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Gamma-ray emission from magnetar surface due to starquake

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ABSTRACT: *A simple model is proposed to study the gamma-ray emission from the polar cap region of magnetar which is predicted to be the cause of starquake. As the strong magnetic field strength is found to be in the order of 10^{15}G due to shear modulus and it evolves to the exterior through the solid crust of a magnetar, an electric current along the magnetic field flowing in a corotating stellar magnetosphere generates a charge density. We estimate the luminosity of magnetar and found to be in the order of 10^{45} erg s^{-1} by adopting and calculating the potential difference between the centre and outer edge of the polar cap, conforming to γ-ray emission. An estimate for characteristic time scale due to magnetic field decay through the ohmic dissipation is made.*

Keywords: *Gamma rays: emission mechanism; starquake; neutron stars: magnetic fields; magnetars.*

I. INTRODUCTION

The magnetic field strengths of neutron stars are calculated by magnetar models (Thompson & Duncan 1995) and found to be in the order of 10^{14}–10^{16}G, above the quantum electrodynamic field strength≈4.4×10^{13}G.These neutron stars are known as magnetars. In the case of magnetar the spin periods p∼ (5–8) s, high spin-down rates $\dot{p}\sim 5\times(10^{-13}–10^{-10})$ s/s and the short lifetime periods $p/2\dot{p}\sim(10^{3}–10^{5})$ years are due strong magnetic fields (Thompson & Duncan 1996) and estimated the luminosity of SGRs in the range 10^{34}–10^{36}erg/s.

Recently, Thompson, Lyutikov, & Kulkarni (2002) have proposed a model of the SGRs based on the dissipation of the internal superstrong magnetic field, generated by a hydromagnetic dynamo as the star is born by external currents flowing in the magnetosphere. They argued that the currents supporting the strongly twisted field inside the neutron stars are gradually transported into the external magnetosphere, where they can be efficiently dissipated. The rate with which the currents are transported into the magnetosphere depends on the tensile strength of the neutron star crust and the strength of the nonpotential (current carrying) magnetic fields. Two regimes are possible: for plastic-type deformations of the crust, the twist is implanted at a more or less constant rate, while for fracturing-type deformations; the twist is implanted in sudden events.

Most of the magnetic energy is contained in the interior, and a smaller (but possibly comparable) amount in the magnetosphere. Rearrangements therefore release energy both in the magnetosphere and in the interior. Apparently, some rearrangement takes place suddenly, cause of fractures. The atmospheric energy release in such an event powers the observed outbursts while the internally dissipated energy leaks out more slowly, adding to the quiescent emission (Thompson & Duncan 1996). A straight forward extension of this interpretation is the possibility that the outburst episodes actually involve cracking the neutron star crust and consequent release of magnetic energy in the magnetosphere (Thompson & Duncan 1995). A slow steady change in the interior field, with the surface field kept in place by the solid crust, would slowly build up magnetic stress at the crust/core boundary, which is released in crustal quakes. As the massive magnetic field of the magnetar moves through the star's solid crust, it stresses and sometimes breaks the crust called starquake (Thompson & Duncan 1996). Each time we see a burst from an SGR, we are observing a starquake in action. Starquakes are probably responsible for the massive amounts of energy released by the SGR.

Flowers and Ruderman (1977) consider a uniform field in the neutron star interior with a potential field outside it. They found this to be unstable on a dynamic timescale. In a fluid star, without stabilizing solid state forces, the equivalent process would be to cut the star in half along a plane along the field lines. This reduces the energy in the potential field outside the star, whilst all energy forms inside the star (magnetic, thermal, and gravitational) remain unchanged.

The non-thermal persistent emission of the SGRs has been ascribed to a static twist imparted to external magnetic field by sub-surface motions during X-rays flares, with the effect of diverting an electrical current from the interior of the star to its exterior(Thompson et al. 2000). Magnetic fields exceeding∼10^{14} G are strong enough to fracture the crust called starquake, at the deep crust of a neutron star and if stronger than∼10^{15} G, will undergo rapid transport through the dense stellar interior over the short period∼10^{4}–10^{5} years active life time of the SGR/AXP sources(Thompson & Duncan 1996; Heyl & Kulkarni 1998).

We describe a model for the high energy γ-ray emission from the polar cap region of a neutron star with strong magnetic field introduced by Sturrock (1971) strongly based on Goldreich-Julian model (1969). Goldreich-Julian model considered a pulsar as a rotating neutron star, where magnetic dipole moment is aligned with rotational axis. As a difference with Goldreich-Julian model, Sturrock model does not require the alignment of the magnetic dipole with rotation axis. Any field line that expands up to the light cylinder is opened and it extends far beyond the light cylinder.The charged particles in the magnetosphere co-rotate with the star. However, because the velocity of the charged particles cannot exceed the speed of light, there is a limit to how far the charged particles can rotate with the star. This limiting distance R_L=c/Ω is referred to as the light cylinder radius (Meszaros 1992). Only magnetic field lines within the light cylinder can close, otherwise particles would be forced to move beyond the speed of light. Beyond the light cylinder field lines open, thus allowing charged particles to escape.

The closed field line region of the magnetosphere is assumed to be in rigid corotation with the star, thus inactive (no current flowing parallel to the magnetic field lines). The maximum potential drop available for acceleration is the potential drop ΔV_{pc} over the polar cap. Presently, the ideas that rotating magnetized neutron stars generate huge potential difference between the centre & outer edge of polar cap region.

In our proposed model, a superstrong magnetic field is assumed to exist in the interior fluid of a magnetar, which continuously evolves towards the magnetosphere (lower energy state) through the solid crust and in this process the crust is subjected to magnetic forces (Thompson et al. 2000) . When the magnetic forces get strong enough (Thompson et al. 2002), they can also yield to the magnetic stress and move plastically. This process heats the interior of the star and occasionally breaks the crust in a powerful ―starquake". Due to the crustal motion and starquake the magnetic fields that drift through the crust are twisted and rearranged. In the case of magnetar the magnetic field strength can be derived by using the Hooke's law of elasticity

$$B= 10^{15}\left(\frac{\mu}{10^{31} erg\ cm^{-3}}\right)^{\frac{1}{2}}\left(\frac{\theta}{10^{-3}}\right)^{\frac{1}{2}} G \tag{1}$$

Where μ is the shear modulus of the stellar crust, and θ is the strain imparted on the crust (Thompson & Duncan 1995). Baym & Pines (1971) calculated the shear modulus of a neutron star's crust and found it to be of the order $\mu{\sim}10^{31}\, erg\ cm^{-3}$. Most materials will fracture at a strain of $\theta{\sim}10^{-3}$.

In this paper, our goal is to investigate the luminosity of γ-ray emission from the polar cap region of the SGRs and characteristic decay timescale for ohmic dissipation due to the strong magnetic field evolving from the interior when it is subjected to magnetic stress. There are several sub-sections in section 2 where we discuss the physical parameters for the γ-ray emission from the polar cap region of magnetar. In this section a graph is shown for luminosity of γ-rays against potential differences. In section 3 we discuss the magnetic field decay through ohmic dissipation and hence calculate the characteristic time scale. Here also a graph is shown for characteristic time scales of magnetar against potential differences. Conclusions & discussions are made in the section 4.

II. PHYSICAL PARAMETERS FOR THE GAMMA-RAY EMISSION

2.1. Generation of current density:

We consider a superstrong magnetic field in the interior of a magnetar, which continuously evolves towards the magnetosphere through the solid crust and the crust is subjected to magnetic stress. This process heats the interior of the star and occasionally breaks the crust in a powerful starquake. Due to the crustal motion and starquake the magnetic fields that drift through the crust are twisted in the magnetosphere. Any field line that extends from the polar cap up to the light cylinder is opened and they extend far beyond the light cylinder and therefore, in the polar cap region, the magnetic field lines will act as natural magnetic funnels. The angular width of the funnel (cf. Baan and Treves, 1973) is given by $\theta_p \approx \mathrm{Sin}\theta_p = \left(\frac{R}{R_{lc}}\right)^{\frac{1}{2}}$ where, R is the radius of the magnetar, R_{lc} is the radius of the light cylinder=c/Ω, and Ω=Angular velocity=2π/p, with spin period p. In our choice of parameter, the spin period of magnetar p$\approx 7s$ & hence one can find out the radius of the polar cap r_p=Rθ_p=R $\left(\frac{R}{R_{lc}}\right)^{\frac{1}{2}} \approx 0.57\times10^4$ cm by adopting R=10^6 cm and $R_{LC} \approx 3\times10^{10}$ cm.

Thompson et al. (2002) proposed a model in which the magnetosphere of a magnetar is threaded by a large-scale current and this current arises from stresses imposed on the crust by highly twisted internal magnetic field due to starquake. Because of the field twisted, there is a component of B pointed around the loop, yielding a non-zero circulation. According to Ampere's law in integral form, current passing through the polar cap

$$I = \frac{C}{4\pi}\oint B_p.dl = \frac{c}{2}B_p r_p \tag{2}$$

Where $\oint B_p.\mathrm{dl} = B_p \oint dl = 2\pi B_p r_p$. In this case B_p is the magnetic field strength in polar cap region and r_p is the radius of the polar cap. We choice the magnetic field strength of magnetar $B_p = 10^{15}$G, & hence the current through the polar cap

$I \approx 0.9 \times 10^{29}$statampere.

Thompson et al. (2002) discussed the properties of the strongly twisted magnetosphere of SGRs and showed the current flowing along field lines which extend out to a radius R by normalizing the Goldreich and Julian current.Thompson et al. (2002) explained for the current that the magnetosphere can support corresponds to the toroidal field, reaching in strength approximately a poloidal field; $B_\Phi \approx B_\theta$ for moderately large twist and hence one can find the current as $I \approx 1.2\times 10^{31}$ stat ampere by adopting our choice of parametars.

2.2. Potential difference in the polar cap region:

Under the reasonable assumption that the magnetar is a rotating conducting sphere in a simplest electrodynamical model for a static, dipolar magnetic field aligned with the rotation axis. When the magnetar rotates, an electric field E is generated, which can compensate for the magnetic force. The vanishing of the net force implies that

$$E = -\frac{v\times B}{c} = -\frac{\Omega\times r\times B}{c} \quad (3)$$

Where $v = \Omega \times r$, with Ω is the angular speed of the magnetar. The electric force that is due to this field near the surface of magnetar (r≈R, radius of the magnetar) on a charged particle is very much stronger than the gravitational force and hence charged particles can be pulled out from the neutron star surface to the magnetosphere around the star. The charged particles spiral around the magnetic field lines and drift along the lines. It should be noted that the particles moving along the magnetic field lines will be accelerated by the electric field component parallel to magnetic field. The electric field may be decomposed as $E = E_\parallel + E_\perp$. In this case we consider the parallel component to the magnetic field in the polar region

$$E_\parallel = \frac{\mathbf{E.B}}{|\mathbf{B}|} = -\frac{\Omega R B_p}{c} \cos^3\theta \quad (4)$$

In the polar cap region the magnetic field lines starting out within an angular region $\theta < \theta_p$ which implies that $\cos\theta \approx 1$ and hence

$$E_\parallel = \frac{\Omega R B_p}{c} \quad (5)$$

Presently, the idea that rotating magnetized neutron stars generate huge potential differences between different parts of their surfaces is widely accepted. We consider a uniform magnetic field in the neutron star interior with a potential field outside it (Flowers and Ruderman 1977). The potential difference between the centre of the star and the outer edge of the polar cap

$$V_{pc} = \int_0^R E_\parallel.\mathrm{dl} = \frac{\Omega R^2 B_p}{c}$$

$$\approx 2.9 \times 10^{16} \left(\frac{B_p}{10^{15}G}\right)\left(\frac{R}{10^6 cm}\right)^2\left(\frac{p}{7s}\right)^{-1} \text{statvolt} \quad (6)$$

Across the open field line region, where B_p is the dipolar magnetic field strength at the pole, $\int_0^R dl = \mathrm{R}$ is the star radius. Zhang and Harding (2000) pointed out that rotating magnetized neutron stars are unipolar inductors that generate huge potential drops, $\Phi \approx 1.0\times 10^{13}$volt, across the open field line region, for the set of parameters, $B_p = 10^{14}$ G, p=8 s, and R=10^6 cm. Under certain conditions, a part, or even total amount of this potential will drop across a charged-depleted region (or a gap) formed in the polar cap area of the pulsar.

2.3. γ-ray emitted from the magnetosphere:

It is predicted that each time of burst from SGR; we observe a starquake in action and hence starquake is supposed to be responsible for energy released from SGR burst. The crustal motions generally drive currents outside the star, in the magnetosphere (lower energy state). In particular, when localized, lateral plastic slippage of the crust creates strongly sheared regions in the magnetic field above the star's surface, strong current will flow due to which X-rays or γ-rays generated and hence the Luminosity is given by

$$L = V_{pc}.I = \pi B_p^2 R^{\frac{7}{2}} R_{LC}^{-\frac{1}{2}} p^{-1}$$

$$\approx 2.6 \times 10^{45} \left(\frac{B_p}{10^{15}G}\right)^2\left(\frac{R}{10^6 cm}\right)^{\frac{7}{2}}\left(\frac{p}{7s}\right)^{-1} \text{erg s}^{-1} \quad (7)$$

across the polar cap region. It is pointed out by Zhang & Harding (2000) that the γ-ray luminosity of SGR, $L_\gamma \approx 1.8 \times 10^{32}$erg s^{-1} provided by the outer gap region, for the set of parameters, p=6s, B=10^{14} G, and R=15 km in which non thermal component has been taken into account and a function of the magnetic inclination angle is set up.

Assuming the potential differences, V_{pc} $\approx 2.9\times$ (10^{15}, 10^{16}, 10^{17}, 10^{18} , *and* 10^{19})stat volt, keeping the current constant by using the equation (8),we calculate the luminosities of γ-rays , L≈2.6×(10^{44}, 10^{45}, 10^{46}, 10^{47}, and 10^{48})erg s^{-1} and plot a graph as shown in the fig.1.

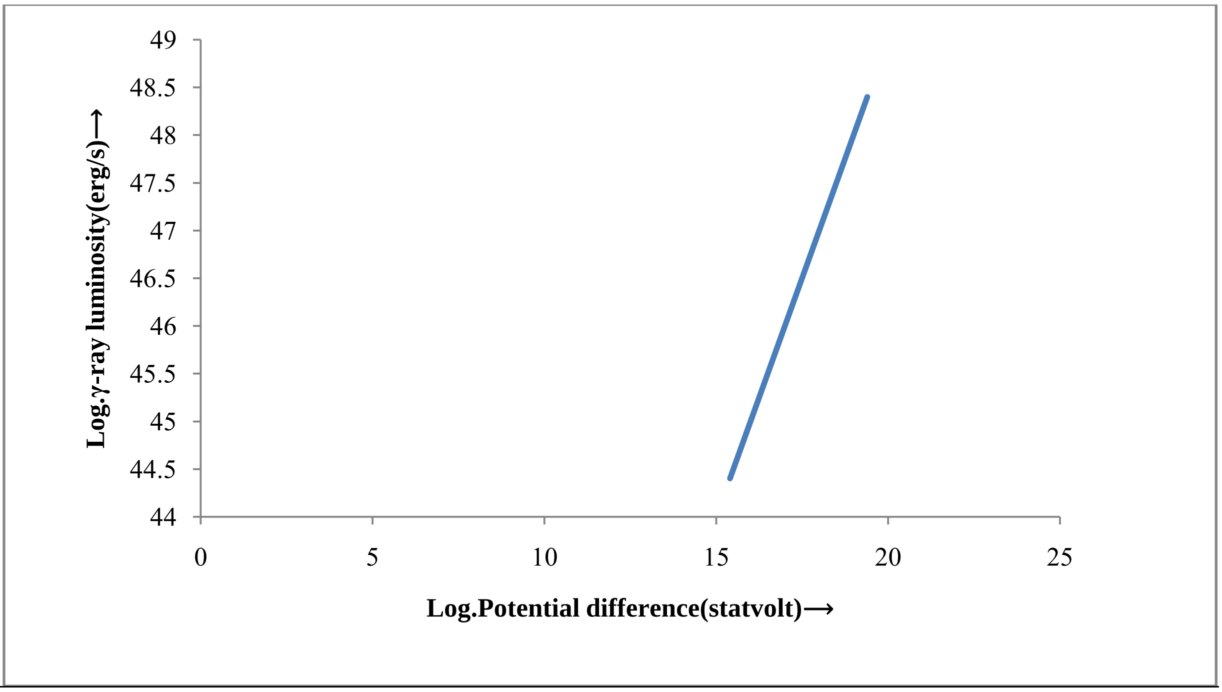

Figure 1: Log. Potential differences in statvolt against Log. Luminosities of γ-ray in erg s^{-1} are plotted.

III. MAGNETIC FIELD DECAY FROM MAGNETOSPHERE

Probably, all stars at all stages of their evolution have some magnetic fields, due to electronic currents circulating in their interiors. However, any decrease in the current I implies a decrease of the magnetic flux Φ. According to Ohm's law it can be stated that the voltage implies a certain effective resistivity in the magnetar magnetosphere,

$$\rho = \frac{V_{pc}}{I} \approx 3.2\times10^{-13}\left(\frac{V_{pc}}{10^{16}statvolt}\right)\left(\frac{I}{10^{29}statamp\ .}\right)^{-1}\text{Ohm} \qquad (8)$$

Where V_{pc} denotes the potential difference between the centre and outer edge of the polar cap, and I be the current in the polar cap. This resistivity leads to spread of the electric current across the magnetic lines. Thompson & Duncan (1996) stated that the magnetic field of a magnetar can provide the energy required to power the star. In order for this energy to power the star magnetic fields must be dissipated, and hence the power of the of the star

$$\frac{\partial}{\partial t}\left(\frac{B_p^2}{8\pi}\frac{4}{3}\pi R^3\right) = \frac{B_p R^3}{3}.\frac{\partial B_p}{\partial t} \qquad (9)$$

Again the power of the star= $V.I$ where the potential can be expressed as $V = E_{\|}r_p$ in the polar cap region.The electric field $E_{\|}$ can be expressed by writing Ohm's law, describing only Ohmic dissipation $E_{\|} = \rho J$ where J is the current density & ρ is the resistivity of the magnetosphere of magnetar. Hence the power in the polar region of the star

$$P = \rho J r_p.I \approx \frac{\rho}{\pi r_p} I^2$$

Where $J = I/\pi r_p^2$ and hence from the equation (2), the power

$$P = \frac{\rho c^2}{4\pi} B_p^2 r_p \qquad (10)$$

From equation (9) and (10), we see that the ohmic dissipation term is

$$\left(\frac{\partial B}{\partial t}\right)_{ohmic} = \frac{3\rho c^2}{4\pi R^3} B_p r_p \qquad (11)$$

We can determine the characteristic time scale τ_{ohmic} for ohmic dissipation

$$\tau_{ohmic} = \frac{4\pi R^3}{3c^2 \rho r_p} \approx 2.5 \times 10^6 \text{ s} \quad (12)$$

Goldreich & Reisenegger (1992) notice that τ_{ohmic} is independent of magnetic field and is only a function of the length scale and the conductivity. In this case we see that τ_{ohmic} is also independent of magnetic field and is only a function of polar cap radius and the resistivity while the magnetar radius is constant. Ohmic dissipation will not be important throughout the entire star; however can play an important role at small length scales (Cumming et al. 2004).

Assuming the potential differences, $V_{pc} \approx 2.9\times (10^{15}, 10^{16}, 10^{17}, 10^{18}, \& 10^{19})$stat volt, keeping the current constant, and using the equation (8) we calculate the characteristic time scales, $\tau_{ohmic} \approx 0.25 \times (10^8, 10^7, 10^6, 10^5, \& 10^4)s$, and plot a graph as shown in the fig.2.

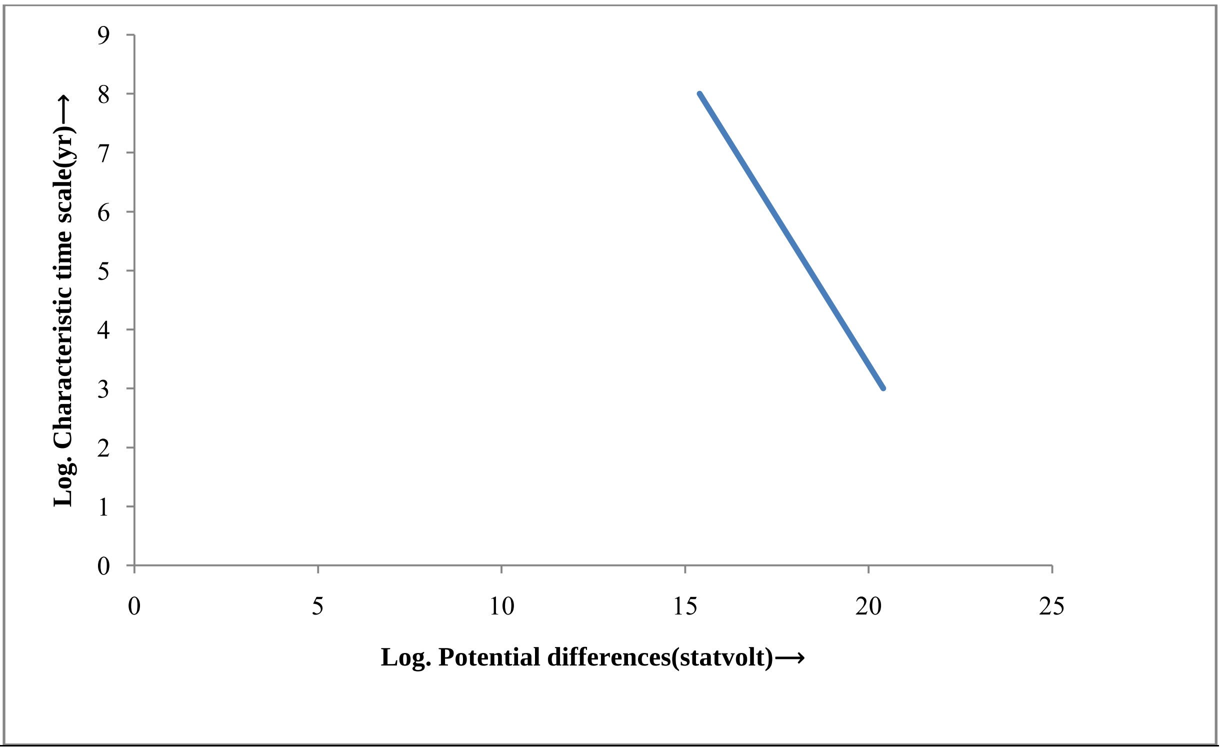

Figure 2: Log. Potential differences in statvolt against Log. Characteristic time scales in s of magnetic field decay for ohmic dissipation are plotted.

Gunn and Ostriker model (1970) in which the exponential decay of magnetic field is assumed. They obtained the value of $\sim 9 \times 10^6$yr for the time constant of the magnetic field decay and Wood et al. (1999) showed that magnetar's characteristic time scale $\tau_c \approx 10^3$yr.

IV. CONCLUSIONS AND DISCUSSIONS

We study the model of the 5th March, 1979; γ-ray event which was proposed by Singh & Duorah (1984), considered as a binary system (Mazets et al. 1979), and found the γ-ray luminosity of the order of $\approx 10^{35}$ erg/s by taking the magnetic field $B \approx 10^{12} G$. In the magnetar model, Duncan & Thompson (1992) suggested that the 5th March, 1979, γ-ray event was an isolated system and associated with supernova remnant (SNR) known as N49 designated SGR 0526-66 and we found the luminosity of the order of $\approx 10^{45}$ erg s^{-1} by adopting the magnetic field $B \approx 10^{15} G$, conforming to γ-ray emission.

We conclude from the figure 1 & 2 that, for a constant current density Gamma-ray luminosity increases with the dicreases of ohmic dissipation time scale of magnetar at particular stage of its evolution. According to Maxwell's equations of electromagnetism, it could be expected that changing the magnetic field strength (B) of magnetar is inversely proportion to its cross-sectional area, i.e.,$B \propto R^{-2}$, where R is the radius of magnetar. Cumming et al. (2004) argued that the ohmic dissipation can play an important role at small length scale. Hence from equation (7) it is concluded that the luminosity of magnetar increases as the core collapses.

In this paper, we discuss about the charge particle acceleration, a dipole configuration for the magnetic component has been assumed, whilst a magnetar magnetosphere is certainly non dipole. Thompson et al. (2002) argued that the SGR/AXP phenomenology is consistent with the hypothesis that the magnetar magnetosphere is globally twisted. So we prefer to study the charge-depleted acceleration regions in such a twisted magnetosphere, both near the ―polar cap" region and in the ―outer gap" region.

In the present case we calculate the characteristic time for ohmic dissipation $\tau_{ohmic} \approx 10^6$s by adopting the magnetic field B=10^{15} G and potential difference $V_{pc} = 2.9 \times 10^{16}$statvolt which is very small as compared with the value calculated by Goldreich & Reisenegger (1992) and explained separately the time scale of Ohmic dissipation $\tau_{ohmic} \approx 10^9\ yr.$ Zhang & Harding (2000) argued that an ambipolar diffusion is the dominant decay mechanism in the case of a field permeating the core, and the field strength is in the magnetar regime.

The pulsar-like behavior, powered by the spin-down energy of the neutron star, has not been firmly detected. Several theoretical efforts have been made to predict spin-down powered activities in magnetars, including low-frequency coherent emission, x-ray emission, γ-ray emission, and possible neutrino emission. Particles are believed to be accelerated in gaps either in the polar cap region near the surface (Harding et al. 1998) or above null charge density. Accelerated primary particles radiate through curvature radiation or Inverse Compton scattering, and the resultant γ-rays produce e^-e^+ pairs either through one photon [γ (B) ⟶ e^-e^+(B)]or two photons (γ γ ⟶e^-e^+) process.

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