The drift model of "magnetars"

(Nature of AXPs, SGRs and radio pulsars with very long periods)

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Abstract

It is shown that the drift waves near the light cylinder can cause the modulation of emission with periods of order several seconds. These periods explain the intervals between successive pulses observed in "magnetars" and radio pulsars with long periods. The model under consideration gives the possibility to calculate real rotation periods P of host neutron stars. It is shown that P $\lesssim$ 1 sec for the investigated objects. The magnetic fields at the surface of the neutron star are of order 10^{11} –10^{13} G and equal to the fields usual for known radio pulsars.

Magnetars

Table 1. Observed parameters of well studied AXPs and SGRs.
(f_{pl} is pulsed part of emission (Kouveliotou et al.1999,Ibrahim et al.2003, Kaspi & Gavriil 2004), W_x pulse width)

№	Source	P_{obs} (s)	$(dP/dt)_{-11}$	log L_x (erg/s)	f_{pl} (%)	W_x/P_{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

If follows from the model of the magneto-dipole slowing down, that magnetic fields B at the surface of a neutron star in AXPs and SGRs must be $10^{14} – 10^{15}$ G, two orders of magnitude higher than fields in "normal" pulsars. It was suggested that X-ray radiation took its energy from a magnetic reservoir. In this case the total energy of such reservoir is

$$E = (B^2/8\pi)(4\pi R^3/3) = 1.7\ 10^{45}\text{-}1.7\ 10^{47}\ \text{erg}, \qquad (1)$$

where R = 10 km is the neutron star radius. The X-ray luminosity of SGR 1806-20 is $2\ 10^{35}$ erg/s. For $E = 10^{47}$ erg this source will exist during 10^4 years only. 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 (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 will convert in very strong magnetic fields ($B >> 10^{12}$ G) into two other gamma-quanta (Baring, & Harding. 1998). Therefore AXPs and SGRs must be radio quiet objects. However Shitov, Pugachev, & Kutuzov (2000) detected radio emission from SGR 1900+14 and Malofeev et al.(2005) 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 AXPs and SGRs are much less than $10^{14} – 10^{15}$ G.

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. Hence, the basic suggestion on the magneto-dipole braking is not correct.

Other models

1. **Accretion (see, for example, Marsden et al. 2001). Accretion from ambient plasma gives an additional energy source for $B_s \sim 10^{12}$ G and it is not necessary to suggest super-strong magnetic fields. However the accretion from the interstellar medium can provide luminosities $L \sim 10^{32}$ erg/s, much less than the observable ones (see Table 1). If accretion is connected with a relic disk then time of life of this disk is very small and such accretion does not describe the observed slowing down of AXPs (Li 1999). Plasma from a secondary component could explain the observed luminosities for the rate of accretion $dM/dt \sim 10^{-11}$, but there were any evidences of such companions in all AXPs and SGRs.**

   2. 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 (dE/dt) ~ 36. It is not enough to explain injection of relativistic particles in ambient SNRs. Moreover extremely short periods of white dwarfs are required.

   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.

   4. Free precession of a neutron star can have periods of order 10 seconds (Shaham 1977, Sedrakian et al. 1999) but such long living precession is doubtful realized. Shaham (1977) was the first author who said that the pulse period was

not equal to the rotation period but was determined by the other periodic process.

We believe also that the interval between two successive pulses is not equal to the rotation period .

In this report we discuss a drift 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.

Mechanism for changing the field line curvature

As was shown by Kazbegi et al.(1991), transverse electromagnetic drift waves could be generated in the magnetosphere. These waves propagate almost perpendicular to the magnetic field and are characterized by the frequency

$$\omega_0 = \mathrm{Re}\,\omega = k_x u_x^b \qquad (2)$$

and the increment

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

In (2) and (3) k is a wave number and u is a drift velocity

$$u_x = \frac{c v_\varphi \gamma_r}{\rho\, \omega_B}, \qquad (4)$$

where ρ is the radius of curvature of the field line and γ_r is the Lorentz factor of the resonant particles.

This increment is quite small: when $\gamma_b \sim 10^6$ and $\gamma_p \sim 10$, we obtain $\Gamma \sim 10^{-4}\,\omega_0$. However, since the wave is almost perpendicular to the magnetic field, it propagates around the magnetosphere and is located in the generation region for a long time. As a result, the amplitude of the drift waves can increase to large values (Kazbegi et al. 1991) via the kinetic energy of the particles moving along the magnetic field with velocity V_φ., while the wave remains in nearly the same place. Its amplitude increases until nonlinear processes (in particular, induced scattering by the particles) begin to transfer wave energy to the region with the minimum wave number k (i.e., the maximum wavelength λ_{max}). The value of λ_{max} depends on the transverse size of the magnetosphere, which can be identified with the radius of the light cylinder $r_{LC} = cP/2\pi$.

The resulting change of the field line curvature caused by such drift waves is

$$K \approx (1 - k_\varphi\, r\, B_r / B_\varphi)/r \qquad (5)$$

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.

The model under consideration

Let us consider the case of small angles β between the rotation axis of a neutron star and the vector of its magnetic moment μ (Fig.1). Radiation from such object can be registered during almost all its period. If a disturbance of field lines takes place due to the interaction with the drift waves, an additional emission appears. This part of emission missed the line of sight before such interaction (the broken line in Fig.1). Now it goes to the observer (the solid line in Fig.1). This part of emission has pulsed character. Its period is $P_{dr} = 2\pi / \omega_{dr}$, and such emission explains the main properties of "magnetars". This period determines the interval between observed pulses:

$$P_{dr} = 2\pi / (k_x u_x^b) = \lambda_{dr} / u_{dr}^b \qquad (6)$$

As we noted earlier the maximum value of the wavelength was $\lambda_{max} = c P/2\pi$. In this case taking for the curvature radius value $\rho = c P / 2\pi$ we can write (Malov, Machabeli, & Malofeev 2003):

$$P_{dr}^{max} = e B P^2 / (4 \pi^2 m c \gamma_b) \qquad (7)$$

To obtain the observed value of the pulse period P_{dr}^{max} ~10 s we must fulfil the following equality:

$$B P^2 = 22.45 \text{ G s}^2 \qquad (8)$$

Here we put $\gamma_b = 10^6$. If magnetic field is dipolar and its value at the surface of a neutron star is $B_s \sim 10^{12}$ G then B ~ 1000 G at distances r ~ 1000 R. The rotation period of such a star must be equal to P = 0.15 s according to the equality (9). Hence "normal" magnetic fields of neutron stars can explain observed periods of "magnetars" P_{obs} ~10 s if there are drift waves in the vicinity of the light cylinder. If the rotation period P = 2 s and the value of the surface magnetic field $B_s = 10^{12}$ G, then $P_{dr}^{max} \approx P \approx 2$ s at the light cylinder. In this case drift of subpulses can be observed (Kazbegi et al. 1991).

The equality (7) gives the possibility to link the observed derivative of the period $(dP/dt)_{dr}$ with the real rate of the slowing down of the neutron star rotation dP/dt:

$$(dP/dt)_{dr} = e B P \, dP/dt / (2 \pi^2 m c \gamma_b) \qquad (9)$$

The dependences (7) and (9) show that if there are jumps of the rotation period and its derivative ("glitches") then similar jumps must be in observed values of P_{dr} and (dP_{dr}/dt) as well.

Taking into account two peculiarities of objects under consideration, namely i) small angles β between rotation and magnetic axes ($\beta < 10^0$) and ii) small rotation periods ($P \lesssim 0.1$ sec) we can estimate the expected number of AXPs and SGRs among the known radio pulsars. The first group (i) contains about 10 % of the whole pulsar population, if neutron stars are formed with an arbitrary angle β. The second one (ii) number approximately 0.1 part of all pulsars. So, we can expect ~ 1 % of "magnetars" in the whole sample of 1500 radio pulsars. In fact, we observe about 15 such objects.

So, our model can describe all main characteristics of the known AXPs and SGRs

Radio pulsars with the registered X-ray pulsed emission are characterized by the mean value of the parameter $\gamma_b^{3/2} / \gamma_p^2$ = 4,37 10^8 (Malov 2003). We take this value for our sample. The estimate for the synchrotron luminosity can be obtained for AXPs and SGRs from L_x, if we take into account the beam width and the percentage of pulsed emission:

$$L = (W/P_н)^2 f_{pl} L_x \qquad (10)$$

Then we can calculate P, dP/dt and B from (7),(9) and the following equality (Malov 2003):

$$L = \frac{3^{1/2}\ \pi^{7/2}\ e}{32\ m^{1/2}\ c^{3/2}} \frac{I\ \gamma_b^{3/2}\ dP/dt}{P^{7/2}\ \gamma_p^2}\ , \qquad (11)$$

We have

$$P\ (s) = 8.32\ 10^{-2}\ \left[\frac{(P_н\ )_{-11}}{(L_x)_{34}\ (W/P_{obs}\ )^2\ P_{obs}\ \ f_{pl}}\right]^{2/5}\ , \qquad (12)$$

$$dP/dt = \frac{P\ (dP/dt)_{obs}}{2\ P_{obs}}\ , \qquad (13)$$

$$B\ (G) = 22.45\ P_{obs} / P^2 \qquad (14)$$

We assume that I = 10^{45} g cm^2 and $\gamma_b = 10^7$. The results of our calculations can be seen from Table 2.

It is worth noting that the values of dE/dt in Table 2 is higher than 10^{37} erg/s for many objects and they are quite enough to explain the observed injection of relativistic particles into ambient SNRs. Moreover the objects in our sample and radio pulsars with X-ray emission have as a rule short periods. For AXPs and SGRs in Table 2 <P> = 89 ms, and for 41 pulsars from the paper of Possenti et al. (2002) <P> = 128 ms.

The values of magnetic field in the region of observed X-ray emission have been calculated without any additional assumptions about its structure and value B_s at the surface of a neutron star. If emission is generated at the light cylinder and this field is dipolar we can estimate B_s (Table 2):

$$\log B_s = 11 + \log B + 3 \log P \qquad (15)$$

The mean value $< \log B_s >$ = 11.73 is similar to the strength of the surface field for normal radio pulsars.

In our model we can expect a modulation of observed emission with the rotation period. The detection of such modulation will be the good evidence of the vitality of this model.

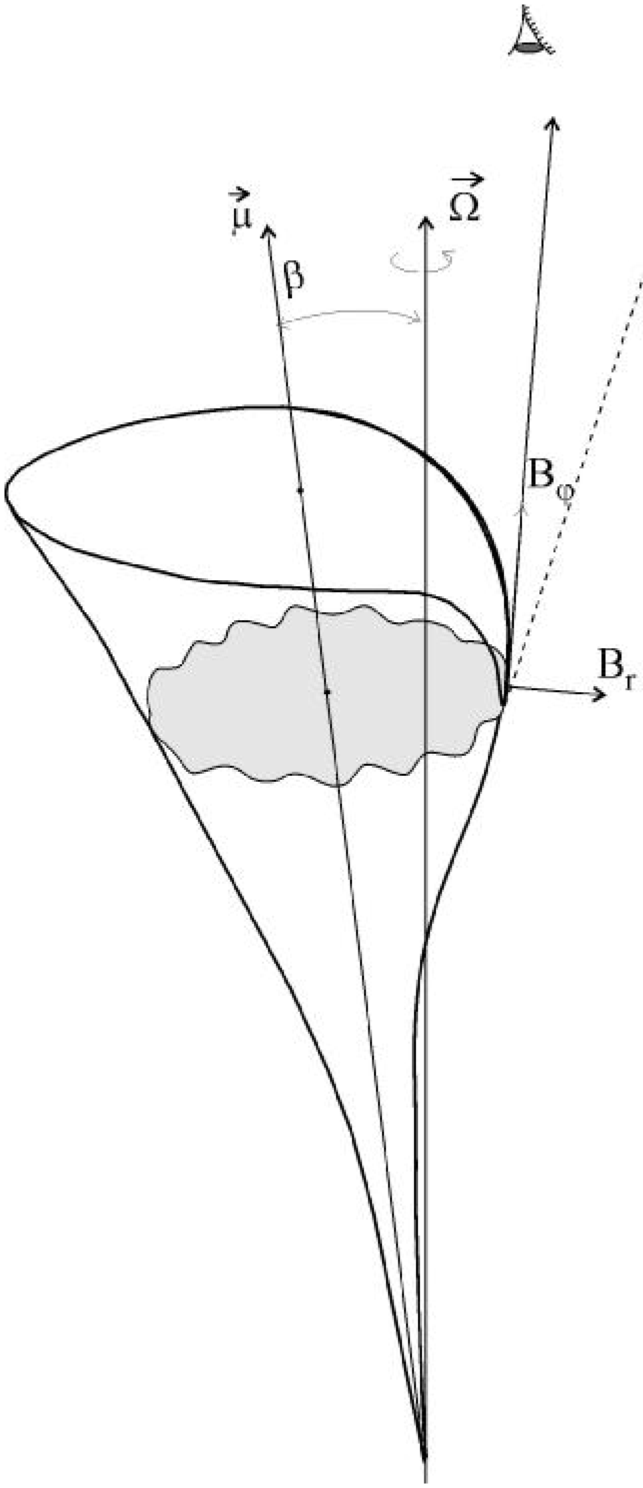

Fig.1. Scheme of the model

Quiescent X-ray emission and gamma-bursts from AXPs and SGRs

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

$$e_m - e_n = (p_{\wedge m}^2 - p_{\wedge n}^2) / 2 m_e = h n_0 S, \qquad (16)$$
$$S = (m - n) = \pm 1, \pm 2, \ldots$$

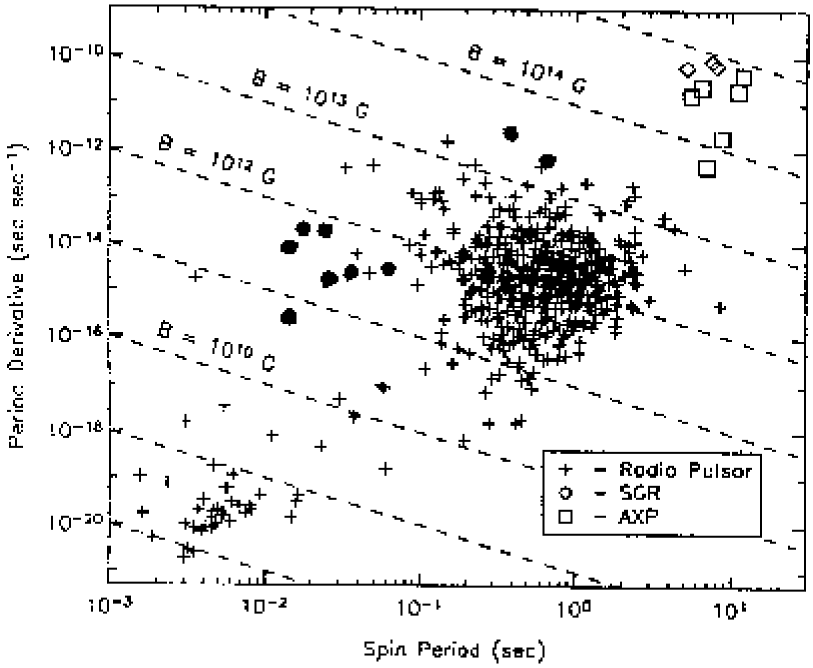

Fig.4. Location of AXPs and SGRs on the diagram (dP/dt)- P in the frame of our model (black circles) and the "magnetar" model (Woods, & Thompson 2004).

Lines corresponding to such harmonics have been detected in fact (Rea et al. 2003). They correspond to B ~ $10^{11} – 10^{12}$ 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 ~ $10^{14} – 10^{15}$ 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 n **in the observer's coordinate system depends on the frequency** n_0 **in the system where** $V_{\|} = 0$ **:**

$$n = n_0 \frac{(1 - V^2 / c^2)^{1/2}}{1 - V \cos a / c}, \qquad (17)$$

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

If the Lorentz-factor of emitting particles g >> **1, and the angle** a **is small, the formula (9) can be presented in the following form:**

$$n = \frac{2 n_0}{1/g + a^2 g} \qquad (18)$$

If $a^2 g << 1/g$**, then** $n » 2n_0 g$**. For** $1 \lesssim a^2 g \lesssim 10$ **and B ~** 10^{12} **G the electron cyclotron frequency 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 too.

Table 2. Calculated parameters of AXPs and SGRs.

№	Source	P (ms)	dP/dt / 10^{-15}	log L (erg/s)	log B (G)	log (dE/dt) (erg/s)	- logη	$\log B_s$ (G)
				AXP				
1.	4U0142+61	19.81	2,23	33,91	5,70	37,06	3,15	11,60
2	1E1048-5937	87.22	2,58	33,72	4,28	37,18	3,46	12,10
3.	RXS1709-4009	11.84	10	35.35	6.25	38.38	3.03	11.46
4.	1E1841-045	22.41	40	34.97	5.72	38.14	3.17	11.77
5.	1E2259+586	10.75	0.372	34.06	6.13	37.07	3.01	11.22
6.	XTEJ1810-197	13.78	14	35.27	5.82	38.33	3.06	11.24
				SGR				
1.	SGR1806-20	25.60	1.42	33.32	5.41	36.52	3.20	11.64
2.	SGR1900+14	520	5545	32.34	2.63	36.19	3.85	12.79

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:

$$P_\nu = P_{\nu 0} \frac{1}{1 - V \cos\alpha / c} \qquad (19)$$

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

$$P_\nu \approx 2 P_{\nu 0} \gamma^2 \qquad (20)$$

So, the power in the gamma-ray range can be 2 g^2 times higher than in X-ray one. If X-ray power is 10^{36} erg/s, the Lorentz-factor must be $g \sim 10^4$ to provide a gamma-ray burst with the power 10^{44} erg/s. In the traditional model such energy characterizes the tail of the distribution function for the secondary particles. To achieve the power 2 10^{46} erg / sec as in SGR 1806-20 we must put $g \sim 10^5$. There are such particles in the tail of the secondary plasma as well. Any changes in the angle a **must cause significant changes in observed spectra as well. This can explain differences between spectra before and after bursts**

Radio pulsars with very long periods (Lomiashvili et al. 2006)

Table3: Radio pulsars with observed long periods.

No	Pulsar	P (s)	dP/dt (10^{-15})	Bs(10^{12} G)	$\dot{E}$(10^{32} erg/s)
I	PSR J2144-3933	8.5	0.48	2	0.00032
II	PSR J1847-0130	6.7	1275	94	1.7
III	PSR J1814-1744	4.0	743	55	4.7

Discussion

One of the main characteristics of observed emission is the stability of pulse periods. The drift waves are stabilized due to the neutron star rotation and the permanent injection of relativistic particles in the region of their generation. Moreover as is shown by Gogoberidze et al. (2005), the nonlinear induced scattering leads to a transfer of waves from higher to lower frequencies. As the result one eigenmode becomes dominant. So the wave energy accumulates in waves with the certain azimuthal number m, characterizing the lowest frequency. This means that the period of the modulation and the interval between observed pulses must be rather stable.

In fact, the spectral energy of the drift waves with smaller periods is much less than that of the mode with the period $P = P_{dr}^{max}$.

We have used the suggestion on the small angles between rotation axes and magnetic moments of neutron stars in AXPs and SGRs. In fact observed X-ray pulses in these objects are quite wide, and this indicates that they are nearly aligned rotators.

Recently discovered transient radio pulsars (McLaughlin et al. 2005) may belong to the population of objects described by our model. Indeed, 5 of them have rather long visible periods (P > 4 sec) and one of them has the surface magnetic field obtained in the magneto-dipole model $B_s = 5\ 10^{13}$ G > B_{cr}. Precession, star-quakes or other reasons can lead to the fulfillment of the condition $\alpha_{min} < \theta$ for a short time and to an appearance of a number of visible pulses.

Table 4. Calculated values of pulsar parameters.

Pulsar	m	P_{dr} (s)	P (s)	$(dP/dt)_{-15}$	B_s (10^{12} G)	dE/dt (10^{32}erg/s)	Δβ (deg)	$\beta_0 \approx \delta$ (deg)	θ (deg)	W_{10}/P
PSR J2144-3933	10	17.0	0.85	0.048	0.2	0.032	7	7	1.5	0.1
PSR J1847-0130	6	13.4	1.12	210	16	61	5	5	3	0.3
PSR J1814-1744	8	8.0	0.5	190	6.9	300	5	5	2	0.2

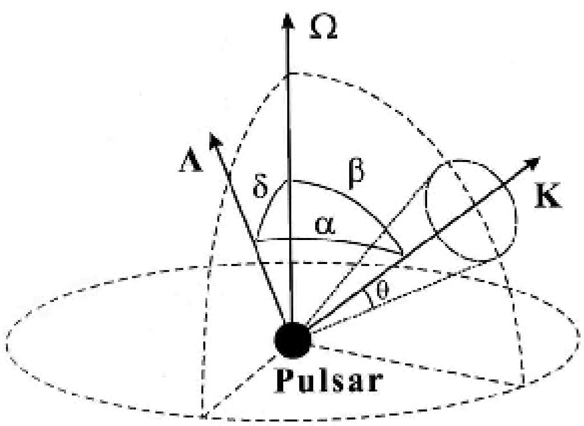

Fig.7. Geometry under consideration. K is emission axis, A is observer's one. Angles δ and θ are constant, while β and α are oscillated with time.

Conclusions

1. **It is shown that there are many difficulties in the magnetar model.**
2. **The drift model is proposed to explain the main peculiarities of AXPs and SGRs.**
3. **In the framework of the drift model rotation periods P, their derivatives dP/dt, and magnetic fields B in the region of emission generation are calculated for AXPs and SGRs. P = 11 -520 ms, <P> = 89 ms, dP/dt = 3.7 10^{-16} - 5.5 10^{-14}, log B = 2.63 – 6.25.**
4. **Magnetic fields at the surface of AXPs and SGRs are estimated: log B_s = 11.22 – 12.79, <log B_s > = 11.73**
5. **In the drift model a modulation of emission with periods of order 0.1 sec should be observed.**
6. **The persistent X-ray emission in the range 1 – 10 keV can be explained by cyclotron radiation at the surface with magnetic fields $B_s \sim 10^{12}$ G.**

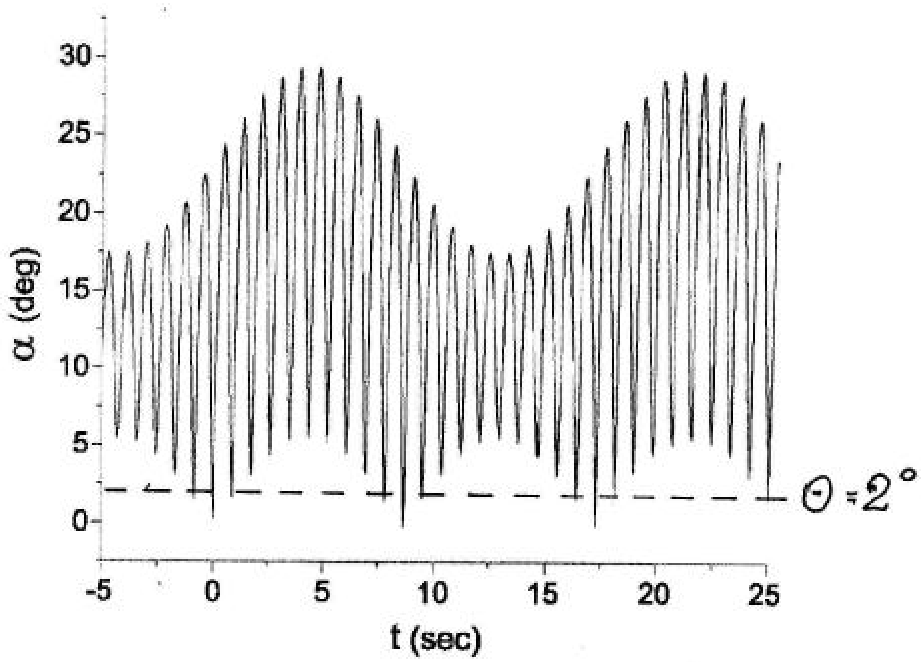

Fig.8. The oscillating behaviour of α with time for $\beta_0 = \delta \approx 0.12$, $\Delta\beta = 0.12$, $\omega_{dr} = 2\pi/17$ sec^{-1}, $\Omega = 2\pi/0.85$ sec^{-1}, $\Phi = 0$.

7. Electron cyclotron lines can be observed in this diapason.

8. If the magnetar model is realized an absorption line with energy of order 1 MeV must be observed

9. Any cataclysms at the surface of a neutron star in AXPs or SGRs should cause bursts of emission in X-ray or gamma-range with power $2\gamma^2$ times higher than persistent X-ray one.

10. Radio pulsars with observed periods P > 4 sec can be described in the framework of the drift model too. In this case observed pulses must be quite narrow, as seen in pulsars under consideration. Sometimes we can see several subpulses as a result of subsequent neutron star rotations. Our model predicts a detection of such objects in future.

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