ASTROPHYSICAL MAGNETIC FIELDS AND ASSOCIATED PHENOMENA: THE EXAMPLES OF SUNSPOTS, PULSARS AND MAGNETARS

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ABSTRACT

The mechanism of production of the planetary and stellar magnetic fields is successfully described by the dynamo theory which uses basic concepts of magnetohydrodynamics (MHD). There will be a full description of this theory and subsequently it will be used for the explanation of the solar, pulsar and magnetar fields. Furthermore there will be a discussion on the concept of sunspots and a reference to the theory of their creation which was proposed by H. W. Babcock.

Finally we will present the most extraordinary magnetic fields in the universe, generated in the interiors of pulsars and magnetars, and we will discuss the importance of studying these objects in modern astrophysics.

Key Words: stars: neutron – gamma rays: bursts – solar: sun spots – MHD: dynamo theory

1. INTRODUCTION

Since the beginning of the second half of the twentieth century there is a great scientific concern on the concept of astrophysical magnetic fields. There has been notable theoretical and observational research on studying the magnetic fields of the Earth and the rest of the planets, as well as the magnetic field of the Sun. Many peculiar and intensive interplanetary phenomena like magnetic storms and ionospheric substorms were given an explanation because of the profound study of the generation and behavior of Sun's magnetic field. Furthermore, observed solar phenomena such as the sun spots and the flares are explained only through the use of classical electrodynamics and magnetism.

The scientific interest around stellar generated magnetic fields became even more intense after the discovery of Pulsars in the mid 60s. These bizarre objects have the most intensive magnetic field ever observed that in some cases reach 10^{15} Gauss (this type of pulsars is called "magnetars"). To put this in perspective we present the following table of magnetic field strengths (Table 1). The existence of ultra – strong magnetic fields cause nature to behave in a completely different way. The application of quantum electrodynamics [3] introduces the quantum electrodynamic field strength:

Earth	0.6 G
Common magnet	100 G
Sunspots	4000 G
Strongest man made field (briefly)	10^7 G
Radio pulsar (surface, polar)	$10^{12} - 10^{13}$ G
Magnetar	$10^{14} - 10^{15}$ G

Table 1. Relative strengths of magnetic fields.

$$B_Q = \frac{m_e^2 c^3}{\hbar e} = 4.4 \times 10^{13} \text{ Gauss} \qquad (1)$$

For fields $B > B_Q$ we observe the following phenomena:

- Classical electrons gyrating in magnetic fields satisfy the equation [3]:

$$r \propto \lambda_e \left(B / B_Q\right)^{-1/2} \qquad (2)$$

where λ_e the electron Compton wavelength. The application of the principle of uncertainty in the ground state gives:

$$rp \propto \hbar \Rightarrow p \propto \frac{\hbar}{r} \propto m_e c \left(B / B_Q\right)^{1/2} \quad (3)$$

Thus, for fields greater than the quantum electrodynamic field strength, the electrons gyrate relativistically. Since there are two eigenstates of electron spin and the energy is proportional to the square of the momentum:

$$\varepsilon_n = 2nm_e^2 c^2 \left(B / B_Q\right) \quad (4)$$

Where ε_n the quantum eigenvalues of the energy. Then the total energy of the electron, considering that it rotates relativistically is:

$$E_n = \sqrt{m_e^2 + p_z^2 + m_e^2 n(2B / B_Q)} \quad (5)$$

Here we have set $\hbar = c = 1$. An approximation for $B >> B_Q$ would give a difference between the ground and the first excited state

$$E_1 - E_0 \approx (2B / B_Q)^{1/2} \quad (6)$$

But for the first excited state putting where $n = 1$ and $p_z = 1 + a / 2\pi$ (where a the fine-structure constant) in (5) we get the final conclusion for the ground state energy for the electron which is [3]:

$$E_0 = m_e \left[1 - (a / 2\pi)(B / B_Q)\right]^{1/2} \quad (7)$$

Equation (7) implies that for $B = (2\pi / a) B_Q$ the rest energy goes to zero while for greater magnetic fields it increases.

Even for magnetic fields generated by magnetars the change on the electrons rest energy is negligible. There are theoretical predictions though for the possible existence of greater, extraordinary magnetic fields around cosmic strings where this phenomenon of the electron's rest energy change would be directly observable.

- Atoms or molecules in ultra strong magnetic fields are completely distorted. For example a hydrogen atom possessing a spherical shape with radius $r_0 = \lambda_e / a$ would appear like a cylinder possessing the same volume as the unmagnetized atom would occupy. Idealizing the system of the magnetized atom of hydrogen with a potential well of length equal to the length of the cylinder $2l$ we get the familiar result for the ground energy (n=1):

$$\varepsilon_1 = \frac{\pi^2 \hbar^2}{2 m_e l^2} \quad (8)$$

Subsequently, with the aid of classical electrodynamics, assuming the magnetized atom as a linear charge distribution of density $\lambda = e / 2l$ we can get the following expression for the electrostatic energy [1]:

$$\varepsilon_{el} = -(e^2 / l) \ln[l / r] \quad (9)$$

where r the quantum gyration radius we de-fined at (2). Taking the first derivative of the total energy of the system $E_0 = \varepsilon_0 + \varepsilon_{el}$ with respect to the length l equal to zero we have the formula:

$$l \approx r_0 \left[\ln(r_0 / r)\right]^{-1} \quad (10)$$

which is the length of the thin atomic cylinder for minimum ground energy, slightly less than the Bohr diameter r_0. Replacing this value of l in the equation of the total energy of the magnetized atom we get the useful expression for the ground energy which implies that:

$$E_0 \propto [\ln B]^2 \quad (11)$$

This is our final conclusion on how strong magnetic fields affect the ground state energy of hydrogen atoms. For heavier elements the corrections are similar, related to the atomic number Z.

- In ultra strong magnetic fields the vacuum is polarized inducing the phenomenon of magnetic lensing. A photon traveling in a magnetized vacuum has two modes, the O-Mode (ordinary mode) where an oscillating electric vector is parallel to the magnetic field and the E-Mode or extraordinary mode where the electric vector is perpendicular to the magnetic field [3]. The indices of refraction of the two modes are very different at $B > B_Q$:

$$n_O = 1 + (a / 6\pi) \sin^2 \theta (B / B_Q) \quad (12)$$

and

$$n_E = 1 + (a / 6\pi) \sin^2 \theta \quad (13)$$

There have been used models based on geometrical optics to model the magnetic lensing induced in the magnetar vicinities.

- Phenomena associated with magnetic lensing are the photon splitting and merging (Figure 1) where an X-ray photon split in two photons or two photons merge to create one X-ray photon. In addition we observe the suppression of photon – electron scattering [3].

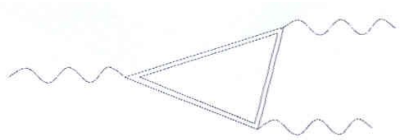


Figure 1. Photon splitting (left to right) and photon merging (right to left).

- Strong magnetic fields enhance the pair density in thermal pair-photon gases. For example in the electron – positron pair – photon gas, the thermodynamic effect is the presence of a sharp peak in the $U_p / U_\gamma - \log(B / B_Q)$ diagram, for fields with $B > B_Q$. Where U_p, U_γ the pair energy density and the photon energy density respectively. This peak is important for the explanation of SGRs (Soft Gamma Repeaters) an intense energetic phenomenon associated with magnetars [3].
- Sufficiently high magnetic fields would cause the vacuum to break down. Magnetic monopoles can spontaneously be created when the energy they acquire exceeds their rest energy. A calculation for the mass of a magnetic monopole coming from superstring theory implies that magnetic fields can never be stronger than $10^{51} - 10^{53}$ G otherwise they could be created, breaking down the vacuum stability. There are not yet known objects capable of generating these fields, although the closest approach on this could come (theoretically) from a superconducting cosmic string ($\propto 10^{30}$ G) [3].

In the rest parts of this project, it will be clear how important are the phenomena associated with ultra strong magnetic fields for studying the behavior of matter and radiation in the areas close to pulsars and magnetars as well as to explain intensive energetically astrophysical phenomena like the Soft Gamma Repeaters (SGRs) and the Anomalous X-ray Pulsars (AXPs).

2. THE THEORY OF DYNAMO

The main purpose of solar theoretical physics since the second decade of the twentieth century is to give a profound explanation to the question of how magnetic fields of celestial bodies are generated. In order to progress towards this direction, a new academic discipline had to be formed which is called Magnetohydrodynamics (MHD).

Hanes Alfven was the one who initiated MHD by solving simultaneously the Maxwell's equations of electromagnetism and the Navier – Stokes equations of fluid dynamics. His goal was the study of the dynamics of electrically conducting fluids such as plasma. Although theoretical work is always important, numerical methods had to be used in order to achieve solutions closer to the real world. Usually in applications what is needed is the so called ideal MHD. The main characteristic of ideal MHD is that magnetic field lines cannot move through the fluid but have to remain attached at the same small domain of the fluid at all times. By this, most electric currents tend to compress into thin, nearly two – dimensional structures called current sheets. Since more than 99% of the matter in the universe is in plasma state, there are great applications of MHD in astrophysics [11]. However there are some energetic astrophysical phenomena like the solar flares where ideal MHD breaks down and more realistic approximations are needed.

Theoretical astrophysicists like J. Larmor, proposed possible mechanisms for the generation of the terrestial magnetic field based on MHD predictions. Furthermore, T.W. Cowling and E.N. Parker applying similar techniques introduced the most satisfying theory around the question of how the solar magnetic field is generated: the theory of magnetic dynamo. The principle is simple: the motion of a conductive body in the presence of a magnetic field acts to regenerate that field. In the case of sun, this moving conducting body is the plasma located on the outer layer of the sun's interior called convection zone. In the convection zone, extremely hot plasma material is circulating forming convection currents. The inner part of these convection currents possesses higher temperature than the outer, so the circulating material carries thermal energy as it flows upwards to the suns photosphere (the sun's outer layer which could be thought as its "surface"). This continuous circulation of plasma is indeed electric current which is responsible for the generation of the magnetic field as Ampere's law indicates:

$$\oint \vec{B} \cdot d\vec{l} = \mu_0 I \tag{14}$$

In addition, dynamo theory proposes that this initially created magnetic field is reinforced due to the fact that the further flow of plasma inside it induces more electric currents. Thus, a dynamo is created which sustains itself.

A version of dynamo theory which is widely used for simplified applications is the so called Kinematic Dynamo Theory [11]. The central idea of Kinematic Dynamo Theory is deduced by combining the Ohm's law

$$\vec{J} = \sigma(\vec{E} + \vec{V} \times \vec{B}) \tag{15}$$

with the Faraday's law and the Ampere's law [1]:

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{16}$$

and
$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} \tag{17}$$

respectively. Taking the curl of (15) to both sides we have

$$\vec{\nabla} \times \vec{J} = \sigma \vec{\nabla} \times \vec{E} + \sigma \vec{\nabla} \times \left(\vec{V} \times \vec{B} \right) \tag{18}$$

Replacing where $\vec{J}$ the equivalent expression from (17) and where $\vec{\nabla}\times\vec{E}$ the negative time derivative of the magnetic field from (16) we get

$$\frac{1}{\mu_0}\vec{\nabla}\times\left(\vec{\nabla}\times\vec{B}\right)=-\sigma\frac{\partial\vec{B}}{\partial t}+\sigma\vec{\nabla}\times\left(\vec{V}\times\vec{B}\right)\Rightarrow$$

$$-\frac{1}{\mu_0}\nabla^2\vec{B}=-\sigma\frac{\partial\vec{B}}{\partial t}+\sigma\vec{\nabla}\times\left(\vec{V}\times\vec{B}\right) \qquad (19)$$

where here we have used the property:

$$\vec{\nabla}\times\vec{\nabla}\times\vec{B}=\vec{\nabla}\left(\vec{\nabla}\cdot\vec{B}\right)-\nabla^2\vec{B} \qquad (20)$$

Finally, solving with respect to the time derivative we get the final result:

$$\frac{\partial\vec{B}}{\partial t}=\vec{\nabla}\times\left(\vec{V}\times\vec{B}\right)+n\nabla^2\vec{B} \qquad (21)$$

with $n=\frac{1}{\mu_0\sigma}$.

The final formula (21) is the induction equation which is the basic result of Kinematic Dynamo Theory. Applying a certain velocity field to a small magnetic field we can determine through observations whether this magnetic field tends to increase or to decrease. In case it increases then the system we observe is capable of dynamo action or is already a dynamo, in the other case the system is defined simply as not a dynamo.

The progress in the field of computational physics though, gave us the ability to create more realistic versions of the dynamo theory which include other factors that determine the final magnetic field such us the solar differential rotation. The first numeric solutions were given by R. Leighton and since then new methods have been evolved such as organizing the solar magnetic field in coherent structures on a wide range of scales ranging from elementary flux tubes to the radius of the sun. Although the large scale magnetic field cannot be given by these numeric calculations due to the limited capabilities of modern computer processors, the solar magnetic field can be studied using small scale subvolumes of the solar interior. Applying averaged MHD calculations in these subvolumes [4] gives the chance to approach the so called solar parameters which are responsible for the small scale magnetic field of the sun. Except of the solar parameters, the dynamo coefficients play a central role to the formation of the simulated computational models and have to be determined with the best accuracy. The dynamo coefficients appear in the averaged induction equation:

$$\frac{\partial\overline{\vec{B}}}{\partial t}=\vec{\nabla}\times\left(\overline{\vec{U}}\times\overline{\vec{B}}+\vec{\varepsilon}-n\vec{\nabla}\times\overline{\vec{B}}\right) \qquad (22)$$

Where

$\overline{\vec{B}}$: the mean magnetic field

$\vec{\varepsilon}=\vec{u}\times\vec{b}$: the electromotive force (emf)

$\vec{u}=\vec{U}-\overline{\vec{U}}$: the fluctuating component of the flow

$\vec{b}=\vec{B}-\overline{\vec{B}}$: the fluctuating component of the magnetic field.

The dynamo coefficients can be determined from a numerical simulation by measuring the vector emf and the mean magnetic field and inverting the relation between them [4]:

$$\vec{\varepsilon}_i=a_{ij}\overline{\vec{B}_j}+\beta_{ijk}\frac{\partial\overline{\vec{B}_k}}{\partial x_j}+\dots \qquad (23)$$

A more profound analysis of formalism is very technical and away from the purposes of this project.

With the aid of computational power, various models of dynamo have been proposed. The most notable of them are [4]:

- Interface dynamo and distributed dynamo: The interface dynamo scenario accommodates the strong differnetial rotation and the presence of super-equipartition magnetic fields in the numerical calculations. The distributed dynamo scenario is almost the same with the interface dynamo with only slight differences on considering some variables of the problem distinctly.
- Flux tube dynamo: This version is based on the idea that the fundamental building blocks of the solar magnetic field are flux tubes, circular areas through which magnetized material flows.
- Babcock-Leighton dynamo: This kind of dynamo models explain the generation of the poloidal magnetic field in terms of the decay of bipolar active regions.

Although the very satisfying results that are gained with the latest computational models for the solar magnetic field there are still some important issues that have to be solved with the most important being the explanation of the poloidal magnetic field. The measurements that were taken from observations of the solar poloidal field do not agree to satisfying degree with the theoretical predictions of the existing dynamo models. However this obstacle could be surpassed with alternative explanations which introduce new factors on determining the poloidal magnetic field. For the shake of completeness, a thing that has to be added is that the measurements of magnetic fields are very accurate based on the Zeeman effect, a method widely applied for all astronomical objects.

3. THE SUNSPOTS

The most well known optical illustrations of astrophysical magnetic fields are undoubtedly the sunspots. From the ancient years there have been references from obser-vations of dark spots on the solar surface. Theophrastus the Athenian had already discovered the existence of dark areas on the solar disk while in the same period Chinese astronomers like Kan Te and Ma Twan Lin be-gun systematically to record the appearance of over one hundred sun spots. The data around sunspots became even more accurate after the invention of the telescope from Galileo Galilei who also did numerous sunspot observations. The theory that people had until the eighteenth century was that sunspots where holes on the sun's surface through which somebody could look into the interior of the sun, an idea mainly supported by the Scottish astronomer A. Wilson [11].

However, a scientific "revolution" around sunspots begun after the observations of the German astronomer Heinrich Schwabe. Schwabe in his attempts to discover a planet closer to the sun than Mercury, he was recording the sun spots so that he could distinguish them from the possible shadow that this hypothetical planet would project to the sun disk. By this, he created a well organized sunspot catalogue for 17 years. By the data in this catalog it was subsequently found that the sunspot appearance rate was periodic, with a period of nearly 11 years. The point of highest sunspot activity during this cycle is known as Solar Maximum (Solar Max), and the point of lowest activity as Solar Minimum (Solar Min). Also, remarkable observations were those of the British astronomer Richard Carrington who found out that the sunspots are moving on the solar photosphere towards the equator. This fact in addition to the periodicity of 11 years forms the Sporer's law (sunspots appear in higher latitudes and by the end of the cycle they have moved closer to the equator reaching the maximum of their activity).

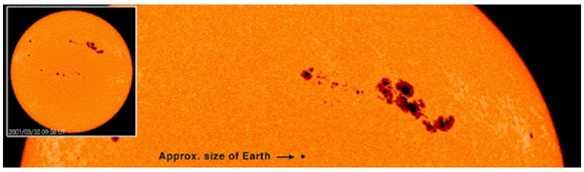


Figure 2. A group of sunspots on the solar disk. The relative size of the Earth is given for comparison.

Investigation on how the sunspots appear on the photosphere by observations enabled us to draw the following conclusions: Small bright structures on the solar surface start to appear. When these structures appear close to the edge of the solar disk they can be observed more clearly and they are termed as faculae. Faculae are bright photospheric supergranules which evolve taking a narrow shape. By observing the further evolution of these structures, it can be seen that small dark areas start to appear on the west edge of faculae. These dark areas (which actually possess lower temperature than the surrounding photosphere and that is why they appear darker) are called pores. A percentage of these pores could evolve into even darker areas forming the sunspots. By later studies, it is found out that only a small percentage of pores finally results in sunspots [2] and that they basically form due to other effects which will be discussed.

Taking a close up view of the sunspots gives valuable details about their structure. There is a central dark region which is called umbra and possesses the lowest temperature, surrounded by a less dark zone that is termed as penumbra. A closer observation of penumbra reveals that there lays a network of fine illuminant filaments which are placed radially with respect to the theoretical center of the sunspot. The structure of a typical sunspot is illustrated in the figure below [2].

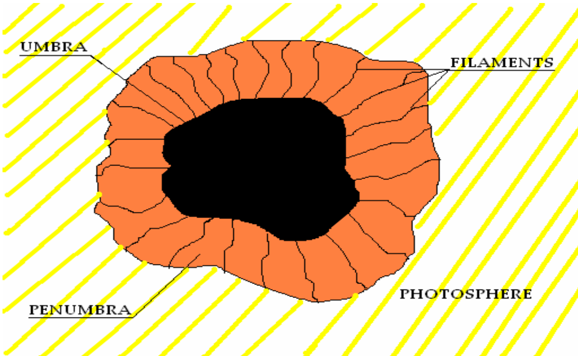


Figure 3. The structure of a typical sunspot.

By accurate CCD photometry, modern astronomers are able to measure the flux F of radiation coming from any distant light source. In the case of sunspots, the result of the comparison of the flux from the umbra and the flux from the solar surrounding photosphere (which is known years ago) is [12]:

$$\frac{F_{umbra}}{F_{phot.}} = 0.1 \tag{24}$$

Additionally, the flux from the penumbra compared to the flux of the photosphere is

$$\frac{F_{penumbra}}{F_{phot.}} = 0.8 \tag{25}$$

Since the Stefan – Boltzmann law indicates that

$$F = \sigma T^4 \tag{26}$$

where σ the Stefan Boltzmann constant and T the temperature of the source, the ratio of the umbra's temperature to the photosphere temperature is [12]

$$\frac{T_{umbra}}{T_{phot.}} = (0.1)^{1/4} \approx 0.56 \tag{27}$$

Owing to the fact that the temperature of the solar photosphere is about 5770 °K we come to the conclusion that the temperature of the umbra is about 3200 °K. That means that the centers of sunspots are not cold areas but just colder that the surrounding photosphere, and in case they were isolated from it they would be illuminant.

Another basic characteristic of sunspots is their equatorward movement. After the appearance of the first sunspot on the west edge of facula, a second sunspot is created on the eastern edge. The system of the two sunspots, initially being in heliographic latitudes of about 35° seems to be moving towards the equator with the west sunspot to be preceding and the east sunspot to be trailing. The sunspots indeed have a life time which is a function of their size. A good approximation of their life time comes from the application of plasma physics in the vicinity of the solar photosphere and the resulting relation is [12]

$$t \propto \sigma r^2 \tag{28}$$

where σ is the plasma conductivity coefficient and r a typical sunspot radius if it is considered as a circular area. After the sunspots in the higher latitudes complete their lifetime, more and more new pairs of sunspots are created closer to the equator reaching a latitude of about 5° by the end of the solar cycle, which is 11 years. Typical life times of ordinary sunspots are 11 days, having a diameter of 10.000 Km. In the extraordinary case of huge sunspots, their life time could reach the 100 days. The general dynamic activity of the sunspots that was described above is concentrated on the famous Maunder or butterfly diagram (figure 3) where time is plotted as a function of the heliographic latitude. The number of the dots corresponds to the number of the sunspots at a specific time at different latitudes [2].

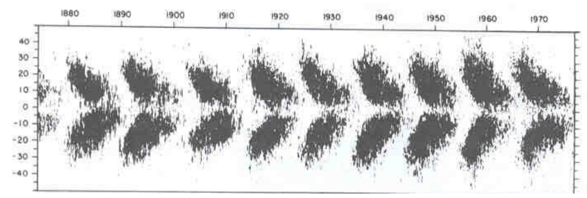


Figure 3. The Maunder diagram

It is of interest that the periodicity of the sunspot activity is the same with the periodicity of the solar cycle where the magnetic field of the sun changes polarity every 11 years (so that the real period of the general phenomenon is 22 years). This observation indicates the tight correlation between the sunspots and the behavior of the solar magnetic field. A magnitude for the sunspot activity is the so called Wolf number R or "relative number of sunspots" which is defined as

$$R = K(10g + f) \tag{29}$$

where K is a constant relative with the observer, the telescope and the light receiver which is used (usually CCD – Charge Couple Device), g the number of the sunspot groups and f the total number of the sunspots. Here it has to be added that usually sunspots appear in groups during the solar cycle. A typical number of the members that usually form a sunspot group is ten.

The most interesting theoretical and observational study of the sunspots is that of their magnetic field. The American astronomer George Ellery Hale found out that sunspots possess a strong magnetic field while theoretical astrophysicists were trying to form a theory to predict the magnitude of this magnetic field. The model which they used is the following one: Umbra and penumbra are taken as areas of neglected ionization because of the lower temperature. Considering a ring around the penumbra of internal radius R_i and external radius R_o where the ionization of the photosphere gas is remarkable, it can be assumed that currents are flowing (as the temperature there is higher) and thus it is possible to calculate the magnetic field at the center of this ring by applying Ampere's law (14). The result will be [5]

$$B = \left(\frac{2\pi I}{R_o - R_i}\right) \ln\left\{\frac{R_o + \sqrt{R_o^2 + \frac{d^2}{4}}}{R_i + \sqrt{R_i^2 + \frac{d^2}{4}}}\right\} \tag{30}$$

Where d is the length of the ring parallel to the axis of symmetry (assuming that this ring is tilted by an angle) and I is the current flowing through the ring. In the case of the sun, matter is in plasma state and the application of plasma physics gives us the answer for the value of I. After putting this result in the equation (30) we get the final theoretical formula for the sunspot magnetic field:

$$B^2 = \frac{16eAd}{\pi\sigma^2}\left(\frac{kT}{2m}\right)^{1/2} \frac{dB_z}{dr} \ln\left\{\frac{R_o + \sqrt{R_o^2 + \frac{d^2}{4}}}{R_i + \sqrt{R_i^2 + \frac{d^2}{4}}}\right\} \tag{31}$$

where A is a constant, e is the electron charge, m is the mass of the ion (usually hydrogen ions - protons), k is the Boltzmann constant, T is the temperature of the solar photosphere, $\pi\sigma^2$ is the ion cross section and dHz/dr the component of the magnetic gradient perpendicular to the direction of the impressed magnetic field. Taking the ordinary values of the above mentioned quantities and making the computation results to a typical sunspot magnetic field of about 2010 Gauss. The observed magnetic field of the sunspots is 2700 and this small deviation can be explained if we take into account that the values we gave to the above mentioned quantities are imperfectly known. So, in general application the above mentioned theory is a satisfactory approximation [5].

The observational measurements of the stellar magnetic fields are done with the aid of the Zeeman effect. According to this, every eigenstate of the energy of an atom is separated into sublevels due to an applied external magnetic field. This results as the solution of Schrödinger's equation for a Hamiltonian which includes the additional terms for the interaction of the atom with the magnetic field. Thus, receiving the spectrum of atoms which are inside a magnetic field, we observe the emission and absorption lines to be split into three or more other lines displaced by a factor of Δλ with respect to their expected position. The equation that correlates this displacement with the strength of the magnetic field is the central conclusion of the Zeeman effect [12]:

$$\Delta\lambda = \left(\frac{e}{4\pi m_e c^2}\right)\lambda^2 \left|\vec{B}\right| \qquad (32)$$

where e is the electron charge, m_e is the electron mass, λ is the wavelength in which the spectral line is observed without the effect of the magnetic field and |**B**| is the magnetic field strength.

For sunspots the magnetic field was measured using the Fe lines to be more than 2000 Gauss and the photosphere magnetic field is measured to be approximately 100 Gauss. This observation indicates the connection between the activity of the sunspots and the solar magnetic field. An intense phenomenon related to the high sunspot magnetic field in contrast with that of the photosphere is the Evershed effect where gas flows from the penumbra towards the photosphere and vice versa. The group of sunspots that appears on the edges of a pore on the north solar hemisphere is defined then as a bipolar group with the two sunspots possessing opposite polarities. Simultaneously, another pair of sunspots appears in the southern hemisphere with its members having opposite polarities than the members of the northern pair. Due to the fact that the general solar magnetic field polarity is reversed every 11 years, the same happens with the polarities of the sunspots. This process is illustrated in the figure 4 below.

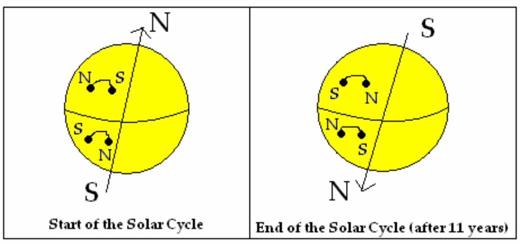


Figure 4. The polarity of the sunspot bipolar groups and their interaction with the total solar magnetic field

The most interesting conclusion that comes out from the fact that there is an intense magnetic field around sunspots is the explanation of why they are areas of lower temperature and gas density. This explanation was given by H.W. Babcock (who also suggested a theoretical model for the creation of sunspots which will be discussed in the next paragraph) who suggested that sunspots are the visible counterparts of magnetic flux tubes in the convective zone of the sun that get "wound up" by differential rotation. If the stress on the flux tubes reaches a certain limit, they curl up quite like a rubber band and puncture the sun's surface. At the puncture points convection is inhibited, the energy flux from the sun's interior decreases, and with it the surface temperature. The Wilson effect tells us that sunspots are actually depressions on the sun's surface. Many scientists refer to this warping of the magnetic field lines around sunspots as a vortex which resembles the terrestial hurricanes. Recent observations from the Solar and Helioscopic Observatory (SOHO) using sound waves travelling through the Sun's photosphere to develop a detailed image of the internal structure below sunspots show that there is a powerful downdraft underneath each sunspot, forming this rotating vortex that concentrates magnetic field lines. This all hypothesis about the lower temperatures of sunspots is based on the simple observation that in order to maintain the equilibrium between the sunspots and the photosphere the energy density in the sunspot and the energy density in the photosphere must be equal

$$U_{s.s} = U_{phot.} \qquad (33)$$

The total energy density for an ionized ideal gas inside a magnetic field is the sum of the magnetic energy density and the plasma energy density:

$$U = U_B + U_g = \frac{1}{2\mu_0}B^2 + NkT \qquad (34)$$

Setting this result in the equation (33) we get the final expression for the equilibrium between the sunspot and the photosphere [12]:

$$\left(NkT + \frac{1}{2\mu_0}B^2\right)_{ss} = \left(NkT + \frac{1}{2\mu_0}B^2\right)_{phot.} \qquad (35)$$

Finally, placing the corresponding values for the photosphere and sunspot magnetic field, particle number N and temperature T we see that equation (35) is true just because of the great sunspot magnetic field strength to which sunspots owe their existence.

As it became clear in this paragraph, the existence of local areas of strong magnetic fields in the sun, and generally in the stars, is the cause of many interesting phenomena. In our solar system, the most intensive phenomena, the solar flares (huge releases of energy and radiation from the solar atmosphere) are based on the solar magnetic field, in combination with its differential rotation. In this particular case, the phenomenon of magnetic reconnection occurs where magnetic lines moving with opposite velocities collide forming huge amounts of magnetic energy density, which is remarkably greater than the plasma energy density and thus the equilibrium (35) is not reached. As a result, breakdown of ideal MHD occurs and the theory that should be used to describe this phenomenon through a formalistic way should be much more complex.

4. THE BABCOCK MODEL

The most satisfactory and comprehensive theory which describes the creation and the evolution of sunspots is the Babcock theoretical model. The procedure through which a sunspot is created according to the Babcock model is illustrated in the figure below [12].

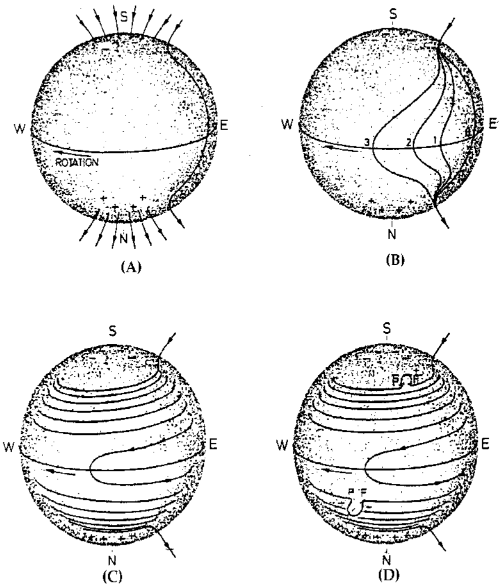


Figure 5. The Babcock model

The algorithm of the procedure is the following [12]:
(A): The sun’s differential rotation results in the existence of higher velocities near the equator than in higher latitudes.
(B): The magnetic field lines are getting more and more distorted near the equator, as opposed with those of higher latitudes.
(C): Magnetic field lines continue to warp and wound up.
(D): Magnetic “pipes” or “knots” are created right under the photosphere (figure 6). Because of high conductivity magnetic field and plasma are moving together in the same direction.

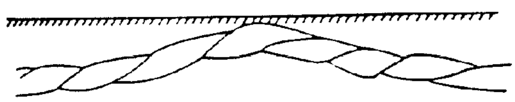


Figure 6. Magnetic knots under the photosphere's surface

As a result of the further warping of the knots, loops and vortices are created right above the photosphere (figure 7).

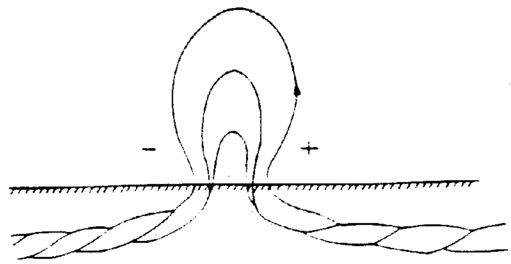


Figure 7. Magnetic loops. Sunspots start to appear at the conjunction points between the loop and the photosphere (-,+).

The conjunction points between the photosphere and the magnetic loops are areas of high magnetic field that cause the matter to be less dense than of the matter in the surrounding photosphere. Thus the temperature in these areas is lower and they appear darker in front of the shiny photospheric background. The sunspots have finally been formed.

Babcock model combines the dynamic of the solar rotation and the theory of the magnetic field generated by a dipole (which is the sun’s magnetic field in first approximation) in a well organized frame where the generation of the dipolar pairs of sunspots and the fact that they emit less radiation than photosphere is explained. Furthermore this model offers a good explanation for the phenomenon of the reversion of the solar magnetic field polarity which was discussed above: As the generated pairs of sunspots approach the equator, both from the north and the south hemisphere, their magnetic vicinities that possess opposite polarity (the polarity of the hemisphere they belong to) approach and annihilate in a way. Thus, the remained fields are those of the sunspots that have opposite polarity than the hemisphere in which they belong and causes the magnetic field to reverse (see figure 4).

4. PULSARS AND MAGNETARS

4.1 Pulsars

The local magnetic fields on the sun and generally on the stars are considerably great being responsible for energetic phenomena. However, studying more exotic – compact objects like pulsars brought the scientific community in front of the discovery of the most intensive magnetic fields in the universe.

When stars with masses above than the Chandrasekhar limit (1.4 solar masses) collapse after the burning of their nuclear fuels, great pressure is applied on their core from the outer collapsing shells. This result in the extraordinary increase of the plasma density making the protons react with electrons and thus form neutrons and neutrinos according to the reaction [2], [12]:

$$p_1^1 + e_{-1}^0 \rightarrow n_0^1 + \nu_0^0$$

This process leads to a great supernova explosion and to the formation of a dense core, consisted mainly of neutrons. The neutron condensate, as a fermionic gas – thus obeying the Pauli Exclusion Principle – is amazingly dense leading to the exertion of great degeneracy pressure that halts the further collapse. The final remnant is an ultra dense central core that radiates great amounts of energy, surrounded by the diffuse outer shell of the dead star which forms a planetary nebula.

The observational and theoretical study of these peculiar objects led to the following results about their nature:

- A combination of special relativity and quantum mechanics leads to the mass – radius relation about neutron stars [2],[12]:

$$R = 0.114\frac{\hbar^2}{Gm_p^{8/3}}M^{-1/3} \qquad (36)$$

where m_p the mass of the proton, R the radius and M the mass of the neutron star.

- Typical values for a neutron star density, temperature and radius [12]:

$$\rho_{NS} \approx 10^{14}\, gr/cm^3 \qquad \text{(Nuclear densities)}$$

$$T_{NS} \approx 10^6\,{}^\circ K$$

$$R_{NS} \approx 15Km$$

- According to the Wien law, the maximum of a typical neutron star emission will be

$$\lambda_{\max} T_{NS} = 0.29 \Rightarrow \lambda_{\max} \approx 30\,\mathring{A}$$

thus neutron stars emit their maximum radiation in the X-rays.

- The rotational periods of neutron stars can be deduced from the law of conservation of angular momentum [12]:

$$J_i = J_{NS} \Rightarrow MR_i^2\omega_i = MR_{NS}^2\omega_{NS} \Rightarrow \frac{R_i^2}{P_i} = \frac{R_{NS}^2}{P_{NS}}$$

and finally

$$P_{NS} = \left(\frac{R_{NS}}{R_i}\right)^2 P_i \qquad (37)$$

Putting where R_{NS} the typical radius of the neutron star that was given above, R_i the initial radius of the star that formed the neutron star (which is calculated theoretically) typically a million kilometers and P_i the initial rotational period of the star, usually around 30 days we get the typical rotational period of neutron stars that is expected theoretically

$$P_{NS} \approx 0.25 m\sec$$

meaning that the neutron stars rotate in really great velocities – actually being the quicker spinning stellar objects in the universe.

The high magnetic fields that a pulsar have, lead some of its surface particles (remaining protons and electrons, mainly on the neutron star's outer crust) to gyrate around the magnetic field lines (on the axis of the magnetic field) with relativistic velocities, thus emitting synchrotron radiation in radio waves. Due to this fact radiotelescopes are widely used for the observation of pulsars. Observing a pulsar with a radiotelescope results in a periodic sing on an oscilloscope which gives directly the period of the pulsar rotation. This happens when the axis of the pulsar dipolar magnetic field is tilted with respect to the axis of the pulsar rotation. Thus when the magnetic axis is oriented alongside the observation direction, radiotelescopes receive the maximum of the radiation (figure 6) [2],[12].

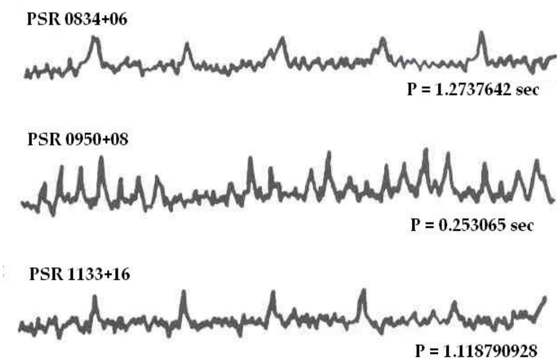


Figure 8. The radio pulses of three pulsars and the corresponding periods.

The most famous pulsar that has been observed with the above mentioned method is the Crab pulsar. A supernova explosion was recorded in 1054 by Chinese astronomers. 900 years later modern astronomers could observe the supernova remnants (SNR) of this old explosion as a diffuse nebula in the center of which lays the Crab pulsar.

- The theoretical models about the internal structure of pulsars are based both on nuclear / particle physics and quantum mechanics. Mostly the star is made up of neutrons which are concentrated on the inner crust and the outer core of the star. On the outer crust there are positrons and electrons which have not reacted to form neutrons (since on the surface of the neutron star the pressure is the minimum). Also, a thin atmosphere is predicted around the pulsar (In heights of the order of some centimeters). The most peculiar area of the interior of a pulsar is the core where the pressure and the density of matter are extremely high. The core of the pulsar possibly consists of quark matter or puon (π) condensate. The neutrons and the protons in the outer core and the inner crust of the star are predicted to be superfluid from the application of quantum hydrodynamics under such physical conditions [9].

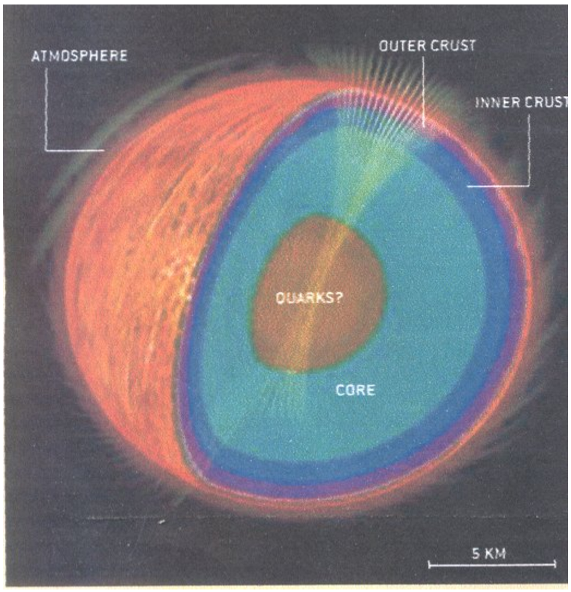


Figure 9. A model for the internal structure of Neutron Stars [12]

- The most interesting characteristic of pulsars study is their ultra strong magnetic field. Observations have shown that neutron stars are the most strongly magnetized objects in the universe. The explanation of this fact comes straight from Maxwell's equations: All stars have relatively weak magnetic fields which can be amplified with the act of compression. When a magnetized object shrinks by a factor of two its magnetic field strengthens by a factor of four. Thus, a stellar core that collapses by a factor 10^5 during the neutron star formation, amplifies its magnetic field by a factor of 10^{10}. The magnetic field of pulsars as well as the magnetic field of any stellar object resembles a dipole magnetic field. In the case of pulsars this dipole amplified magnetic field is generated during the vigorous, high Rossby number convective episode which follows the formation of the neutron star. The Rossby number is a typical parameter which determines the dynamo efficiency for pulsars. It is defined as the ratio of the rotation period P to the convective overturn time τ [6]:

$$R_o = \frac{P}{\tau} \qquad (38)$$

In a turbulent fluid with Rossby number of order of unity or less an efficient dynamo results, since the amplification of the magnetic field is not suppressed by turbulent diffusion. Larger Rossby numbers result in less effective mean – field dynamos.

- The existence of ultra strong magnetic fields in the case of pulsars is the cause of the observed increase of pulsar rotational period or, in other words, spindown. The field lines are anchored to the neutron star surface, because they are generated by circulating electric currents inside the star. Thus as the star turns the field also must turn. This drives magnetic waves outward, along with diffuse winds of charged particles (which emit the radio beams from just above the magnetic poles), carrying off energy and causing the star to gradually spin down. The measured rate of spindown allows the magnetic field to be estimated. For almost all young pulsars it is a few times 10^{12} Gauss at the magnetic poles. The relative formalism that determines the pulsar spindown comes from the study of rotating decelerating magnetic dipoles and the basic result is that [12]

$$t = \frac{P_o}{2\dot{P}} \qquad (39)$$

where P_0 is the observed present rotational period, $\dot{P}$ is the observed decrease of the rotational period and t is the time from the formation of the neutron star until the present. The observed magnetic field is then given by the equation

$$B \approx 3\times10^{15}\,(Tesla/\mathrm{sec})\left(P_o\,\dot{P}\right) \qquad (40)$$

which states that the magnetic fields of pulsars extinguish in one hundred million years.

- The pulsar formation rate in our Galaxy is estimated to be 1 per 50 to 300 years. Additionally the total number of pulsars that have been observed and studied is more than 1000 [12].
- Interesting results arise from the recent study of binary systems of pulsars. An example of this is the binary system PSR 1913+16 with rotational period around the center of the mass 7.75 hours and pulsar spin periods of approximately 60 milliseconds. Binary systems of pulsars turn out to be very important for the theoretical predictions of the general theory of relativity since they are sources of gravitational waves [12].

4.2 Magnetars

Neutron stars with unusually strong magnetic dipole fields ($10^{14} - 10^{15}$ G) can form when conditions for efficient dynamo action are met during the first few seconds after the gravitational collapse. These ultra magnetized neutron stars were termed as "magnetars" from the theoretical work of Robert Duncan of the University of Texas and Christopher Thompson of the Canadian Institute for Theoretical Astrophysics (CITA). These scientists claimed [6] that if a dynamo works with ideal efficiency in a hot, newborn neutron star, it would generate a field even of 10^{16} Gauss (max): 10000 times stronger than was actually found in pulsars. As the star cools, convection and dynamo action cease. This happens after only about 10 or 20 seconds in a neutron star, but 10 seconds is enough time for a very strong field to build up. After that, the field can remain trapped by the heavy, stratified liquid of neutrons and protons inside the neutron star. The same criterion for the dynamo action must hold for magnetars as it is for pulsars, and that is the Rossby number. The Crab pulsar with spin period of 20 msec was not capable of completely effective dynamo action that could generate a magnetic field on the order of the magnetic fields that magnetars possess.

The internal structure of magnetars is similar with the one of pulsars with a higher internal convention which is responsible for the generation of the extraordinary magnetic field. In general the comparison of the pulsar and magnetar fields ordinarily gives [6]:

$$\frac{B_{dipole}(magnetar)}{B_{dipole}(pulsar)} \propto 100$$

This great magnetic energy that magnetars have is the cause of many energetic phenomena of great interest. A magnetar's field is strong enough to push material around in the star's interior and crust, leading to the dissipation of a significant amount of magnetic energy during the first ten thousand years. The consequences of this are observable and namely they are [10]:

- Steady X-Ray Emission. The shifting magnetic field outside the star must drive electrical currents along arched magnetic field lines. This gives rise to streaming charged particles that inevitably impart energy to X-ray photons by scattering against them.
- Soft Gamma Repeater (SGR) bursts. They come as a result of magnetic reconnection, a mechanism that was introduced for the explanation of solar flares [7].

The magnetar X-ray and soft Gamma bursts are thought to occur because of the phenomenon of starquakes [7]. The crust of a neutron star has odd properties. It is very difficult to compress crust material very much, or to move elements of crust up or down, because strong gravity and pressure forces maintain a firm balance, holding the crust on the level and at nearly constant volume. It is much easier to move parts of the crust horizontally, in ways which apply only "shear strains" to it. In a young magnetar, the magnetic field evolves over time, seeking a lower energy state and in the process, subjecting the crust to strong magnetic forces. For example, magnetic field lines continually drift through the star's liquid interior stressing the crust from below. The field isn't strong enough to drive much compression or vertical motion in the crust, but it can drive significant twisting motion of patches of crust along horizontal directions, (since this involves pure shear strains between the field and the crust) and that is what causes the starquakes. Whenever starquakes happen, magnetic field lines outside the star also get twisted because they are anchored to the crust. Electric currents are created alongside the magnetic lines and subsequently they decay. This decay leaves back a hot trapped fireball. The fireball cools by releasing X-rays from its surface and finally it evaporates in minutes or less [8].

The fact that magnetars lose energy through the above mentioned mechanisms causes them to spindown even more drastically than ordinary pulsars. An additional recoil mechanism which causes the magnetar spindown is the anisotropic neutrino emission which can be deduced in a number of ways by strong magnetic fields. Duncan & Thompson (1992) have proposed a momentum loss formula for the neutrino recoil mechanism [6]:

$$\frac{\Delta p}{p} \propto 0.02B\left(\frac{a}{0.3}\right)\left(\frac{E_e}{5MeV}\right)^{-2}\left(\frac{\tau^{\nu}}{0.3\tau^{\nu e}}\right) \quad (41)$$

where B the magnetic field, α a constant, E_e the electron Fermi energy near the surface of last scattering, τ^{ν} the effective mean-free time between the scatterings of the neutrino (by all processes) and $\tau^{\nu e}$ the mean-free time for the neutrino electron scattering. The above mentioned quantities are in units where ($\hbar = c = 1$).

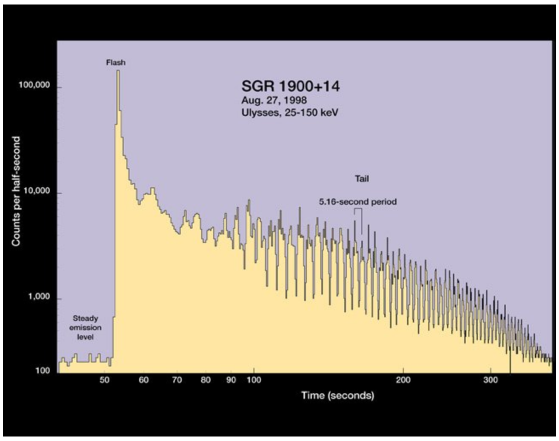
Duncan & Thompson published a series of papers since 1992 completing their theoretical predictions about magnetars. However, the Greek NASA astronomer Chryssa Kouveliotou, associated the theoretical predictions with the observations of Soft Gamma Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs) which became the observational evidence for the existence of magnetars [6],[7],[8].

4.3 Observational Evidence for magnetars

4.3.1 The Soft Gamma Repeaters (SGRs)

Since 1960 numerous missions have been carried out for the study of energetic gamma ray sources. The first and most interesting result of the observations was the Gamma Ray Bursts (GRBs): huge releases of energy from random di-rections of the sky. There is still discussion about the na-ture of these phenomena. However, two events marked the history of Cosmic Gamma Ray observations and proved that GRBs are not the only energetic sources in the universe. In March 5, 1979 the gamma ray detectors of the Soviet interplanetary space probes Venera 11 and Ve-nera 12 received 10,000 counts in one second and later it was confirmed from other spacecrafts that the source was the Supernova Remnant (SNR) N49 in the Large Magella- nic Cloud (LMC). In the first two tenths of a second, the burster radiated away as much energy as the Sun [9] radiates in 3000 years.

There were lots of theories for the origin of this burst; mainly that the burster was a young, isolated neutron star with peculiar properties. Alternative theories were that the March 5th event was due to a small planet or a large asteroid slamming into a neutron star, or a "phase transition" in the core of a neutron star (the neutron star's core somehow abruptly changed its state as it cooled, like water does when it freezes, releasing energy in the process). After the introduction of the magnetar theory, it was clear that these properties resemble the properties that are predicted for mangetars. Another notable event, marked the history of Cosmic Gamma ray explorations in the August of 1998. A giant flare from SGR 1900+14 set new records for the most intense flux of gamma-rays ever detected from a source outside our solar system. It blitzed gamma-ray and X-ray detectors on seven different spacecraft at lo- cations throughout the solar system. The Ulysses spacecraft was equipped with a very sensitive gamma ray de- tector and performed valuable measurements of the gamma ray flux from this burst. In the graph above the intensity of the SGR 1900+14 burst is plotted as a fun- ction of time [10].



Graph 1. The August 27 Event. The measurements were gained by the Ulysses spacecraft.

These events marked the discovery of the Soft Gamma Repeaters (SGRs), stellar objects that were associated with magnetars.

There are notable difference between the properties of SGRs and GRBs [8], [9]:

- The SGR events are recurrent phenomena coming from the same source in the sky, in opposition with GRBs which come randomly from all directions. Consequently, the sources of SGR are stable objects rather than flashes of destructed objects which are probably the origins of GRBs.
- The SGR spectra is "soft" compared to the GRB spectra. This means that the gamma ray photons generated from SGRs are less energetic (hard X-rays) than the ones originated from GRBs.
- The durations of the SGR bursts (in the order of a second or less) are shorter compared to the ones of GRBs which may last some minutes.

The SGRs also appear to be energetic X-ray sources. The production of these X-rays happens due to magnetic field decay, with processes similar with those that were described for the explanation of SGR bursts. Since the discovery of the first SGR, 3 more bursters have located throughout our Galaxy (Table 2) [11].

SGR	Characteristics
SGR 1806-20	distance from earth: 50000 light years, radius of about 20 Km, rotational period 7.5 seconds, over 100 detected bursts
SGR 1900+14	giant flare of August 27 event
SGR 1801-23	point source of X-rays or SNR
SGR 1627-41	rotational period: 6.4 seconds

Table 2. The four known SGRs and their basic characteristics.

The most interesting recent observations of SGRs and GRBs have been carried out with the Compton Observatory providing a clear picture for the distribution of SGRs in the Milky Way.

4.3.2 The Anomalous X-ray Pulsars (AXPs)

Another class of peculiar bursters that are less energetic than GRBs are the Anomalous X-ray Pulsars (AXPs): young, isolated, highly magnetized neutron stars characterized by slow rotational periods of ~5-12 seconds [11]. Several models have been proposed to explain the properties of AXPs [8]:

- Accreting neutron stars in binary systems with a very low mass companion.
- Isolated accreting neutron stars that evolve from Thorne – Zytkov objects (stars that are the result of a merger of a neutron star and a high mass companion).
- Magnetars

The latest observations and the theoretical predictions insist that indeed the third hypothesis is right and that AXPs are a type of magnetars. These modern observations made it also possible to distinguish AXPs from binary systems in which one of the members is a pulsar. The differences between AXPs and this kind of binary systems are that the AXPs possess softer spectra, their periods are in a very narrow range (5-12 seconds) and they exhibit a secular spindown of their periods. Table 3 below gives more details about the known AXPs [11].

AXP	Rotational Period (sec)
AXP 1E 2259+586	6.98
AXP 1E 1048-59	6.45
AXP 4U 0142+61	8.69
AXP 1RXS 1708-40	11.0
AXP 1E 1841-045	11.8
AXP AXJ1844-0258	6.97
AXP CXJ0110-7211	5.44

Table 3. The confirmed AXPs and their corresponding rotational periods.

4.4 Latest theories about magnetars

As it was mentioned above, it was Chryssa Kouveliotou who associated SGRs and AXPs with magnetars by making careful comparisons of the periodicity of the soft gamma repeater SGR 1806-20. The period of this burster had increased by 0.008 seconds since 1993, leading her, using equation (40), that this could be explained by a magnetic field strenght of 8×10^{14} G, a value that is in the range of magnetar fields [11].
As a result of further theoretical analysis and study of modern observational data, a theory for the evolution of magnetars was formed: Young magnetars start to live their lives as SGRs (for roughly 10000 years) and the next 30000-40000 years as AXPs. The last stage of magnetar evolution may be what has been observed in X-rays as a solitary neutron star with very low luminosity. Simoultaneously as the magnetar evolves the rotational period increases (like in ordinary pulsars) and the Gamma ray flash activity decreases reaching the zero value as the SGR magnetar becomes an AXP. The final dead magnetars remain strongly magnetized. This would drive them to spin down to ever-slower rotation rates. Dead magnetars would then be seen as dim, very slowly pulsating X-ray sources, most easily detected when they lie near Earth.

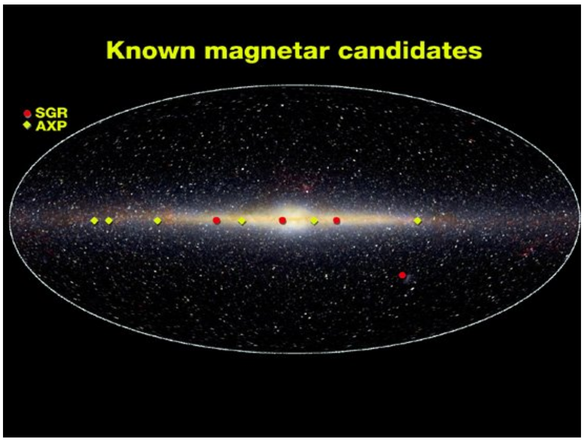


Figure 10. Known magnetar candidates and their distribution in the Milky Way.

The most reliable observational confirmation of the above mentioned theory of magnetar evolution arises by the measurements of the SNR (supernova remnant) ages and by comparing them with the age of the observed magnetars. This leads to the conclusion that AXPs are older objects than SGRs as it was predicted from the theory [10].
It is calculated that magnetars are 10% of the newly born neutron stars and that the magnetar formation rate in our Galaxy is 1 per 100 years [8]. This fact provides the ability to estimate the total number of magnetars in our Galaxy today (since we know the age of the Galaxy and the time that a massive star takes to collapse to a neutron star) and the result is approximately 10000 [6]. The question that follows this result is obvious: why the rest magnetars have not yet being observed? The answer is that most magnetars are born fast, with speeds of thousands of kilometers per second (as suggested by the large displacements of the March 5th and August 27th flare sources from the centers of supernova remnants in which they seem to have formed), and thus they drift into the remote halo of our Galaxy escaping from the Galaxy altogether. Such distant stars would be especially hard to detect. The known magnetar candidates and their distribution in our Galaxy are shown in the figure above.
Finally it should be added that magnetars could be a possible explanation of the rare phenomenon of Ultra High Energy Cosmic Rays (UHECRs). UHECRs are probably single protons or light nuclei possessing extraordinarily great energies - higher than normal cosmic rays. They are detected when they strike the upper layers of our atmosphere and dissipate their energy, creating showers of high energy particles which can be seen as flashes of light. Young magnetars with their very rapid spins and high magnetic fields generate very strong electric fields that could accelerate particles to ultra high energies. UHECR energies would then come ultimately from the rapid spin of a nascent neutron star [10].

5. CONCLUSIONS AND DISCUSSION

The magnetic fields of the astrophysical bodies vary in strength but they all have a common characteristic which is that they are all generated by dy-namo action. Based on Maxwell's equations and classical electromagnetism (in combination with hydrodynamics), we can give satisfactory explanations of the magnetic fields that are generated in the interior of the stars.
Moreover, studying the stellar magnetic fields of main sequence stars like the sun in association with their differential rotation led us to the explanation of energetic phenomena in our solar system that straightly affect the modern human civilization: the solar cycle and the solar flares. It became clear, that every energetic phenomenon on the photosphere and in the atmosphere of the sun is originated from its own complicated magnetic field behavior.
Furthermore, we investigated the evolution of the magnetic field of massive collapsing stars that result in the formation of pulsars and magnetars. These objects are of great scientific interest as they possess the strongest magnetic fields in the universe, something that is responsible for high range energetic cosmic phenomena like the SGR bursts and the UHECRs. In addition, this observation is very important for the application of physics in the presence of ultra strong magnetic fields. As it became clear in the introduction of this project, ultra strong magnetic fields cause nature to behave in a completely different way associated with peculiar phenomena. Some of these phenomena like the electron photon pair gas peak beyond the quantum electrodynamic field strength are observable in the vicinities of magnetars, something that makes their study even more important.

However, there are still some unanswered questions under investigation for all these energetic astrophysical magnetic phenomena [4], [8]:

- Satisfactory explanation of the solar polar magnetic field associated with dynamo action.
- Exact explanation of the solar flare phenomenon and observational confirmation.
- If the flashes and flares from SGRs and AXPs are indeed due to starquakes, should we be able to detect aftershocks in the light curves of the magnetar bursts?
- How often should we expect the giant flares in SGRs? Is it possible that these flares have a periodicity and if so due to which fact?

The scientific research, with the aid of modern technology and higher computational power continues both in the observational and the theoretical field and more and more papers are published which approach the possible answers to the above mentioned problems.

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ApJ: Astrophysical Journal
MNRAS: Monthly Notices of Royal Astronomical Society
PNAS: Proceedings of the National Academy of Sciences
ASPC: Astronomical Society of the Pacific
AIPC: American Institute of Physics