit continuum model for the second precursor interval with 4 absorption lines (RXTE/PCA 2–30 keV), from [30].

4 Radiopulsars with very high magnetic fields and slow rotation

Radio pulsars are rotating neutron stars that emit beams of radio waves from regions above their magnetic poles. Popular theories of the emission mechanism require continuous electron-positron pair production, with the potential responsible for accelerating the particles being inversely related to the spin period. Pair production will stop when the potential drops below a threshold, so the models predict that radio emission will cease when the period exceeds a value that depends on the magnetic field strength and configuration. It was shown in [61, 60] that the pulsar J2144-3933, previously thought to have a period of 2.84 s, actually has a period of 8.51 s, which is by far the longest of any known radio pulsar. Moreover, under the usual model assumptions, based on the neutron-star equations of state, this slowly rotating pulsar should not be emitting a radio beam. Therefore either the model assumptions are wrong, or current theories of radio emission must be revised. The period 8.51 second is characteristic for SGR/AXP objects, but this pulsar does not show any violent behaviour, and behaves like an ordinary radio pulsar.

Soon after this discovery, several other radio pulsars were found, where also $\dot{P}$ and, therefore, magnetic field strength was measured [40, 14, 51, 52]. These pulsars include:

1. PSR J1119-6127, $P = 0.407$ s, $\dot{P} = 4.0 \cdot 10^{-12}$ s/s, $B = 4.1 \cdot 10^{13}$ G;
2. PSR J1814-1744, $P = 3.975$ s, $\dot{P} = 7.4 \cdot 10^{-13}$ s/s, $B = 5.5 \cdot 10^{13}$ G.

It was noted in [14] that "both PSR J1119-6127 and PSR J1814-1744 show apparently normal radio emission in a regime of magnetic field strength where some models predict that no emission should occur. Also, PSR J1814-1744 has spin parameters similar to the anomalous X-ray pulsar (AXP) IE 2259+586, but shows no discernible X-ray emission. If AXPs are isolated, high magnetic field neutron stars ('magnetars'), these results suggest that their unusual attributes are unlikely to be merely a consequence of their very high inferred magnetic fields."

3. PSR J1847-0130, $P = 6.7$ s, $\dot{P} = 1.3 \cdot 10^{-12}$ s/s, $B = 9.4 \cdot 10^{13}$ G.

It was noted in [51] with the title "PSR J1847-0130: A radio pulsar with magnetar spin characteristics" that "the properties of this pulsar prove that inferred dipolar magnetic field strength and period cannot alone be responsible for the unusual high-energy properties of the magnetars and create new challenges for understanding the possible relationship between these two manifestations of young neutron stars."

4. PSR J1718-37184, $P = 3.4$ s, $B = 7.4 \cdot 10^{-13}$ G.

It was noted in [52] that "these fields are similar to those of the anomalous X-ray pulsars (AXPs), which growing evidence suggests are 'magnetars'. The lack of AXP-like X-ray emission from these radio pulsars (and the non-detection of radio emission from the AXPs) creates new challenges for understanding pulsar emission physics and the relationship between these classes of apparently young neutron stars."

5 SGR/AXP with low magnetic fields and moderate rotation

SGR/AXP J1550-5418 (1E 1547.0-5408) was visible in radio band, showing pulsations with a period $P = 2.069$ s [15]. The pulsations with the same period have been observed first only in the soft X-ray band by XMM-Newton [26]. In the hard X-ray region statistics of photons was not enough for detection of pulsations. In the strong outbursts in 2008 October and in 2009 January and March, observed by Fermi gamma-ray burst monitor, the period of 2.1 s was clearly visible up to the energy $\sim$110 keV [32]. The INTEGRAL detected pulsed soft gamma-rays from SGR/AXP 1E1547.0-5408 during its Jan-2009 outburst, in the energy band 20–150 keV, showing a periodicity with $P = 2.1$ s [33]. This object is the only SGR/AXP with a relatively low period, all previous have periods exceeding $\sim$4 s.

A low-magnetic-field SGR0418+5729 was detected by Fermi gamma-ray burst [55]. This soft gamma repeater with low magnetic field SGR0418+5729 was recently detected after it emitted bursts similar to those of magnetars. It was noted that "X-ray observations show that its dipolar magnetic field cannot be greater than $7.5 \cdot 10^{12}$ Gauss, well in the range of ordinary radio pulsars, implying that a high surface dipolar magnetic field is not necessarily required for magnetar-like activity".

6 The magnetar model

In the paper [18] it was claimed that dynamo mechanism in the new born rapidly rotating star may generate NS with a very strong magnetic field 10^{14}–10^{15} G, called magnetars. These magnetars could be responsible for cosmological GRB and may represent a plausible model for SGR. In the subsequent paper [19] the connection between magnetars and SGR was developed in more detail. The authors presented a model for SGRs, and the energetic 1979 March 5 burst, based on the existence of neutron stars with magnetic fields much stronger than those of ordinary pulsars. They presented the following arguments point to a neutron star with B(dipole) $5 \cdot 10^{14}$ G as the source of the March 5 event [19].

1. Existence of such a strong magnetic field may spin down the star to an 8-s period in the 10^4 yr age of the surrounding supernova remnant N49.

2. Magnetic field provides enough energy for the March 5 event.

3. In presence of such magnetic field a large-scale interchange instability develops with the growth time comparable to the 0.2-s width of the initial hard transient phase of the March 5 event.

4. A very strong magnetic field can confine the energy that was radiated in the soft tail of that burst.

5. A very strong magnetic field reduce the Compton scattering cross-section sufficiently to generate a radiative flux that is $\sim 10^4$ times the (non-magnetic) Eddington flux;

6. The field decays significantly in $\sim 10^4$–10^5 yr, as is required to explain the activity of soft gamma repeater sources on this time-scale; and

7. The field power the quiescent X-ray emission $L_X \sim 7 \cdot 10^{35}$ erg s^{-1} observed by Einstein and ROSAT as it diffuses the stellar interior. It is proposed that the 1979 March 5 event was triggered by a large-scale reconnection/interchange instability of the stellar magnetic field, and the soft repeat bursts by cracking of the crust.

These suggestions were justified only by semi-qualitative estimations. Subsequent observations of P and $\dot{P}$ in several SGR [27] seem to support this model. However, when the rotation energy losses are much less than observed X-ray luminosity, B estimations using $\dot{P}$ are not justified, because magnetic stellar wind could be the main mechanism of angular momentum losses. The jump in $\dot{P}$ observed in the giant burst of PSR1900+14 (Fig. 8) is plausibly explained by a corresponding increase of the magnetic pulsar wind power, while the jump in the dipole magnetic field strength is hardly possible. The jumps in $\dot{P}$, as well as in the pulse form (Figs. 6,7) have not been seen in the radio pulsars. In the fall-back accretion model of SGR [17, 1, 58, 57] the estimations of the magnetic field using P and $\dot{P}$ give the values characteristic for usual radiopulsars, in presence of a large scale magnetic field in the fall back accretion disk [12].

When the energy density of the magnetic field is much larger than that of matter, as expected in the surface layers of the magnetar, the instability should be suppressed by magnetic forces.

The observations of radio pulsars, showing no traces of bursts, with magnetar magnetic fields and slow rotation (Section 4), detection of SGR with a small rotational period and low magnetic field, estimated from P and $\dot{P}$ values similar to radio pulsars (Section 5), give a strong indication that inferred dipolar magnetic field strength and period cannot alone be responsible for the unusual high-energy properties of SGR/AXP. Therefore, another characteristic parameter should be responsible for a violent behaviour of SGR/AXP. The unusually low mass of the neutron star was suggested in [7, 12] as a parameter distinguishing SGR/AXP neuron stars from the majority of neutron stars in radio pulsars and close X-ray binaries.

7 Model of nuclear explosion

It was shown in [9] that in the neutron star crust full thermodynamic equilibrium is not reached, and a non-equilibrium layer is formed there during a neutron star cooling (see Fig. 10).

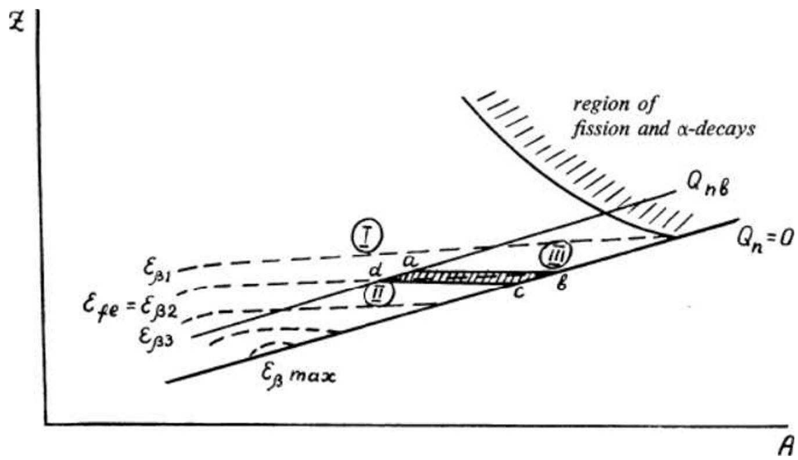

Figure 10 The formation of chemical composition at the stage of limiting equilibrium. The thick line $Q_{\rm n} = 0$ defines the boundary of the region of existence of nuclei, the line $Q_{\rm nb}$ separates region I, where photodisintegration of neutrons is impossible from regions II and III. The dashed lines indicate a level of constant $\varepsilon_\beta = Q_{\rm p} - Q_{\rm n}$; $\varepsilon_{\beta 1} < \varepsilon_{\beta 2} < ... < \varepsilon_{\beta\rm max}$. In region I we have $Q_{\rm n} > Q_{\rm nb}$; in region II we have $Q_{\rm n} < Q_{\rm nb},\ \varepsilon_{\rm fe} < \varepsilon_\beta$; and in region III we have $Q_{\rm n} < Q_{\rm nb},\ \varepsilon_{\rm fe} > \varepsilon_\beta$. The line with the attached shading indicates a region of fission and α-decay. The shaded region *abcd* determines the boundaries for the values of (A, Z) with a limited equilibrium situation, at given values of $Q_{\rm nb}(T)$ and $\varepsilon_{\rm fe}(\rho)$, from [9].

The non-equilibrium layer is formed in the region of densities and pressure $\rho_2 < \rho < \rho_1$, $P_1 < P < P_2$, with

$$\rho_1 \simeq \mu_{\rm e} 10^6 \left(\frac{8}{0.511}\right)^3 \simeq 3.8 \cdot 10^9 \mu_{\rm e}\ \text{g/cm}^3 \simeq 1.5 \cdot 10^{10}\ \text{g/cm}^3$$

$$\rho_2 \simeq \mu_{\rm e} 10^6 \left(\frac{33}{0.511}\right)^3 \simeq 2.7 \cdot 10^{11} \mu_{\rm e}\ \text{g/cm}^3 \simeq 10^{12}\ \text{g/cm}^3$$

$$P_1 = 7.1 \cdot 10^{27} \text{ in cgs units}, \quad P_2 = 2.1 \cdot 10^{30} \text{ in cgs units.}$$

The mass of the non-equilibrium layer is defined as [9]

$$M_{\rm nl} = \frac{4\pi R^4}{GM}(P_2 - P_1) \simeq 0.1(P_2 - P_1) \simeq 2 \cdot 10^{29}\ \text{g}\ \simeq 10^{-4}\, M_\odot,$$

and the energy stored in this non-equilibrium layer is estimated as

$$E_{\rm nl} \simeq 4 \cdot 10^{17}(P_2 - P_1) \approx 10^{48}\ \text{erg}.$$

Here a neutron star of a large ($\sim$2 $M_\odot$) was considered, where the nonequilibrium layer is relatively thin, and its mass, and the energy store are estimated in the approximation of a flat layer. The nuclei in the non-equilibrium layer are overabundant with neutrons, so the number of nucleons per one electron is taken as $\mu_{\rm e} \simeq 4$, and the energy release in the nuclear reaction of fission is about $5 \cdot 10^{-3}\, c^2$ erg/g. A schematic cross-section of the neutron star is represented in Fig. 11 from [2].

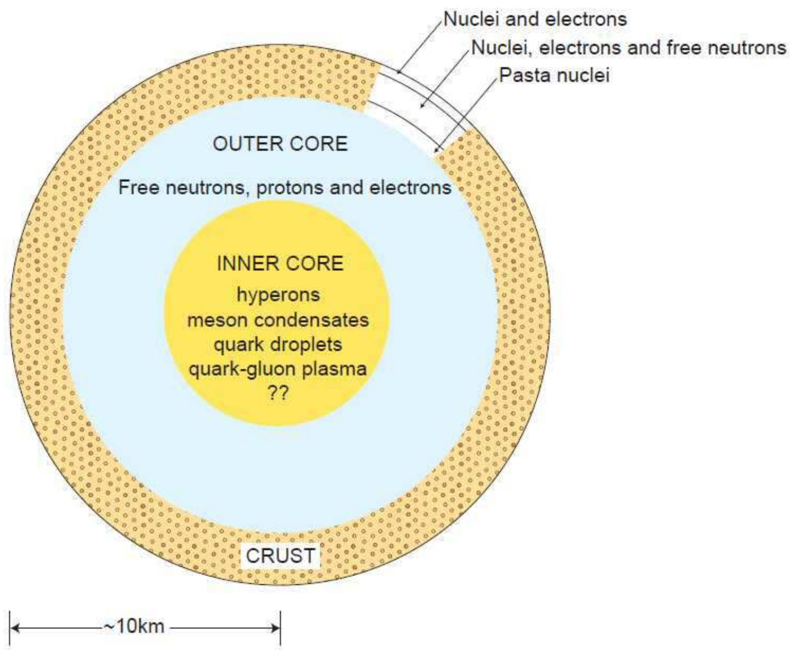

Figure 11 Schematic cross section of a neutron star, from [2].

Soon after discovery of gamma ray bursts the model of nuclear explosion was suggested [11], in which the non-equilibrium layer matter is brought to lower densities during a starquake. At the beginning GRB have been considered as objects inside the Galaxy, and the outburst was connected with period jumps in the neutron star rotation similar to those observed in the Crab nebula pulsar. It was suggested that "ejection of matter from the neutron stars may be related to the observed jumps of periods of pulsars. From the observed gain of kinetic energy of the filaments of

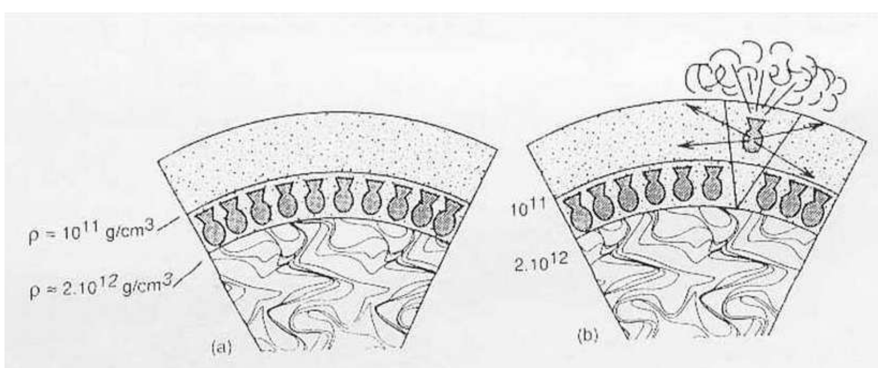

Figure 12 The schematic picture of non-equilibrium layer in the neutron star: a) in a quiescent stage; b) after starquake and nuclear explosion, from [4].

the Crab Nebula ($\sim 2{\cdot}10^{41}$ erg) the mass of the ejected material may be estimated as ($\sim 10^{21}$ g). This leads to energies of the γ-ray bursts of the order of 10^{38}–10^{39} erg, which agrees fully with observations at the mean distance up to the sources 0.25 kpc". A more detailed model of the strong 5 March 1979 burst, now classified as SGR 0526-66 in LMC, was considered in [10]. It was identified with an explosion on the NS inside the galactic disk, at a distance $\sim$100 ps. The schematic picture of the nuclear explosion of the matter from the non-equilibrium layer is presented in Fig. 12.

The cosmological origin of GRB, and identification of a group of non-stationary sources inside Galaxy as SGR/AXP lead to considerable revision of the older model, presented in [11]. It becomes clear that SGR represent a very rare and very special type of objects, which produce bursts much more powerful, than was thought before, in comparison with quakes in Crab nebula pulsar. Besides, the SGR are the only sources for which the nuclear explosions could be applied, because the energy release in the cosmological GRB highly exceed the energy store in the non-equilibrium layer.

It was suggested in [7, 12] that the property making the SGR neutron star so different from much more numerous of them in radio pulsars, single and binary X-ray sources, is connected with the value of their mass, but not the magnetic field strength (see [14, 51] and Section 4). Namely, it was suggested that the neutron stars in SRG/AXP have anomalously low mass (0.4–0.8) $M_\odot$ compared to the well measured masses in binary systems of two neutron stars, where neutron stars have masses $\geq 1.23\ M_\odot$ [16]. The violent behaviour of the low-mass NS may be connected with much thicker and more massive non-equilibrium layer, and accretion from the fall-back highly magnetized accretion disk could trigger the instability, leading to

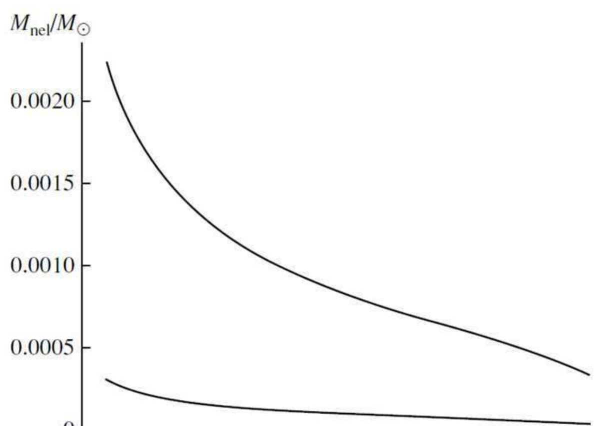

Figure 13 Dependence of the mass of the non-equilibrium layer on the neutron-star mass. The lines show the top and bottom boundaries of the layer mass measured from the stellar surface. The equation of state of the equilibrium matter [3, 53] was used to construct the model of the neutron star, with the boundaries of the layer specified by the densities. Using a non-equilibrium equation of state will increase the mass of the layer, but should not fundamentally change the values given in the figure (from [7], calculated and prepared by S.O. Tarasov).

outbursts explosions [12]. The NS radius is increasing with mass rather slowly, so in a flat approximation the mass of non-equilibrium layer is inversely proportional to the mass. More accurate estimations have been obtained from calculations of neutron star models, presented in Fig. 13. In Sect. 7 the calculated mass of the non-equilibrium layer $M_{\rm nl} \approx 10^{-4}\ M_\odot$ belonged to the neutron star with the mass $\sim 2\ M_\odot$. For $M_{\rm ns} = 0.45\ M_\odot$ the mass of the non-equilibrium layer is ~7 times larger. The energy store reaches $\sim 10^{49}$ erg, which is enough for ~1000 giant bursts.

The observational evidences for existence of neutron stars with masses, less than the Chandrasekhar white dwarf mass limit have been obtained in [31]. Observations of the binary pulsar system J1518-4904 indicated the masses of the components to be $m_{\rm p} = 0.72(+0.51, -0.58 M_\odot) \quad m_{\rm e} = 2.00(+0.58, -0.51) M_\odot$ with a 95.4% probability. It was suggested in [12] that low mass neutron stars could be formed in the scenario of the off-center explosion [13], but more detailed numerical investigation is needed to prove it. X-ray radiation of SGR/AXP in quiescent states was explained in [12] by the fall back accretion from the disk with a large scale poloidal magnetic field, which could also be a trigger for development of instability, leading to the mixing in the neutron star envelope, and nuclear explosion of the matter from the non-equilibrium layer.

8 Conclusions

1. SGR are highly active, slowly rotating neutron stars.
2. Nonequilibrium layer (NL) is formed in the neutron star crust, during NS cooling, or during accretion onto it. It may be important for NS cooling, glitches, and explosions connected with SGR.
3. The mass and the energy store in NL increase rapidly with decreasing of NS mass.
4. The properties of pulsar with high magnetic fields prove that inferred dipolar magnetic field strength and period cannot alone be responsible for the unusual high-energy properties of SGR/AXP. The NL in low mass NS may be responsible for bursts and explosions in them.

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