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Magnetars- A Review

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Abstract. Magnetars are neutron stars in which a decaying high magnetic field is the source of energy production. The suggestion that magnetars are the dominant source of energy for soft gamma repeaters and anomalous x-ray pulsars is examined. Some questions that arise, because of the very high magnetic fields, are considered.

Keywords : Neutron stars– high magnetic fields– magnetars

1. Introduction

Astrophysicists generally feel that they have understood stellar evolution quite well. The classic books of Eddington, Chandrasekhar, Schwarzschild and others have laid down the basics of this understanding. The recent vindication of the solar models by neutrino observations have further justified our understanding, though lot of details yet remain to be clarified. However the endpoints of stellar evolution still produce lots of puzzles. The end points of stellar evolution can be white dwarfs, neutron stars or black holes. The white dwarfs have been under observation and study for more than 60 years. They are more or less well understood. The black holes study seems to be proceeding in two totally different directions. One is astrophysical and includes identification, accretion, advection, jets etc. The other directon is purely theoretical and includes Hawking radiation, information loss, holography, modifying quantum mechanics etc. Our interest in this talk would be on the third end point of stars, the neutron stars.

2. Neutron Stars

The neutron stars were first seen in 1968 as pulsars. Since then thousands of pulsars have been seen and a lot of information has been collected but the neutron stars are still not well understood. Their structures involve knowledge of their inner cores which could exist in many forms

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including quark matter; the cores can often be superconducting. The main difficulty is our lack of knowledge of the behaviour of the interior matter or the equation of state of the interior matter at the very high densities that the neutron stars have. Another difficulty is the different types of neutron stars that one encounters. We find:

(i) Radio pulsars with high magnetic fields (10^{12} Gauss)
(ii) Millisecond pulsars with much lower magnetic fields. (10^8 Gauss)
(iii) Soft gamma repeaters (SGR)
(iv) Anomalous X-ray pulsars (AXP)

The first two classes of pulsars seem to be powered by rotation or accretion while the last two may be powered by decay of very high magnetic fields.

3. Soft Gamma Repeater

The SGR have the following properties:

(i) Emission of X-rays and gamma rays
(ii) Periodic bursts (of the order of months)
(iii) Giant flares (probably once in a lifetime) Two giant flares on record are given below.

0526-66	Mar 5, 1979	4×10^{44} ergs	8.00 s
1900+14	Aug 27, 1998	1×10^{44} ergs	5.16 s

The flares have short intense spikes ($t \sim 0.2 - 0.5$ s) and have luminosity much greater than (3×10^6 to 10^7 times) the Eddington luminosity $L_{\rm Edd}$. $L_{\rm Edd} = 2 \times 10^{38}$ erg/s for a neutron star of mass $1.4M_\odot$. The ensuing emission lasted 200 to 400 s.
(iv) The X-ray luminosity ($\sim 2 - 60$ keV) is about 10^{35} to 10^{36} erg/s
(v) 0526-66 coincides with SN remnant N49 in LMC of age $\sim 7 \times 10^3$ years. The other three SGRs are also associated with SNR and regions of massive star formation, with varying uncertainty.
(vi) Magnetic field $B_{\rm dipole} \sim 6 \times 10^{14}$ Gauss.

4. Anomalous X-ray Pulsar

The properties of the six or so known anomalous X-ray pulsars are as follows:

(i) persistent x-ray pulsation with $L_x \sim 3 \times 10^{34} - 10^{36}$ ergs/s.
(ii) spin periods ~ 6 to 12 s.
(iii) Characteristic age $\frac{P}{\dot{P}} = 10^3 - 10^5$ yrs.

(iv) All spinning down.

(v) At least three associated with supernova remnants (SNR)

(vi) No bursts (In Oct/Nov 2001 two bursts were observed from 1E1048.1-5937, an AXP till then. Hence it is sometimes called the 'Missing Link'.)

(vii) $B_{\rm dipole} \sim 10^{14}$ Gauss.

(viii) Pulsar J 1814 − 1744 has also $B_{\rm dipole} \sim 10^{14}$ G, but has around 0.01 to 0.1 of AXP luminosity. There could be a bifurcation into two classes at high magnetic fields.

5. Origin of Pulsar Magnetic fields

In pulsars the magnetic field plays a very important role. The origin of these high magnetic fields has, so far, been assumed to be due to the frozen flux of the progenitor star. The contraction from solar radius (10^{12} cm) to neutron star radius (10^6 cm) takes the magnetic field to 10^{12} G, if solar field was 1 Gauss. At these fields the magnetic force on a charged particle is much greater than the gravitational force. This could result in a magnetosphere of charged particles around the neutron star. However the source of energy for a radio pulsar seems to be the rotational energy and not the magnetic energy of the star. It is the decrease in rotational energy that is the source of pulsed and other emission in such a neutron star. The magnetic pressure is much smaller than the hydrostatic pressure even at $B \sim 10^{12}$ G.

Are higher magnetic fields possible? Duncan and Thompson (1992) examined the possibility of creation of high magnetic fields at the time of the supernova explosion which produced the neutron star. They argued that the large neutrino flux created at the time of the explosion can cause a vigorous convection inside the star. When this is combined with rapid rotation it would result in a helical dynamo action which may produce a high magnetic field. They find that turbulent diffusion does not suppress the helical dynamo action if Rossby number $R_d = P/t_{\rm convection} = 1 \times (P/1 \text{ ms})$ is less than unity. They claim that magnetic fields as high as $B \sim 3 \times 10^{17}$ Gauss can be generated. (The Crab pulsar has $P \sim 30$ ms $\gg 1$ ms, so B is only $\sim 10^{12}$ G.)

The consequences of such high magnetic fields are very unusual and highly significant. The effects of quantum electrodynamics or QED become very important above $B_{\rm qed} = m^2/e = 4 \times 10^{13}$ G ($\hbar = c = 1$). At these fields the Landau splitting $eB/mc = mc^2$. (Erber 1966, Adler 1970, Meszaros 1992). Processes such as

$$\gamma \rightarrow e^+ + e^- \qquad \text{(pair production)}$$
$$\gamma \rightarrow \gamma + \gamma \qquad \text{(photon splitting)}$$

become increasingly possible as magnetic fields increase, and so do some exotic reactions like

$$\gamma \rightarrow \text{positronium}$$

(Bhatia, Chopra and Panchapakesan, 1992, Shabad and Usov, 1982). The photon polarisations in the plane containing the magnetic field and the propagation vector (O mode) and the one perpendicular to the plane (E mode) behave quite differently.

As the first Landau level is high, Compton scattering is reduced sharply, which in turn reduces the radiation pressure. So the Eddington luminosity goes up

$$L_{\rm Edd}(R) = 2.1 \times 10^{40}(B(R)/B_{\rm qed})^{4/3} \quad \text{erg/s}.$$

It becomes possible to explain high luminosities $\sim 10^4 L_{\rm Edd}$ seen in SGR and AXPs. When magnetic fields higher than $B_{\rm qed}$ ($= 4 \times 10^{13}$ G) become possible we have a new form of neutron star. Such a star whose source of energy, for x-ray and particle emission, is decaying magnetic field, and not rotation or accretion, is called a Magnetar. Its observable signatures are

(i) Persistent X-ray and particle emission

(ii) When the magnetic field $B > (4\pi\theta_{\rm max}\mu)^{1/2}) = 2 \times 10^{14}(\theta_{\rm max}/10^{-3})^{1/2}$ Gauss (where μ is the shear modulus and $\theta_{\rm max}$ is the yield strain in deep crust) sudden outbursts triggered by fractures of rigid crust.

6. Explanation of Flares

The explanation of flares in the magnetar model is summarised below. The trigger for the flare is large scale reconnection or interchange instability of the stellar magnetic field. The soft repeat bursts are due to cracking of the crust. The initial spike, seen on March 5, 1979 and August 1998, is an expanding fireball produced by Alfven waves and neutrinos. The neutrinos escape out. The short tail and short soft repeat bursts are due to pair plasma trapped in the stellar magnetosphere. The plasma cools by releasing energy as the edge of "Pair dominated region" propogates inward in a cooling wave. If the cooling is mainly by emision of ions and electrons from the surface, the temperature of surface radiation depends only on the surface magnetic strength and has the value T ~ 9 kev. The theory outlined above (Thompson and Duncan, 1995) explains only the thermal emission. The timing noise must be due to instabilities. The observations imply a need for modifying the theory. In much weaker magnetic fields high scattering depth chokes radiative flow in about 0.1 s. Hence type II X-ray bursts at $B \sim 10^{12}$ G have much lower luminosity than SGRs.

7. Which is older, AXP or SGR

The relationship between AXPs and SGRs has its own puzzles. The AXPs are closer to the centre of the SNRs near which they are found than are the SGRs. So one can conclude that AXPs are younger than SGRs. However the ages determined by taking $P/\dot{P}$ do not agree. The AXPs seem to have ages around 10^5 years compared to the ages of SGRs which are around 10^3 yrs. One explanation can be that the measured spin rate must be accelerated with respect to the long term average. Woods et.al find that spin rates do have changes of this type, though there are no close relationships between timing noise and flares. As mentioned above one AXP was seen to emit x-ray bursts and so seems closer to SGR. One of the SGR is also close to AXP in its behaviour. These are sometimes called missing links.

Observations do seem to indicate that fields are higher than what is indicated by spin torques. Recent studies are attempting to explain non-thermal emissions, the high toroidal fields, X-ray spectra and pulse profiles assuming twisted magnetic fields (Lyutikov et.al. 2001).

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