Magnetars: A New Type of Star

Vanisha Swabhanam

Student ID: VXS210083

vxs210083@utdallas.edu

Magnetars

Vanisha Swabhanam*

(Dated: August 28, 2022)

A neutron star is the collapsed core of a red giant that was between $10 - 29 M_{sun}$ (solar masses). Neutron stars generally have magnetic fields ranging from 10^9 to $10^{15} G$, and there extends a further classification for certain neutron stars with an extremely high magnetic field of and above the magnitude of $10^{14} G$ called **magnetars**. These magnetic neutron stars are known to erupt and generate the most intense magnetic field in the observed universe (1). The need to distinguish the magnetar as an extremely-magnetic neutron star arose due to the March 5th event of 1979: at 10:51 A.M. EST, several space probes received an unprecedented flux of gamma rays and the on-board detectors jumped from 100 to 40,000 counts, and then off-scale, in a fraction of a millisecond. This paper will follow the history of the magnetar in relation to this 1979 event leading up to its classification and basic properties. We will delve into the properties of the magnetar's magnetic field because the magnetar model describes a specific type of neutron star that describes both steady X-Ray emission and Soft Gamma Repeater Bursts (SGRs) in terms of dynamo action (2). For our purposes, we shall also delve into SGRs, Anomolous X-Ray Pulses (AXPs), and Gamma Ray Bursts (GRBs) in the context of the magnetar model.

Usage: Use of publications to describe the magnetar as a model for SGRs, AXPs, and GRBs.

Keywords: magnetar, soft gamma repeater, anomolous x-ray pulsar, gamma ray bursts

I. HISTORY LEADING UP TO THE MAGNETAR

Gamma rays consist of high-energy photons, and since gamma ray detectors are relatively cheap, they were added to several space missions to send data back to Earth about Gamma Ray Bursts (GRBs) (2). The March 5th, 1979 event caused several GR-detectors onboard space probes to flood and break scales of detection due to the extremely strong wavefront. This is distinguishable from a GRB because this burst, for the next 16 years, had the residual effect of fainter bursts from the same spot and they lasted 0.2s each time after the first faint burst, which was 1.5s. This distinguishable difference is what led to the classification of Soft Gamma Repeaters, and the magnetar seems to be the most agreed-upon model for this phenomenon given certain evidence uncovered about the March 5th burster (2). The burster was located to lie inside the region of a supernova remnant about 1.8 $\times 10^5$ light years away. The burster is speculated to be a young neutron star because neutron stars are known the form within supernovae, and assuming it was in the center of the supernova explosion, it would have a fast velocity similar to the burster.

The unpredictability of magnetars was already being studied due to their differences between the general pulsar population in terms of rotation period and the more intense magnetic field, and this relation to the SGR prompted further magnetar research.

II. THE MAGNETAR AS A *NEW* TYPE OF STAR

While the magnetar is a classification of a neutron star that is highly magnetized, interestingly, it proves to be a new model of stars due to its energy source. Magnetars arent powered by conventional mechanisms such as nuclear fusion or rotation, they represent a new way for the star to shine (1). This is significant in differentiating the magnetar from radio pulsars because the persistent X-ray luminosity of the magnetar is much larger than their inferred spin-down power and thus, rotation cannot be a significant energy source. This rotation energy quickly becomes negligible. Magnetic energy seems to be the ultimate source of both the bursts and of the persistent radiation from a magnetar, and the magnetic field is strong enough to push material into the stars interior and crust, leading to the dissipation of this magnetic energy in the first 10^4 years (1). To qualitatively understand this phenomenon, we will describe the dynamo action process, which is the prediction of what gives rise to the magnetic field in a neutron star. For the purposes of our paper, well discuss the dynamo as the agent that maintains the magnetic field, the alternative that this paper will not include is the idea of fossil flux. If you would like to know more about the fossil flux theory, please check Section V - Notes for a link to a paper.

Ultra-dense neutron star fluid can conduct electricity very well through the free electrons and protons present with the neutrons, and this current allows the magnetic field lines to be swept in convective motions (2). If the star rotates fast enough, the star's magnetic field builds up via **dynamo action**. The dynamo theory suggests the process of a self-sustained magnetic field in a celestial body through rotating, convection, and electrically conducting fluid. Qualitatively, the free electrons and neutrons create the electrically conductive fluid required to sustain a dynamo, along with rotation. Dynamo's that are extremely efficient can generate a magnetic field of about 10^{16} G in a hot, young neutron star (2). The difference between the Magnetar and another classification of a neutron star, such as the radio pulsar, is that the dynamo in the radio pulsar isn't as efficient because it wasn't born rotating fast enough. The spin period has to be very small for the dynamo process to be efficient; it must be in the range of a millisecond (2). The observed emission of radio pulsars is powered by a residual loss of rotational energy, however, a magnetar spins down too rapidly to be easily detectable like a radio pulsar.

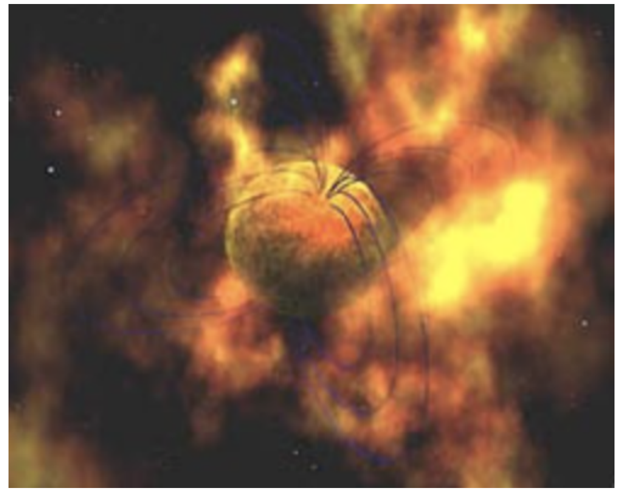

FIG. 1: Artist's conception of a magnetar burst

FIG. 2: Artist's conception of the cracking of the magnetar's crust.

The physics of the magnetar is described through the central equations of magneto-hydrodynamics (MHD), and the creation of the magnetic field is described through the MHD induction equation. This induction equation is derived from Maxwell's equations and Ohm's law. Maxwell's equations are a set of partial differential equations that provide a conceptual insight into electromagnetism(as seen in equations 1 and 2), and Ohm's law states that the current through a conductor between two points is directly proportional to the voltage across the two points (as seen in equation 3).

$$\nabla \times \mathbf{E} = -\frac{d\mathbf{B}}{dt} \tag{1}$$

$$\nabla \times \mathbf{B} = \mu \mathbf{J} \tag{2}$$

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \frac{\mathbf{J}}{\sigma} \tag{3}$$

Combining equations 1-3 and eliminating **E** and **J**, we get the induction equation for an electricially resistive fluid.

$$\frac{d\mathbf{B}}{dt} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} \tag{4}$$

Here, η is the magnetic diffusivity, **B** is the magnetic field, and **v** is the velocity. The magnetic Reynolds number, R_m, is the ratio of the two terms on the right hand side of the induction equation. It approximates to $\frac{LV}{\eta}$ at typical speed V (which is scaled from **v**) and length scale L where $\nabla \sim \frac{1}{L}$. The R_m is a dimensionless group that gives an estimate of the relative induction of the magnetic field to the diffusion of the field. For the purposes of the **dynamo theory**, the fluid is assumed to have infinite electric conductivity, and the first term on the right side of the induction equation vanishes because $\eta \to 0$. This leads to a very large R_m, and this results in an ideal conductive fluid in the magnetar's plasma. The induction equation assumed with a perfectly conducting limit (which serves to be a good approximation in dynamo theory) is:

$$\frac{d\mathbf{B}}{dt} = \nabla \times (\mathbf{v} \times \mathbf{B}) \tag{5}$$

In this case, we'd have an extremely high R_m which essentially means that diffusion is unimportant and in this case, we can focus on the influence of the magnetic field on the flow. The magnetic Reynold's number for a magnetar will be in the order of magnitude of $\sim 10^{17}$ (2).

1. *Magnetar's Magnetic Field in Reference to the Field of Other Celestial Bodies*

The first-ever estimate of a magnetar's magnetic field places it at $6 \times 10^{14} G$ (1), which is about 1.2×10^{14} times greater than the magnetic field of the Sun. The strongest magnetic field on earth would be from an MRI scan, which is on the order of $10^4 G$, and any magnetic field

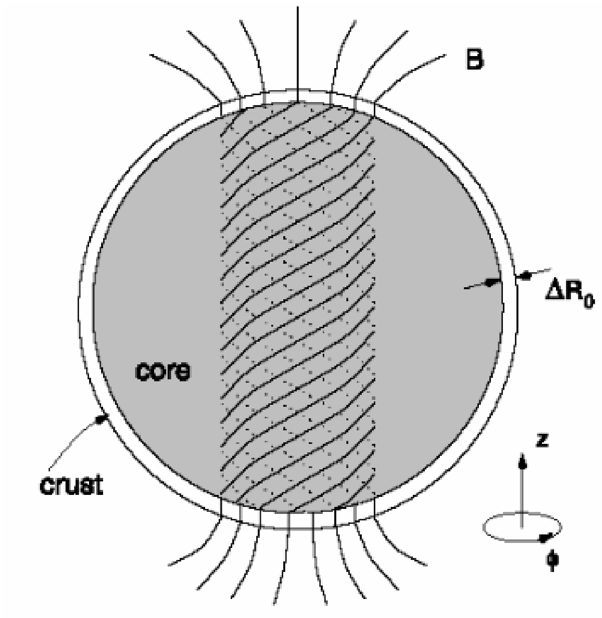

FIG. 3: Magnetar Diagram

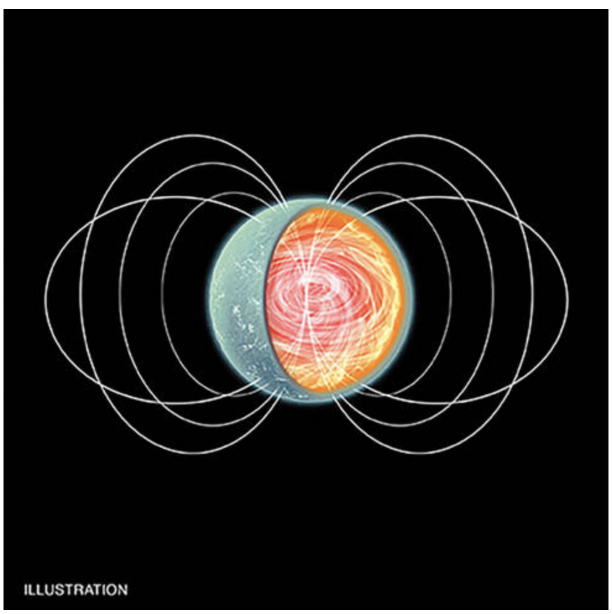

FIG. 4: Illustration - Magnetic Field Lines for the Magnetar

stronger than $10^9 G$ proves to be instantly lethal through pure static magnetism. If you'd like a more quantitative explanation, please check Section V - Notes.

III. MAGNETAR OBSERVABLES

Having touched base with the discovery of the Soft Gamma Repeater, we will delve with more detail into how the Magnetar proves to be the accurate model for this observable. Another phenomenon that utilizes the 'Magnetar model' to explain its emission scenario is the Anomalous X-Ray Pulsar (**AXP**), which will be discussed on a high-level later on in the paper. The last observable that could possibly be extrapolated by the magnetar model is the Gamma Ray Burst (**GRB**), but it must be noted that this is highly speculative in nature. We will discuss the possible implications of the magnetar model on long and short duration GRBs. Lastly, in this section, we shall cover the observable magnetar magnetic field produced in the merger of two binary neutron stars.

A. The Magnetar as a model for Soft Gamma Repeaters

On a high-level, the magnetar serves as the leading model to describe SGRs because the ultra-strong magnetic field drifts through the magnetar's crust, and it stresses the crust with forces that causes shifts within the crust that lead to outbursts. As a small class of neutron stars powered by the decay of their intense internal magnetic fields, almost all magnetars have been observed to exhibit repeated bursts of soft (30keV), short duration (0.1s) gamma-ray bursts. These are of an energy of 10^{45} erg. These outbursts are periodic, serving as the most plausible model for SGRs given the properties that are modelled in an SGR burst. These crustal fractures are driven by magnetic stresses and diffusive processes that allow catastrophic releases of magnetic energy to plausibly occur, roughly similar to stellar flares (2).

Magnetars are well above the quantum critical field of $B_c = \dfrac{2\pi m^2 c^2}{eh} = 4.41 \times 10^{13} G$, and above this threshold, the magnetic confinement is so strong that the space available to an electron is comparable to its Compton wavelength. Alongside this, the theoretically inferred properties of magnetar as having a luminosity higher than the rotational power of the neutron star (4) distinguishes it as its own observable class different from other neutron star classifications. This primary claim that magnetars are powered by the decay of their overcritical magnetic fields is what fundamentally defines it. A reliable estimate of SGR magnetism was done in 1998 by C. Kouveliotou, and it gave evidence for a magnetic field of $8 \times 10^{14} G$ (2) which substantiates the model of the magnetar.

B. Interesting note on Magnetar SGR 1900+14's Effects on Earth

August 27th, 1998 marked a flare with a gamma-ray flux so intense that it was the highest ever detected gamma-ray emission from outside the solar system. This flare proved to be so intense that it strongly ionized the Earth's outer atmosphere and affected radio communications (2). The atoms in the ionosphere were ionized at night-time in the same way they are ionized during the day-time due to the sun, and this caused the ionosphere height to vary over a period of 5.16 seconds (2). This period is actually the spin period of the SGR, and the fluctuations in height of the ionosphere affected long-wavelength radio transmissions. This intense flare affected the Earth directly, and its interesting to see its range fluctuation.

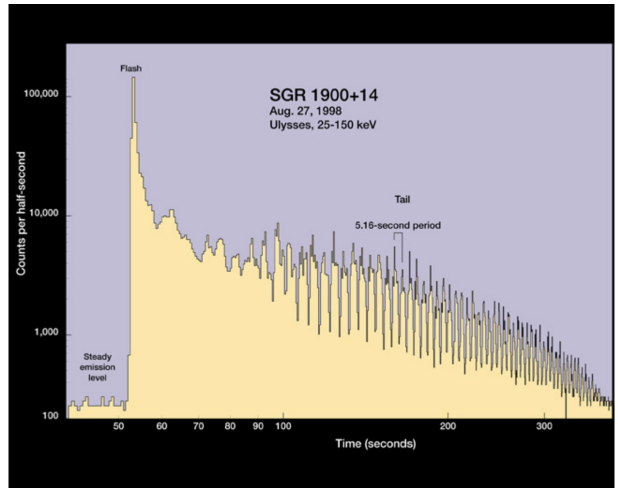

FIG. 5: August 27th, 1998 Flare

C. Anomalous X-Ray Pulsars

AXPs serve as another kind of magnetar candidate, and many of their properties are shared by SGRs. These sources have soft-spectrum X-ray emissions modulated on pulse periods between 5-12s (2). This class, similar to the SGR class, has been associated with supernova remnants, which argues for an interpretation of young neutron stars. The AXP isn't a rotation powered pulsar, and in June 2004, a burst was observed from the AXP 1E 1048-5937 (5). This was predicted in the proposed magnetar model by Thompson and Duncan in 1996, which both supports the magnetar as a model for AXPs and it also strengthened the relation between AXPs and SGRs.

1. Summary of the Magnetar Model to describe SGRs and AXPs

A neutron star with an extremely efficient dynamo coupled with a break-up velocity limit of 1ms (the breakup velocity is when the centrifugal force outweighs the neutron stars gravity, anything past this velocity means that the centrifugal force would be too strong and could rip apart the star) ideally results in a magnetic field on the magnitude of $10^{16}G$. The first 10,000 years of this star exhibit SGR characteristics because the decay of the extremely strong magnetic field, which above the quantum critical point, causes outbursts in the range of x-ray and gamma-ray emissions. The next 30,000 years of the magnetar seems to be modeled by the AXP (5) once the magnetar becomes old and much of its magnetism has decayed away. After 10,000 years, the magnetar emits very little energy. The distinguishable time where a neutron star either becomes an ordinary pulsar or a magnetar depends on the spin of the star. If it spins fast enough, it generates a magnetic field intense enough to reach magnetar levels.

The differences between radio pulsars and magnetars can be outlined through the following points (9):

- Magnetar fields have a faster magnetic field decay rate that's given by ambipolar diffusion (definition in Section V - Notes):

$$t \cong 10^5 yr(\frac{B_{core}}{10^{15}G})^{-2} \tag{6}$$

- Magnetars undergo greater crustral stresses, one consequence of which is SGR bursts. This crustral stress for the magnetar is given by the following equation:

$$B_{yield} = 2 \times 10^{14} G(\frac{\theta_{max}}{10^{-3}})^{1/2} \tag{7}$$

D. Gamma Ray Bursts

GRBs are flashes of extremely high-energy photons, and they consist of two kinds: long-duration GRBs and short-duration GRBs.

1. Long GRBs

Long-duration GRBs have long been attributed to the core-collapse of a very massive star, such as in the model for the supernova, but cannot result in a black hole because its too heavy to form a stable neutron star (1). This core-collapse model is the most popular and substantiated model, and we discussed in class that it results in a fast-spinning black hole that has an ultra-magnetized disk of dense matter orbiting around it. This propels a jet of a moving panel that produces more power than any model involving a neutron star; however, there **does** exist an alternative model for the powering of a GRB that suggests a rapidly-spinning magnetar. This alternative theory consists of an engine model called the millisecond magnetar in which the central engine powering the GRB is from the magnetar. This especially serves as a model to explain certain long-duration GRBs with low power and are intrinsically faint (1). The maximum energy that can be stored in a rotating neutron star is $2 \times 10^{52} erg$, and the typical timescales for a magnetic field in the magnitude of $10^{15}G$ is 100s (6), which is comparable to almost all LGRBs observed. However, the magnetar model's biggest issue is the amount of available energy, and the detection of a GRB of energy greater than what a magnetar can store can disclaim this model. Whether the magnetar could be a potential model for a long-duration GRB is currently still under speculation.

2. *Short GRBs*

Short GRBs are of timescales comparable to SGRs, and the sources of some SGRBs could certainly be from magnetar bursts. NASA launched the Swift satellite in 2004, and it was designed to determine how many SGRB sources are magnetar flares, and upon detecting a GRB, the satellite can pinpoint its location (1) using X-ray and UV telescopes if there's an afterglow (assuming from x-ray emission).

E. Binary Neutron Star Mergers

Binary neutron star mergers can amplify magnetic fields via instabilities in the plasma, such as the Kelvin-Helmholtz (KH) instability (6). The KH instability refers to the instability and transition of fluids of different densities moving at different speeds. This instability in relation to the two neutron stars that merge result in a magnetic field amplification. Through assuming dynamo saturation, the first ever simulation (sub-grid model for general relativistic magneto-hydrodynamic simulations of BNS mergers) was used to study small-scale magnetic field amplifications and it was found that magnetic field values in the order of $10^{16}G$ can easily be produced in BNS mergers (check Section V - Notes for link to paper about subgrid model) (7).

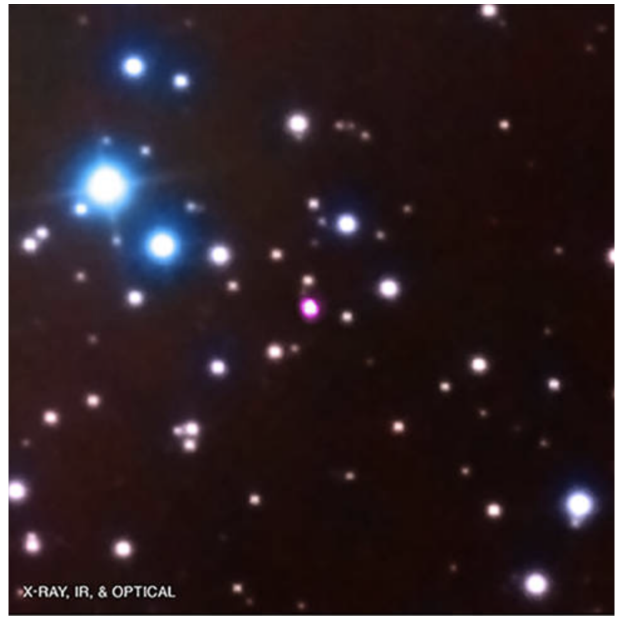

FIG. 6: Image - Region with a Real Magnetar (SGR 0416)

IV. CONCLUSION

Magnetar research is still an up-and-coming field characterized by the unpredictability and highly variable bursts in the x-ray and gamma-ray energy ranges. As of July 2017, 26 isolated x-ray pulsars have shown magnetar-like activity (7). We will delve into the properties of one specific magnetar, SGR 1806-20, which was originally characterized as a gamma ray burst rather than an SGR, and we'll outline its history of the Giant Flare in 2004, and the following years after this major bursting episode. This will help us succinctly summarize what we have learned in this paper through following the model of an observed magnetar.

1. *SGR 1806-20*

SGR 1806-20 has historically proved to be the most active magnetar, and has been emitting short bursts regularly since its discovery (8). It also had major bursting episodes in 2004, and this culminated with the Giant Flare, which is the strongest emission on record so far with a peak luminosity of about $10^{47} erg/s$ (7). Along with the observed spin period by NASA's RXTE of 7.5s, it has reached a persistent x-ray flux level after the major bursting episode in 2004, and has decayed by a factor of 50% over the subsequent 7 years (8). This model fits the magnetar star model discussed throughout the paper in all formats: the period, the short characteristic bursts, and then the large flare that represent major crustal reconfigurations. It seems as though 2004 was a period of intense activity for the magnetar, and the basic energetics and timescales involved are well understood in terms of the magnetar model.

*2. **Future Magnetar Studies***

The study of magnetars is a field increasing in popularity from SGR and AXP observations, and these studies provide major insight about the physics of neutron stars. The model of the magnetar as a new type of star which is powered not by rotation, but by the decay of its immensely strong magnetic field may possibly lead to explanations of previously unexplained astronomical phenomena. NASA's RXTE (Rossi X-ray Timing Explorer) was launched in 1995, and it aims to provide more insight into environments about white dwarfs, neutron stars, and other celestial bodies that emit x-rays. Data from RXTE established the existence of highly magnetized neutron stars, and while this signifies the start of magnetar science, theres much more left to learn about these elusive stars.

V. NOTES

In this paper, we discuss the Magnetar model an approach to distinguishing between SGRs, AXPs, and potentially GRBs. However, the **model of accretion** for GRBs which is the more popular and substantiated approach to distinguishing among GRBs.

We also spoke of the magnetic field that is formed from the merging of binary neutron stars, and the information about the subgrid HRMHD simulation is past the scope of this paper, and thus, we just summarized the results. If you'd like to take a look at this paper and delve into the details, please visit (6) in the bibliography.

If you'd like to learn more about magnetar outburst mechanisms that are beyond the scope of this paper, please visit (7) in the bibliography. And lastly, in this paper we discuss the process of dynamo theory. There exists an alternative to this theory, which is the fossil field hypothesis. For more information about the debate between the dynamo theory and the fossil field theory, you can visit the following link: https://arxiv.org/pdf/1504.08074.pdf.

Definition of **ambipolar diffusion** - Ambipolar Diffusion refers to the decoupling of neutral particles in the neutron plasma in which if they were not coupled with the plasma, they would be coupled in a cloud that would undergo gravitational collapse.

1. *Quantitative Explanation for High Magnetic Field in Magnetars*

The traditional formula used to infer a neutron star's magnetic field is to equate its rotational energy loss of the neutron star (following equation 4) to the radiating power of a rotating magnetic point dipole in a vacuum (following equation 5) where Ω is the rotational angular velocity of the star, μ is the component of magnetic dipole perpendicular to magnetic field B, and $\dot{P}$ is the rotational period and spin-down rate of the pulsar, and I is the moment of inertia.

$$\dot{E_{rot}} = -4\pi^2 I \frac{\dot{P}}{P^3} \tag{8}$$

$$P_{dip} = -\frac{2}{3}\frac{\mu^2\Omega^4}{c^3} \tag{9}$$

In the case of a magnetar, we see that $L_{neutron} > \dot{E_{rot}}$ and this suggests that the 'missing link (4)'between rotation-powered neutron stars (pulsars) and the magnetars is that magnetars are powered by the decay of their overcritical magnetic fields. This is true given that they have magnetic fields with values higher than the critical field for quantum electrodynamical effects.

[1] NASA. [*NASA - Magnetars, and FIG 1*]. `https://www.nasa.gov/missions/deepspace/f_magnetars.html`

[2] Magnetars. [*Magnetars, Soft Gamma Repeaters Very Strong Magnetic Fields, FIG 5*]. `http://solomon.as.utexas.edu/magnetar.html`

[3] Origin and Evolution of Magnetic Fields. [*ORIGIN AND EVOLUTION OF NEUTRON STAR MAGNETIC FIELDS*]. `http://www.if.ufrgs.br/hadrons/reisenegger1.pdf`

[4] Magnetic Field of Pulsars. [*ON THE MAGNETIC FIELD OF PULSARS WITH REALISTIC NEUTRON STAR CONFIGURATIONS*]. `https://arxiv.org/pdf/1411.2621.pdf`

[5] Observing Rotation Pulsars and Magnetars. [*Observing Rotation-powered Pulsars and Magnetars in the X-ray and Gamma-Ray Sky*]. `https://eud.gsfc.nasa.gov/Volker.Beckmann/school/download/Hermsen_pulsars_magnetars2.pdf`

[6] Binary Neutron Stars. [*PRODUCING MAGNETAR MAGNETIC FIELDS IN THE MERGER OF BINARY NEUTRON STARS*]. `http://iopscience.iop.org/article/10.1088/0004-637X/809/1/39/pdf`

[7] Magnetar Outbursts. [*Systematic study of magnetar outbursts*]. `https://arxiv.org/pdf/1710.04671.pdf`

[8] Giant Flare 2004. [*THE SLEEPING MONSTER: NuSTAR OBSERVATIONS OF SGR 180620, 11 YEARS AFTER THE GIANT FLARE*]. `https://arxiv.org/pdf/1711.00034.pdf`

[9] Figure 2. [*Figure 2 Citation*]. `https://phys.org/news/2016-08-magnetars.html`

[10] Figure 4 and 6. [*Figure 4, Figure 6 Citation*]. `https://www.nasa.gov/mission_pages/chandra/multimedia/sgr0418.html`