Magnetars

We now have our second "frontiers" lecture. This time, the subject is magnetars. The idea is that some neutron stars may have such strong magnetic fields, $B > 10^{14-15}$ G, that a variety of exotic quantum electrodynamic processes, which are otherwise negligible, may become dominant. Since these processes cannot be observed in terrestrial laboratories, magnetars may be our only chance for the forseeable future to test the predictions of QED in this extreme environment. We'll start by describing the evidence circa 1995 that magnetars exist, then talk about more recent developments, then discuss some of the QED effects themselves.

Early evidence for magnetars

To understand the early evidence for magnetars we have to have a brief discussion about gamma-ray bursts (which we'll talk about in much more detail at the end of the course). Gamma-ray bursts are, well, bursts of gamma rays that last, typically, a few seconds. They were discovered in the late 1960s by orbiting satellites designed to determine if the evil Russkies were testing nuclear weapons in space. In the late 1970s and early 1980s, it was discovered that some of the sources repeated, although most did not. It now seems that the repeating sources have a number of differences from classical gamma-ray bursts, so they deserve their own class designation. The repeating sources (1) repeat (irregularly), (2) have relatively soft spectra, meaning spectral peaks in the 20-30 keV range instead of 200-300 keV, and (3) have bursts that are typically short, maybe a tenth of a second or less. This class goes by the name "soft gamma-ray repeaters", or SGRs for short. However, like many another class in astronomy (high-energy astronomy in particular), this is a rather sparse class: only four SGRs are known, with a fifth possible candidate!

The fact that SGRs repeat meant that their locations could be identified much more accurately than the locations of classical GRBs, which are essentially one and done. This location led to the early conclusion that all of them were associated with supernova remnants. **Ask class:** if they were associated with supernova remnants, what kind of objects could they be? Neutron stars or black holes. **Ask class:** if the supernova remnants were still there, what does this say about the ages of the objects? Supernova remnants are not visible after $\sim 10^5$ yr, so these had to be relatively young objects.

Additional analysis indicated that at least a couple of the SGRs were not in the center of the remnant. Assuming that the birthplace of the SGRs was the center, and using the inferred age of the remnants, this suggested a very high transverse velocity, more than 1000 km s^{-1}. Assuming the SGRs were indeed in the supernova remnants, the persistent and bursting flux (assuming isotropic emission) implied that the persistent luminosity was typically 10^{35-36} erg s^{-1} and the bursting luminosity was 10^{39-42} erg s^{-1}, depending on the burst. During bursts, the peak emission remains in the 20-30 keV range. Finally, one of the SGRs, in the Large Magellanic Cloud, had one burst dramatically different from the typical burst, on 5 March 1979. For one thing, it was extraordinarily luminous: the peak flux implied an isotropic luminosity of 2×10^{45} erg s^{-1}! It was also an extremely long burst, lasting over 200 seconds. In addition, during the long tail clear pulsations with a period of 8 seconds were discovered.

In 1995, Chris Thompson and Rob Duncan considered this evidence. The following is a simplified version of their arguments and conclusions.

First, the regularity of the pulsations in the March 5 light curve indicates that these objects are neutron stars, not black holes. As with the argument that pulsars are not black holes, black holes simply don't have any structure that a regular pulsation could grab onto.

Next, what could be the ultimate power source of the emission? We need to determine what energy has to be explained. **Ask class:** how do we do this? Start with the persistent luminosity. With 10^{36} erg s^{-1} over 20 years, that's 6×10^{44} erg, and if you assume that this emission has been typical over the $\sim 10^3$ yr age of the supernova remnant, that's 3×10^{46} erg. One must also consider the energy in the March 5 event: there had to be enough energy to power one 10^{45} erg event at that time.

Ask class: what energy reservoirs can you think of? Rotation, accretion, and nuclear energy are all important for one neutron star or another, so let's consider them. What about rotation? The total energy of a rotating object is $\frac{1}{2}I\Omega^2$. Assuming that the 8 s period of the March 5 event was its rotation period (and it is consistent with that interpretation), and using $I = 10^{45}$ cgs, the energy is only about 3×10^{44} erg. This is not enough to power the March 5 event, and is also not enough to power the subsequent persistent emission. Therefore, argued Thompson and Duncan, rotation can be ruled out.

What about accretion? **Ask class:** given how Bondi-Hoyle accretion works, do they expect a high accretion rate from an object moving at 1000 km s^{-1}? No way! The accretion rate goes like v^{-3}, so such a high-velocity object accretes practically nothing from the interstellar medium (around 10^6 g s^{-1}, in fact, giving a paltry 10^{26} erg s^{-1} maximum). The only way that accretion could be a significant source of energy would be if the neutron star brought along a companion with it. But with such an enormous velocity, presumably produced in the supernova explosion that formed the neutron star (pre-SN high-mass stellar systems are very low velocity), it would be almost impossible to carry along a companion. For this and other reasons, Thompson and Duncan argued that accretion can also be ruled out.

What about nuclear energy generation? This is a non-starter, for several reasons. **Ask class:** how can nuclear energy generation be ruled out as the primary source of energy for SGRs? One problem is that there is nowhere that the fuel could come from, if it isn't accreting actively. Another problem is that the ultrahigh luminosity of the bursts, much above Eddington, does not mesh with a nuclear burst, or accretion for that matter, unless the magnetic field is extremely high.

What about magnetic fields? This was the model proposed by Thompson and Duncan. Suppose that somehow a few neutron stars have dipolar fields on the order of $B = 10^{15}$ G. If this is approximately the average throughout the star, then the total magnetic energy is $E_B = (B^2/8\pi)(4\pi R^3/3) \approx 10^{47}$ erg. If this energy is converted into thermal energy or another form through dissipation of the magnetic field, this is enough to power the persistent emission and bursts. The ultrastrong fields, and the fact that the emission is supposed to be powered by them, led Thompson and Duncan to call these objects "magnetars".

Thompson and Duncan also pointed out several other arguments in favor of fields this strong. For example, as we'll see later, the Thomson scattering cross section is decreased dramatically in very strong magnetic fields. This is important, because otherwise a strongly super-Eddington flux (as observed) would create a strong wind, which would move the visible surface to such a large radius that the emission would be at much lower temperatures and hence energies. This is not observed, so something needs to hold the plasma in place. In addition, standard magnetic dipole spindown can take an initially rapidly spinning neutron star and slow it to an 8 s period in $\sim 10^3$ yr, as needed for the March 5 event, if the field is $\sim 10^{15}$ G.

These are reasonable arguments, but in 1995 when T+D presented it, there was a lot of initial skepticism (including from me!). One reason was the magnitude of the field; although 10^{15} G isn't impossible, it is roughly a hundred times stronger than seen in any rotation-powered pulsar, so why such a gap? Another reason is that these arguments are quite indirect. Where is the smoking gun?

SGR spindown

While I don't think that definitive evidence is yet at hand (more on that later), in 1998 observations of two of the SGRs, SGR 1900+14 and SGR 1806-20, made the case extremely strong. In late 1996, BATSE caught SGR 1806-20 in a burst-active phase. That is, it started bursting at a much greater rate than had been typical in the previous decade. RXTE was pointed in its direction, and it caught more than 80 bursts in a two-week period. In 1998, analysis of the RXTE data from the bursts and from persistent emission revealed a clear 7.5-second periodicity. Even better, previous observations of this source with ASCA also showed the periodicity (the periodicity in the ASCA data was now significant because only a small frequency interval around the RXTE frequency was searched). This showed a clear period derivative as well, of $\dot{P} = 10^{-10}$. Using the standard magnetic dipole model, $B = 3 \times 10^{19}\sqrt{P\dot{P}} = 8 \times 10^{14}$ G! Later in 1998, SGR 1900+14 had a giant burst similar to the March 5 event. This had a period of 5.2 s and a period derivative of 10^{-10}, so again the implied field was about 8×10^{14} G.

These enormous implied fields strongly support the Thompson and Duncan model. It has been pointed out, however, that if there are strong ionized winds from these sources that the spindown behavior might not be what the magnetic dipole model predicts. If so, the field could be weaker (maybe "only" 1×10^{14} G).

Why, then, do I not think that this really is the smoking gun that establishes the existence of magnetars? It's pretty close to definitive, but the problem is that again there is only an indirect measurement of the magnetic field (backed up, it is true, by strong physical arguments). The evidence that would settle the issue is related to the reason why all this has fundamental physical interest: a spectral signature unique to ultrastrong magnetic fields. To think of these we now need to catalog some photon interactions unique to high fields.

Modifications to scattering

The first major change is to the basic process of photons scattering off of free electrons. Recall that in zero field, the process of Compton scattering has a frequency-independent scattering cross section (the Thomson cross section) for photon energies much less than $m_e c^2$. However, this is no longer the case when the magnetic field is strong. Remember that Compton scattering can be thought of as (1) an electron accelerated by the electric field of a photon, followed by (2) the accelerated electron radiating. If, in a strong field, the electron is accelerated along the field, there is no resistance and the process happens as before. However, if the electron is accelerated across the field, the field resists strongly. The upshot is that in ultrastrong field, scattering is suppressed (hence the cross section is lowered) for polarizations that are perpendicular to the field. The cross section for the parallel, or high cross section, mode is $\sigma \sim \sigma_T$, whereas the cross section for the perpendicular, or low cross section, mode is $\sigma \sim (\omega/\omega_c)^2 \sigma_T$, where ω is the frequency of the photon and $\omega_c = eB/m_e c$ is the cyclotron frequency. There is also a dependence on the propagation angle θ relative to the direction of the magnetic field. The reduction in cross section can be a factor of 10^6 for magnetar-type fields. The really low cross section means that most of the flux is transported in this polarization. **Ask class:** why is that? Because when there are separate channels (separate polarizations, in this case), the lower cross section channel is where the flux goes.

There is also the possibility that a cyclotron resonance may be in the frequency range of interest. However, instead of the electron cyclotron resonance (with $\hbar\omega_c \approx 11(B/10^{12}\ \mathrm{G})$ keV), it could be a proton resonance or alpha-particle resonance. This would be a fairly weak resonance, but might be detectable under some circumstances.

Finally, there is a really weird effect in high fields, called the vacuum resonance or the second vacuum frequency. Having a strong magnetic field around produces "vacuum polarization": virtual pairs induced by the field change the dielectric tensor of the vacuum, which changes normal modes and propagation effects. In addition, the presence of matter also changes the dielectric tensor (as seen in everyday life, where the index of refraction isn't unity in matter). The two combine, in a narrow range of density that depends on the magnetic field and photon frequency, to effectively "cancel out" each other. The net result is that for a given frequency in an atmosphere with varying density, there is a region where the scattering cross section is nearly Thomson for both polarizations. Therefore, it scatters in this layer, and its frequency shifts until it is out of the critical frequency interval. The spectrum should, therefore, have a pronounced dip in it, around 10-40 keV depending on the scale height and other things. For the record, the critical frequency is $\hbar\omega_{c2} \approx 30 n_{26}^{1/2}(B_c/B)$ keV for $B \ll B_c = m_e^2 c^3/\hbar e = 4.414 \times 10^{13}$ G (the quantum critical field) and $\hbar\omega_{c2} \approx 13 n_{26}^{1/2}(B_c/B)^{1/2}$ for $B \gg B_c$. Here the number density is $n = 10^{26} n_{26}$ cm^{-3}. Tomek Bulik and I suggested this might leave a clear signature in the spectrum (1997, MNRAS, 288, 596), but it hasn't been seen yet.

Photon splitting

Now let's think about a strange process: photon splitting. **Ask class:** suppose that a photon is traveling by itself in a vacuum. Can it split into two photons? No, but the argument is somewhat subtle. To conserve energy and momentum, the two photons produced must both be traveling in exactly the same direction as the original photon. That means that there is zero solid angle for this process, so it is kinematically forbidden. That's distinct from pair production, which violates energy or momentum conservation in a vacuum.

A photon traveling in a magnetic field may split into two photons, so that after a distance d the number of unsplit photons is $N(d) = N_0 e^{-S(\hbar\omega, B_\perp)d}$, where N_0 is the original number of photons. From Adler (1971) the attenuation coefficient for photon splitting in a magnetic field $B < B_c$ is

$$S(\hbar\omega, B_\perp) = 0.12 \left(\frac{\hbar\omega}{m_e c^2}\right)^5 \left(\frac{B}{B_c}\right)^6 \sin^6\theta \ \mathrm{cm}^{-1} \tag{1}$$

where the photon is assumed to be traveling at an angle θ to the field. The fraction of photons which undergo splitting is $\approx 1 - e^{S(\hbar\omega, B_\perp)d}$. So, for $S(\hbar\omega, B_\perp)d < 1$ an insignificant number split, while for $S(\hbar\omega, B_\perp)d > 1$ most split (roughly speaking). Unlike magnetic pair production and similar processes, the attenuation coefficient for photon splitting is not exponential. Also, the splitting is highly polarization-dependent; defining $\perp$ as the photon polarization mode with an electric field vector perpendicular to the $B - k$ plane, and $\|$ with an electric field vector parallel to the $B - k$ plane, kinematic and CP selection rules imply that only $\perp \rightarrow \| + \|$ is allowed. Some photon splitting occurs in all systems with photons in the $\perp$ mode. However, splitting is insignificant except for high-energy photons in fields close to B_c.

Other effects and summary

In addition to the previous effects, remember that in strong fields atomic physics is drastically modified, and in particular the transition energies are much greater than they are in zero field. If one could find many such spectral lines, this would also be a clear signature of magnetar-strength fields.

However, at this time there are no such clear signatures. The spectra are smooth continuum spectra, and you may remember from the lecture on signatures of strong gravity that smooth spectra can unfortunately be fit by a number of models. High-resolution X-ray experiments, such as Chandra, XMM-Newton, or (in the future), Astro-E or Constellation-X, may be able to resolve this. Until that point, although I think that the case for magnetars is strong, we won't have our smoking gun. Even more importantly, we won't be able to test the predictions of strong-field QED that are the main reason (in my opinion) that such objects are especially interesting.