# Magnetism: Peak Performance

# Space is a crazy place, home to some of the most outlandish phenomenon and objects that the human mind can conceive of. What, though, could the *most* outlandish phenomenon and inexplicable celestial body *be*? While there are many candidates, one that stands out above many, many others, is the magnetar. Not only are magnetars the compressed aftermath of gigantic stars, but they also boast the most intense magnetic fields known to the universe and showcase the curious depth of the relationship between electricity and magnetism. And just what makes them tick?

# In order to understand magnetars, one must understand neutron stars. For a star larger than our sun, but smaller than capable of creating a black hole, when it dies, the star will collapse in on itself and the outer layers will reverberate off the inner, increasingly compressed layers, and bounce off, creating a supernova. Provided the star is large enough, that compression in the middle is where things get interesting. The atoms are pushed together so hard that the protons and electrons literally fuse together, leaving behind an incredibly dense mass, a neutron star. After taking such a large object and compressing it, thanks to the conservation of angular momentum, the newly formed object spins. Very. Very. Fast. Similarly, the previous star’s magnetic field is amplified, and if it is spinning fast enough, a so-called ‘dynamo effect’ will amplify the field yet again, resulting in a magnetar (Dixon 2003). Think compressing the sun down to the size of Manhattan, and as much as it shrinks, it spins faster. With a dynamo, multiply that spin by 100.

# Currently, there are many questions and possible answers regarding magnetar mechanics, but many are hard to prove based on our limited exposure to their data. For example, there are only around 10 known magnetars from which to collect this data, but there are many pulsars (another type of neutron star) we *can* take data from that are similar. Our current information comes largely from theory, as well as radiation readings from satellites and probes (Dixon 2003). For example, we can measure the period of a distant magnetar by reading the time between radiation signals we receive, and can thus measure the strength of their magnetic field using:

# Bd=3.2×1019√PṖ G (1)

# With extremely fast rotation periods, we see magnetic fields between 1014 -1015 G (Mereghetti 2013). Fields of this strength are capable of polarizing the vacuum around them. A hydrogen atom, under these conditions, will be stretched 200 times narrower and into a long cylinder thinner than the quantum-relativistic wavelength of an electron (Dixon 2003). Right now, one of the theories regarding these gargantuan fields simply comes down to conservation of angular momentum: the strong magnetic fields are simply remnants of the most magnetically active stars, amplified by the 1.5 million-fold compression of the star. The leading theory, however, expands upon this by describing why there is a multi-order of magnitude difference in the magnetic fields between pulsars and magnetars. This model agrees with the previous, but additionally comments on how ionized fluids within the newly born neutron star can cause a dynamo effect and further amplify these fields (Mereghetti 2013).

# In fact, both the earth and our own Sun have magnetic fields because they also experience dynamo action, but to a much lesser extent. One way to visualize this phenomenon is by looking at a current computational model. In this technique, the dense fluid of neutrons inside a neutron star (before becoming a magnetar) resemble convection in a pan of boiling water – hot patches of fluid rise and cool ones fall. As this hot, dense fluid is circulating, the free electrons and protons in the fluid get caught up and carried by these currents. Flowing electrons are current, and these currents can sweep by and pick up any of the magnetic fields that are already inside of the neutron star. Normally, this ionic fluid flows in varying directions and strengths in different parts of the star and can cancel each other out or slow other currents down. The dynamo theory states that pulsars are stopped here; their magnetic field is amplified from compression alone. Whatever currents there are inside are sporadic and non-uniform and do not contribute much additional energy to the pulsar. If a star was already rotating faster than normal, however, once compressed to a neutron star in the early stages of its life – also called a protomagnetar - it could spin so fast that ionic currents inside the star align and become far more uniform (Bonanno 2006). This uniformity of spinning electric fields serves to amplify the magnetic fields even more, making them stronger than any other in the universe.

# In a more concrete sense, in nature, we find that the Rossby number (Ro) of a neutron star determines the strength of its dynamo action. Where P is the period of a spinning neutron star and Pc is the period of convection inside the star, Ro = P/Pc. Where Ro >> 1, there will be little or no dynamo. For Ro ~ 1, there may be some dynamo action typical to a pulsar. And where magnetars are concerned, Ro ≤ 1 (Bonanno 2006). The reason that the Rossby number of a neutron star is so indicative of its magnetic field strength is rooted in the Law of Inductance/Dynamo Equation

# = λ∇2B + ∇ x (u x B). (2)

# The two different terms can be broken down into an entropy gradient and a lepton gradient: as entropy and/or the flow of leptons (electrons) within the neutron star increase, so too does the magnetic field. What’s more, knowing | Bt/Bp| ≡ ξ, where Bt is the toroidal component of the magnetic field and Bp is the poloidal component of the magnetic field (shown below), we can use the poloidal magnetic field equation

# Bps ≈ Beq(1 + ξ)−1 G (3)

# where Beq depends on the physical speed, size, and density of the neutron star.

# 

# The blue arrow represents poloidal motion, while the red arrow represents toroidal motion

# We can use this equation because, for a low enough Ro, we can treat the magnetar almost as a rigid rotator and only pay attention to it’s rotational (poloidal) components. Continuing, if the period of rotation is small enough (P < Pc[1 + (1 + ξ)2]−1), then the dynamo leads to a very strong magnetic field: Bps > Beq ∼ 3×1013 G. That, however, is pulsar-level magnetization. In order to achieve our sought-after field, the period must be even shorter, less than ~0.1Pc. When this *is* the case, from Eq. (3), we find that

# Bps ∼ 0.3Beq ∼ 1013 G. (4)

# The smallest period for a neutron star is around 1 millisecond, allowing the dynamo to produce a field ∼3 × 1014 G (Bonanno 2006). If a field is any stronger (we mentioned that they can reach up to 105 G), then the dynamo will be used in addition to the already present and amplified rotation from when the star was compressed. Do note that all the dynamo action occurs within the first 30-40 seconds of a newly formed neutron star’s life.

# It was also previously mentioned that the more unity the internal convection of the neutron star had, the more likely it was to result in a dynamo. To shed further light on this, we find that the resulting magnetic field after the birth of a neutron star (Bsat) is dependent on its density (ρ), the size of its internal dipoles (p), and the speed at which the convecting fluids complete a full rotation in the star (τcon) (Duncan and Thompson 1992). They are related through

# Bsat = p / τcon G. (5)

# This makes sense because the denser the star is after its collapse, the faster it should spin. Likewise, the larger the dipoles within it, and the shorter its rotation period, the larger the resultant magnetic field will be. Observing the sum of the small, unorganized dipoles in a standard pulsar, the saturation field corresponds to ~1012-1013G. On the order of 1 ms, as mentioned above, is where the additional field strength of magnetars is found. When organized, the strength of the magnetic field can be increased by up to two orders of magnitude because “the wrapping of field lines around the star by the shear motion allows the formation of larger scale magnetic structures” (Duncan and Thompson 1992).

# However, the force behind these magnetic fields - 100 MG greater than any created here on Earth (Duncan 1998) - are not easy to sustain. As we learned in class, any change in magnetic flux is met by electrical resistance, and this is true even in the extreme magnetosphere here. With so much fluctuating magnetism, there is so much force acting against magnetar rotation that they are doomed to an active life 10,000-100,000 times shorter than their cousin the pulsar (Duncan and Thompson 1992). Most of the rotation in a protomagnetar is dampened within 10 seconds after formation and magnetic torques continue to slow them down at the rate of about 0.6\*BSDP2hr/(G2ms2), where BSD = Bdipole/1015 G (Duncan and Thompson 1992). Unfortunately, it seems that the cost of being one of the most powerful phenomena in the universe comes at the price of a very fast death.

# While the current models have some concrete bases and seem to make sense in the general sense, if it feels like there is still an air of doubt, of theory, then you’re right to feel that way. Magnetars are mysterious, and when it comes down to it, they’re rare. While we may have an idea of how they function, there is no changing the fact that we cannot create magnetic fields within a laughable comparison to the ones they boast. The amount of energy displayed by these once-stars is difficult enough to maintain that they only last for the blink of an eye (cosmically speaking) and there are only a handful that are known (Dixon 2003). This makes physical experimentation nearly impossible and observational data collection limited. This is what keeps magnetars in the realm of theory and computation, with a weak comparison arising out of the earth and suns weak dynamo actions. Here I have outlined the *leading* theories with the most evidence to back them, but there are several other, weaker-but-present theories regarding how the laws of our universe reach their limits under these strange circumstances. This work seems to describe them accurately now, but they most likely aren’t perfect. And that’s what’s beautiful about physics, isn’t it? No matter how strange, how abstract, how extreme and impossible some things may seem, some of the greatest minds in the world are working tirelessly to figure them out and improve our understanding of everything around us. Right. Now.