MAGNETIC FIELDS OF NEUTRON STARS: OBSERVATIONS AND MODELS

G. S. Bisnovatyi-Kogan

Space Research Institute of Russian Academy of Sciences
84/32 Profsoyuznaya St., 117810 Moscow, Russia
e-mail: gkogan@mx.iki.rssi.ru

Estimations of magnetic fields of neutron stars, observed as radio and X-ray pulsars, are discussed. It is shown that theoretical and observational values for different types of radiopulsars are in good correspondence. Magnetic fields of X-ray pulsars are estimated from the cyclotron line energy. In the case of Her X-1 this estimation exceeds considerably the value of its magnetic field obtained from long term observational data related to the beam structure evolution. Another interpretation of the cyclotron feature, based on the relativistic dipole radiation mechanism, could remove this discrepancy. Observational data about soft gamma repeaters and their interpretation as magnetars are critically analyzed.

INTRODUCTION

First theoretical estimations of neutron star magnetic fields have been done from the condition of the magnetic flux conservation during contraction of a normal star to a neutron one [9]: $B_{ns} = B_s \left(\frac{R_s}{R_{ns}}\right)^2$. For the main sequence stellar magnetic field $B_s = 10 \div 100$ Gs, and the stellar radius $R_s = (3 \div 10)R_\odot \approx (2 \div 7)\times 10^{11}$ cm, we get $B_{ns} \approx 4\times 10^{11} \div 5\times 10^{13}$ Gs, for a neutron star radius $R_{ns} = 10^6$ cm. As shown below, this simple estimation occurs to be in a good correspondence with most observational data.

RADIO PULSARS

It is now commonly accepted that radio pulsars are rotating neutron stars with inclined magnetic axes. For rotating with angular velocity Ω dipole, the rotational energy losses [17, 29] are determined as $\dot{E} = AB^2\Omega^4$. The rotational energy is $E = \frac{1}{2}I\Omega^2$, I is the inertia momentum of a neutron star. By measuring of $P = 2\pi/\Omega$ and $\dot{P}$, we obtain the observational estimation of the neutron star magnetic field as

$$B^2 = \frac{IP\dot{P}}{4\pi^2 A}. \qquad (1)$$

It was shown in [11] that energy losses by a pulsar relativistic wind are important also when the magnetic and rotational axes coincide, and one may use (1) with $A = \frac{R_{ns}^6}{6c^3}$, and B_{ns} corresponding to the magnetic pole, at any inclination angle. Magnetic fields of radio pulsars estimated using (1) with observational values of P and $\dot{P}$ lay in the wide range between 10^8 and 10^{13} Gs [21]. There are two distinctly different groups: single radiopulsars with periods exceeding 0.033 sec and magnetic fields between 10^{11} and 10^{13} Gs, and recycled pulsars (RP), present or former members of close binary systems with millisecond periods and low magnetic fields between 10^8 and 10^{10} Gs. Low magnetic field of recycled pulsars is probably a result of its damping during preceding accretion stage [6].

X-RAY BINARIES

There are several ways to estimate observationally the magnetic field of an X-ray pulsar. During accretion, matter is stopped by the magnetic field at the alfvenic surface, where gaseous and magnetic pressures are in balance. At stationary state, the Keplerian angular velocity of an accretion disk at the alfvenic surface is equal to the stellar angular velocity [30] $\Omega_K = \Omega_s = \Omega_A$. Otherwise a neutron star would be accelerated due to absorption of matter with large angular momentum, or decelerated due to throwing away matter with additional angular momentum [15] . X-ray pulsars may have spin-up and spin-down stages [2], but most of them show average spin-up, indicating that their angular velocity is less than the equilibrium one. This is observed in the best studied X-ray pulsar Hex X-1 [34, 7, 33]. Analysis of spin-up/down phenomena in the X-ray pulsars indicate important role of the mass loss [19], and to stochastic origin of spin-up/down transitions [20].

For a given luminosity $L_{36} = L/(10^{36}\,\mathrm{erg/s})$ and dipole magnetic field at the stellar equator $B_{12} = B/(10^{12}\,\mathrm{Gs})$, we get the following value of the equilibrium period [18] for the neutron star mass $M_s = 1.4\,M_\odot$

$$P_{eq} \approx 2.6\,B_{12}^{6/7}\,L_{36}^{3/7}\ \mathrm{s}. \tag{2}$$

For Her X-1 parameters $L_{36} = 10$, $P = 1.24$ s, we get a magnetic field corresponding to the equilibrium rotation $B_{12}^{eq} = 0.9$. Taking into account the average spin-up of the pulsar in Her X-1, we may consider this value as an upper limit of its magnetic field. Even more rough estimations of the magnetic field in X-ray pulsars follow from the average spin-up rate under condition $\dot{J}_{rot} = \dot{M}\,\Omega_A$, or restrictions on the polar magnetic field value following from the observed beam structure and a condition of local luminosity not exceeding the critical Eddington one. These conditions lead to smaller values of the magnetic field of Her X-1 on the level 10^9-10^{10} Gs [4].

Observations of low mass X-ray binaries (LMXB) point to very low values of their magnetic fields due to absence of X-ray pulsar phenomena. Modulation of the X-ray flux allowed to reveal the rotational period of the neutron star in the LMXB SAX J1808.4-3658 corresponding to the frequency 401 Hz, due to RXTE observations (see review [37]). This observations fill a gap and form a long-awaited link between LBXB and recycled millisecond pulsars [31], as neutron stars with very low magnetic field (up to 10^8 Gs).

The most reliable estimation of the magnetic field of the X-pulsar Her X-1 comes from detailed observations of the beam variation in this pulsar on different stages, made on the satellites ASTRON [34], GINGA and RXTE [7, 33]. This pulsar, in addition to 1.24 s period of the neutron star rotation, is in a binary system with an orbital period 1.7 days, and shows a 35 day cycle, where during only 12 days its luminosity is high. During other 23 days its X-ray luminosity strongly decreases, but small changes in the optical luminosity and remaining strong reflection effect indicate that the X-ray luminosity remains almost the same during all 35 day cycle. A visible decrease of the X-ray flux is due to an occultation phenomena. The model which explains satisfactory the phenomenon of the 35 day cycle is based on the precession of the accretion disc with the 35 day period, and occultation of the X-ray beam during 23 days. Analysis of the beam structure during high and low X-ray states leads to the conclusion that during the low state we observe not the direct X-ray flux from the neutron star, but the flux, reflected from the inner edge of the accretion disc. This conclusion is based on the 180 deg phase shift between the X-ray beams in high and low states. In order to observe the X-ray flux reflected from the inner edge, situated near the Alfven radius of the accretion disc, it cannot be very far away from the neutron star. The estimations give an upper limit to the ratio of the Alfven and stellar radii $\frac{r_A}{r_s} \leq 20$. The schematic picture of the accretion disc and its inner edge orientation around the neutron star at different stages of the 35 day cycle is shown in Fig. 1, taken from [34]. As was indicated above, the value of the Alfven radius is determined by the neutron star mass ($M_s = 1.4\,M_s$), mass flux $\dot{M} = 3\times10^{16}$ g/s, corresponding to the luminosity $L = 10^{37}$ erg/s, and the value of the magnetic field. Taking dipole radial dependence of the magnetic field $B = B_s(r_s/r)^3$, and the neutron star radius $r_s = 10^6$ cm, we obtain the ratio in the form $r_A/r_s \approx 300 B_{12}^{4/7}$. To have this ratio not exceeding 20 we get an inequality $B \leq 3\times10^{10}$ Gs.

The feature in the spectrum of Her X-1 at energies between 50 and 60 KeV was found in [36]. Its interpreting as a cyclotron line feature according to $E_X = \frac{\hbar e B}{m_e c}$ leads to the value of the magnetic field $B_{cycl} = (5-6)\times10^{12}$ Gs that is much higher than any other above mentioned estimations. Spectral features were observed also in other X-ray sources. Recent observations on RXTE [13], and Beppo-SAX [32] of the pulsating transient 4U 0115+63 have shown a presence of 3 and 4 cyclotron harmonics features, corresponding to the magnetic field strength of 1.3×10^{12} Gs. A comparison of the shapes of the beam in cyclotron harmonics may be used for testing the nature of these features. Cyclotron features have been observed in several X-ray sources [27], and they always have corresponded to large values of magnetic fields $B_{cycl} > 10^{12}$ Gs. Such a situation is not in good accordance with a well established observational fact, that all recycled pulsars, going through a stage of an X-ray source, have much smaller magnetic fields, usually not exceeding 10^{10} Gs. Particularly, for the Her X-1 the value of its magnetic field, following from the cyclotron interpretation of the spectral feature, is in contradiction with all other observations, including the most reliable, based on the beam shape variability during 35 day cycle.

RELATIVISTIC DIPOLE INTERPRETATION OF THE SPECTRAL FEATURE IN HER X-1

It seems likely that this conflict is created by using the non-relativistic formula connecting cyclotron frequency with a value of the magnetic field. According to [5] , ultrarelativistic electrons with a temperature $\sim 10^{11}K$, may be formed in the non-collisional shock during accretion, emitting a relativistic dipole line. The mean energy of

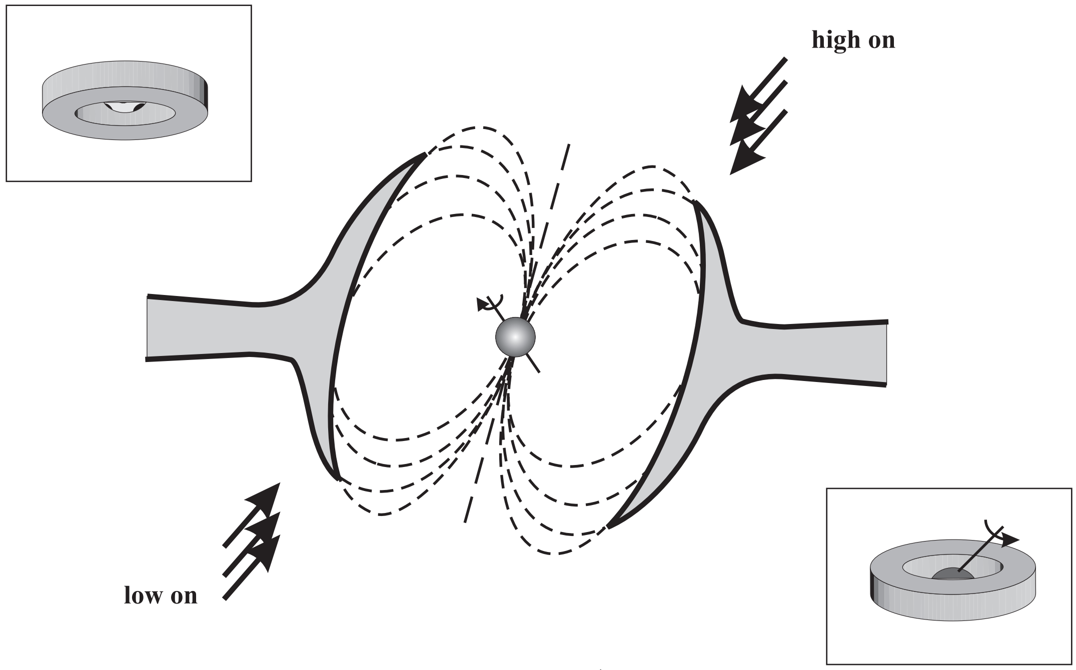

Figure 1: Configuration of the inner edge of the disk and the neutron star; neutron star and the disk in the "high-on" state (left top box), and in the "low-on" state (right bottom box)

this line is broadened and shifted relativistically, in comparison with the cyclotron line, by a factor of $\gamma \simeq \dfrac{kT}{mc^2}$. The spectrum profile of the relativistic dipole line is calculated in [1] for various electron distributions, where the model of the hot spot for Her X-1 is considered, and it is shown that the overall observed X-ray spectrum (from 0.2 to 120 KeV) can arise under the fields near 5×10^{10} Gs which are well below B_{cycl}, and are not in the conflict with other observations.

According to [10, 3], in the magnetic field near the pulsar the cross component of a momentum of electrons is emitting rapidly, while the parallel velocity remains constant. Hence, the momentum distribution of the electrons is anisotropic $p_\perp^2 \ll p_\parallel^2$, with $p_\perp \ll mc$, $p_\parallel \gg mc$. Assume for simplicity that the transverse electron distribution is two-dimensional Maxwellian $dn = \dfrac{N}{T_1}\exp\left(-\dfrac{mu^2}{2T_1}\right) d\dfrac{mu^2}{2}$, $T_1 \ll mc^2$.

In the relativistic dipole regime of radiation, the electron is non-relativistic in the coordinate system, connected with the Larmor circle. In the laboratory system, where the electron is moving with a velocity V, the angle between the magnetic field and electron momentum vectors is smaller than the angle of the emitting beam. At these conditions we may consider that the radiation is all emitted along the magnetic field with an intensity $J(0)$, at frequency ω_{md} [1]

$$J(0) = \frac{2Ne^4B^2T_1}{\pi c^5 m^3 (1-\frac{V}{c})}, \qquad \omega_{md} = \omega_{cycl}\sqrt{\frac{1+\frac{V}{c}}{1-\frac{V}{c}}} \approx 2\omega_{cycl}\frac{E_\parallel}{m_e c^2}, \tag{3}$$

where $\omega_{cycl} = \dfrac{eB}{mc}$. That gives $1 - \dfrac{V}{c} = \dfrac{2\omega_{cycl}^2}{\omega^2}$. Let us consider the parallel momentum distribution of the electrons as: $dn = f(p_\parallel)\, dp_\parallel$. Substituting dn for N and using $p_\parallel = \dfrac{mc}{2}\dfrac{\omega}{\omega_{cycl}}$, we obtain for the spectral density

$$J_\omega = \frac{e^2T_1}{2\pi c^2\omega_{cycl}}\omega^2 f\left(\frac{mc}{2}\frac{\omega}{\omega_{cycl}}\right) d\omega. \tag{4}$$

Let us consider two cases. The first is the relativistic Maxwell distribution $f = \dfrac{n_0 c}{T_2}\exp\left(-\dfrac{p_\parallel c}{T_2}\right)$, where n_0 is

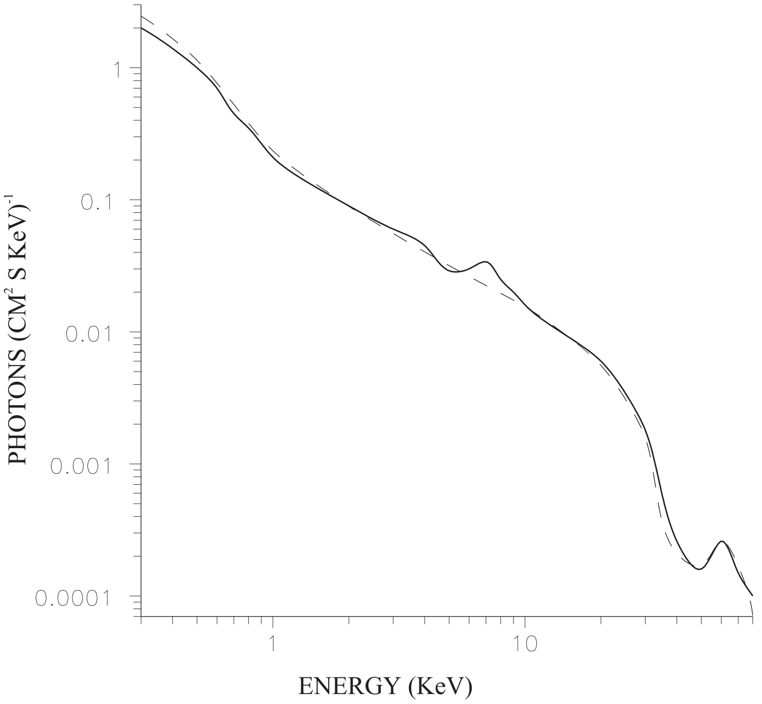

Figure 2: Comparison of the observational and computational X-ray spectra of Her X-1. The solid curve is the observational results taken from McCray *et al.* (1982), the dot curve is the approximation with $T_s = 0.9$ KeV, $T_e = 8$ KeV, $\tau_e = 14$, $a = 7\times10^{-4}\ \frac{\text{eV}\cdot\text{s}}{\text{cm}}$, $\sigma = 10^{-4}\ \frac{\text{eV}\cdot\text{s}}{\text{cm}}$, $B = 4\times10^{10}$ Gs

the number of emitting electrons. The spectrum is

$$J_\omega = \frac{n_0 e^2}{2\pi c\omega_{cycl}} \frac{T_1}{T_2}\omega^2 \exp\left(-\frac{mc^2\omega}{2\omega_{cycl}T_2}\right)\, d\omega. \tag{5}$$

It has a single maximum at $\dfrac{\omega}{\omega_{cycl}} = \dfrac{4T_2}{mc^2}$. In the second case $f = \dfrac{n_0}{\sqrt{\pi}\sigma}\exp\left[-\dfrac{(p_\parallel - a)^2}{\sigma^2}\right]$. The spectrum of radiation is

$$J_\omega = \frac{n_0 e^2 T_1}{2\pi^{3/2}c^2\omega_{cycl}\sqrt{\sigma}}\omega^2 \exp\left(-\frac{\left(\dfrac{mc}{2}\dfrac{\omega}{\omega_{cycl}} - a\right)^2}{\sigma^2}\right)\, d\omega. \tag{6}$$

When $\sigma \ll a$ this spectrum has a single maximum at $\omega \simeq \dfrac{2a}{mc}\omega_{cycl}$. The experimental spectra taken from [26, 25] have been approximated in [1]. The last spectrum (solid line) and its fitting (dashed line) are shown in Fig. 2. In accordance with [5] it was taken $a = 7\times10^{-4}\ \frac{\text{eV}\cdot\text{s}}{\text{cm}}$, corresponding to average electron energy $E_\parallel = ac \approx 20$ MeV. The best fit for the line shape was then obtained at the magnetic field strength $B = 4\times10^{10}$ Gs. In this model the beam of the “cyclotron” feature is determined by the number distribution of the emitting relativistic electrons, moving predominantly along the magnetic field, over the polar cap.

In order to obtain the whole experimental spectrum of the Her X-1 the following model of the hot spot (Fig. 3) was considered in [1]. A collisionless shock wave is generated in the accretion flow near the surface on the magnetic pole of a neutron star. In its front the ultrarelativistic electrons are generated. Under the shock there is a hot turbulent zone with the temperature T_e and the optical depth τ_e, situated over a heated spot with smaller temperature on the surface of the neutron star.

The whole X-ray spectrum of pulsar Her X-1 from [25] is represented in Fig. 3 by the solid line. There are three main regions in it: a quasi-Planckian spectrum between 0.3 and 0.6 KeV that is generated (re-radiated) near the magnetosphere of the X-ray pulsar; power-law spectrum $(0.6 \div 20)$ KeV with a rapid decrease at

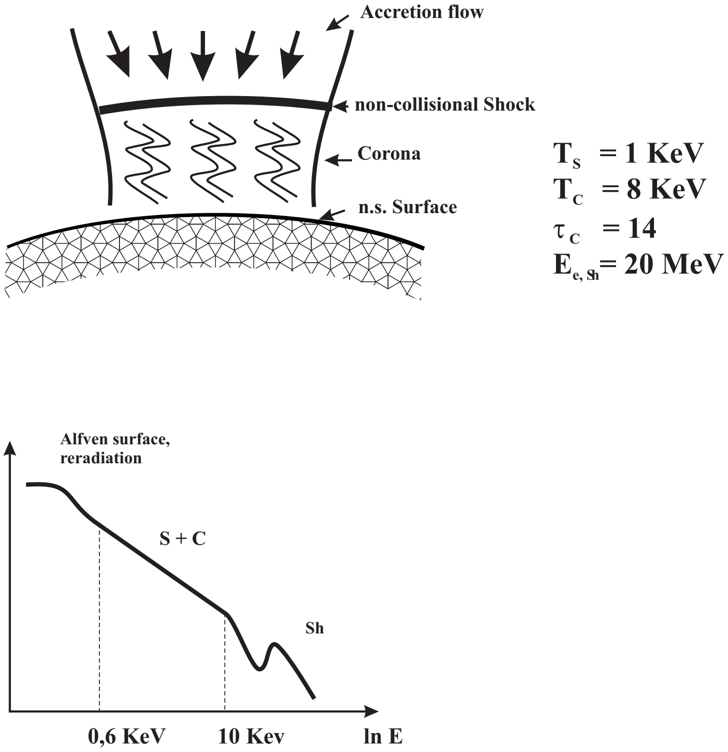

Figure 3: Schematic structure of the accretion column near the magnetic pole of the neutron star (top), and its radiation spectrum (bottom)

20 KeV, and the "cyclotron" feature. The power-law spectrum is a result of comptonization in the corona of a black-body spectrum emitted by the stellar surface. The comptonized spectrum has been calculated according to Sunyaev and Titarchuk (1980). Setting the neutron star radius equal to 10 km, distance to the X-ray pulsar 6 Kps, hot spot area $S = 2{\times}10^{12}$ cm^2, the best fit is found at $T_s = 1$ KeV, $T_e = 8$ KeV, $\tau_e = 14$, which is represented in Fig. 3 by the dashed line.

The observations of the variability of the "cyclotron" lines are reported in [27]. Ginga detected changes of the cyclotron energies in 4 pulsars. The change is as much as 40% in the case of 4U 0115+63. Larger luminosity of the source corresponds to smaller average energy of the cyclotron feature. These changes might be easily explained in our model. The velocity of the accretion flow decreases with increasing of the pulsar luminosity because locally the luminosity is close to the Eddington limit. As a result, the shock wave intensity drops as well as the energy of the ultrarelativistic electrons in its front, leading a decrease of the relativistic dipole line energy.

MAGNETARS

Among more than 2000 cosmic gamma ray bursts (GRB) 4 recurrent sources had been discovered, and were related to a separate class of GRB, called soft gamma repeaters (SGR). Besides observations of short, soft, faint recurrent bursts, three of them had given giant bursts, most powerful among all GRB. All four SGR are situated close or inside SNR, three of them show long periodic pulsations. These properties had separated SGR, situated in our or nearby galaxies, in a quite special class, very different from other GRB, which are believed to have a cosmological origin at red shifts $z \sim 1$. One SGR 1627-41 was discovered by BATSE [38] and three other were discovered in KONUS experiment in 1979 [23, 12]. Three of SGR show regular pulsations, and for two of them $\dot{P}$ were estimated, indicating to very high values of the magnetic fields, up to 10^{15} Gs, and small age of these objects [14, 16, 23, 24].

The physical connection between SGR and related SNR is not perfectly established: SNR ages are much larger than ages of SNR estimated by P and $\dot{P}$ measurements, and all four SGR are situated at the very edge of the corresponding SNR, or well outside them. Using the pulsar age estimation we come to conclusion of a very high speed of the neutron star at several thousands km/s, exceeding strongly all measured speeds of radiopulsars. Physical properties of the pulsars observed in SGR are very unusual. If the connection with SNR is real, and the distances to SGR are the same, then the pulsar luminosity during giant bursts is much larger than the critical Eddington luminosity. As follows from simple physical reasons, when the radiation force is much larger than the force of gravity, the matter would be expelled at large speed, forming strong outflow and dense envelope around the neutron star which could screen pulsations. No outflowing envelope around SGR have been found. The large difference between $\dot{E}_{rot}$ and average $L_x + L_\gamma$ luminosity needs to suggest a source of energy, much larger than the one coming from the rotational losses. It is suggested that in magnetars the energy comes from the magnetic field annihilation [8]. It is rather surprising to observe the field annihilation without formation of relativistic particles, where considerable part of the released energy should go. Radio emitting nebula should be formed around the SGR, but have not been found. So, it is not possible to exclude that there is no physical connection between SNR and SGR, that SGR are much closer objects, their pulsar luminosity is less than the Eddington one, and their magnetic fields are not so extremely high.

There is a striking similarity between SGR and special class of X-ray pulsars called anomalous X-ray pulsars (AXP). Both have periods in the interval 6–12 seconds, binarity was not found, spin-down of the pulsar corresponding to small age ~ 1000 years, observed irregularities in $\dot{P}$. The main difference is an absence of any visible bursts in AXP, characteristic for SGR. Suggestions have been made about their common origin as magnetars [16]. We may expect that the establishing of the nature of AXP would help strongly for the determination of the nature of SGR.

CONCLUSIONS. SOME QUESTIONS AND ANSWERS ABOUT MAGNETARS

1. Magnetic fields of radiopulsars are in good correspondence with theoretical estimations. **2**. RP and LMXB have small magnetic fields, which very probably were decreased by damping or screening during accretion stage. **3**. Contradiction between high B_{cycl} and other observational estimations of B in the LMXB Her X-1 may be removed in the model of relativistic dipole mechanism of the formation of a hard spectral feature by strongly anisotropic relativistic electrons, leading to conventional value of $B \approx 5 \times 10^{10}$ Gs. **4**. Very high magnetic fields in magnetar model of SGR needs further confirmation and investigation.

1. **Q**. Is it possible to observe an influence of a giant burst on the related SNR ? **A**. Maybe. Radio observations of SNR are needed with search for changes, wisps like in the Crab nebula.
2. **Q**. What could we see if SGR would be 10 times farther ? **A**. Ordinary short GRB.
3. **Q**. How many "SGR" we should have seen in neighboring galaxies (Andromeda) by their giant busts? **A**. ~ 10 in Andromeda. Better statistical estimation and search in BATSE/KONUS data are needed.
4. **Q**. Are short GRB identical with distant SGR? **A**. Maybe yes.
5. **Q**. How many SGR remnants should be in the Galaxy if SGR-SNR connection is real? **A**. About 10^8 neutron stars.
6. **Q**. Is it possible to provide γ-radiation by magnetic field annihilation without appearance of the large number of ultra-relativistic particles and strong nonthermal emission in other spectral bands? **A**. Solar flashes produced by field annihilation are characterized by very broad spectrum, from radio to gamma.
7. **Q**. Is it possible to use pulsar-like formula for age estimation of SGR and its magnetic field from P and $\dot{P}$ measurements, when $L_{tot} \gg \dot{E}_{rot}$? **A**. Probably not [22].

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