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Modelling the Atmosphere of a Magnetar during a Burst

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Summary

In this thesis, I have studied how the emission of a magnetar influences its atmosphere, and how the atmosphere influences the emission. A magnetar is a type of neutron star with an extremely strong magnetic field. In turn, a neutron star is one of the end products of stellar evolution, and is formed when a massive star (8-30 times the mass of the sun) has used up all its fuel for nuclear fusion. When this happens, the star collapses, as it no longer creates the energy needed to support itself against gravity. This collapse causes an explosion known as a supernova, which causes most of the material the star was made of to be blown away. However, the core of the star remains. Because the material in the core is no longer supported against gravity by the pressure generated by nuclear fusion, it collapses into a much smaller object. This is a neutron star. A neutron star has a mass between one and three times the mass of the sun, but a diameter of only about 20-30 km. This means that a neutron star is much denser than any other type of object in the universe (with the possible exception of black holes, depending on the definitions of ‘density’ and ‘object’).

The main reason for studying neutron stars is that this is the only way to study what happens to matter at the extreme pressure and density of a neutron star. In terms of simple physics, we expect that when matter is compressed, atoms break apart into their component particles (protons, neutrons and electrons) and protons and electrons are fused into neutrons, creating matter that mostly consists of neutrons. This is where the name neutron star comes from, although we now know that the actual composition of a neutron star is much more complicated. There are different theories for what happens to matter when it is compressed even further, as well as for what happens in the several intermediate stages. Testing these theories, and thus gaining a better understanding of the fundamental physics of matter, is one of the key goals of neutron star research, and neutron stars are essential to this work, as the extreme environment of a neutron star cannot be simulated in a laboratory.

A magnetar is a special type of neutron star, which in addition to being extremely compact also has an extremely strong magnetic field. Neutron stars were already the

strongest magnets known in the universe, when magnetars were discovered to have a magnetic field between a hundred and ten thousand times stronger than that of a typical neutron star, giving them a magnetic field of approximately one hundred billion (10^{11}) Tesla. This is approximately a hundred million times stronger than the strongest magnetic fields made in laboratories. Thus, magnetars are a unique testing ground for what happens to matter at the highest possible magnetic field strengths.

Magnetars were first observed in the 1970s and '80s as a strange type of repeating gamma-ray burster, the origin of which was unknown. While these bursts resembled X-ray bursts observed from normal neutron stars, it was initially thought that the objects producing these bursts, called soft-gamma repeaters (SGRs) could not be neutron stars, as the bursts were too energetic. Neutron stars typically emit energy that either comes from their own rotation, slowing down as they do so, or which comes from material from another star that falls onto the neutron star. The SGRs did not show any evidence of having a companion star from which they could receive material, and did not rotate quickly enough to be powered by rotation. In the end it was proposed that these observations could be explained by a neutron star with an extremely strong magnetic field, and that the energy for the observed emission could come out of this magnetic field. Since then, we have observed many different magnetars, in several different ways.

Many magnetars are seen through their SGR bursts, which are short (usually less than a second in duration) bright flashes of radiation on the edge between X-ray and gamma-ray radiation. Some of these magnetars also show larger bursts, called intermediate flares, which emit more energy. These bursts also have a fast bright part, but regularly also continue to emit slightly less brightly for several minutes after the initial flash. Then there are the giant flares, which are some of the brightest events in our universe. Only three of these have ever been observed, in 1979, 1998 and 2004. Each time one of these giant flares occurred, it was observed by every single satellite capable of detecting X-rays or gamma-rays, regardless of whether the satellite was pointing in the right direction. These giant flares show similar behaviour to the intermediate flares: a short extremely bright flash, followed by slightly less bright emission that gradually fades away over a timespan of five to ten minutes. Finally, magnetars are observed as anomalous X-ray pulsars (AXPs), emitting a continuous narrow beam of X-ray radiation. We observe this beam as pulses of radiation, as the beam crosses our line of sight as the magnetar rotates.

Since their discovery much work has been done on understanding the properties of magnetars. However, there are still many gaps in our knowledge of these objects. Many of the observed properties of these objects have not been fully explained, while many of the theoretical models that do exist have not been fully tested. I have attempted to address part of that second problem in this thesis, by performing numerical calculations based on theoretical models of how magnetars are believed to work. The results of these computations can then be compared to observations.

Chapters 2 and 3 of this thesis are about the influence of magnetar bursts on the atmosphere of the magnetar. When radiation interacts with matter, it exerts a small force on that matter. This force is usually too weak to be significant on earth, but in bursts of radiation from neutron stars (as well as several other types of star), the radiation can be sufficiently intense to let this force become as strong as gravity. When this happens, part of the atmosphere of the star may be blown away, creating an outflow. It is also possible that the luminosity is sufficient to counteract gravity, but not to blow matter away from the star. This is what happens in photospheric radius expansion (PRE) bursts on accreting neutron stars, where the radiation force from a thermonuclear explosion deep in the surface layers causes the atmosphere to expand from its normal size of a few metres to a size of up to a hundred kilometres.

When a neutron star undergoes a PRE burst its atmosphere gradually evolves from its normal height of a few metres to a height of between ten and a hundred kilometres, without ever becoming unstable and having its matter blown away by the strong radiation force. Thus, for a star to be able to have PRE bursts, it has to be able to have very large stable atmospheres, that are supported against gravity by radiation forces without being blown away by them.

The expansion of the atmosphere during a PRE burst causes the outer regions of the atmosphere to cool down, as they get much further away from the hot star. This causes the radiation emitted by the atmosphere to become less energetic, which in turn causes it to fall below the energy range of the X-ray satellites used to detect these bursts. When the luminosity goes down towards the end of the burst the atmosphere contracts again, heats up, and emits in the X-ray range once more. All in all, this event causes the observed X-ray light curve to have a big dip in the middle where the radiation was not detectable. Because the radiation intensity at which radiation force balances gravity (the Eddington luminosity) is a relatively simple function of the mass and radius of the neutron star, observations of PRE events can be used to constrain the mass-radius relation of neutron stars, which is extremely useful in constraining theories of the internal composition of neutron stars.

In 2008 the magnetar SGR 0501+4516 showed a double-peaked light curve similar to the light curves of neutron stars exhibiting PRE. This led to the theory that this magnetar might also be undergoing a PRE event. In Chapter 2 I have created models of the atmosphere of a magnetar to test whether magnetars can have PRE bursts. These models are made by solving the differential equations of stellar structure for a stable magnetar atmosphere. By increasing the luminosity going through these atmosphere models, I have tried to make the atmospheres as large as possible, to see if magnetars can have the large, stable, radiation supported atmospheres required for a PRE event to occur.

The result of this work is that magnetars cannot have a stable atmosphere higher than a few metres, in contrast to regular neutron stars which can have stable atmospheres up to 200 km high. This also means that magnetars cannot have PRE bursts. This large difference is caused by the fact that the scattering opacity is very different in magnetars. The opacity describes how easily a photon scatters in a gas, and thus how many interactions it has as it travels through the gas, which determines the amount of radiation force it exerts on the matter. For normal neutron star atmospheres, the opacity is almost constant throughout the atmosphere, but in magnetars it changes greatly between different heights because of the effects of the magnetic field. This makes it impossible for the radiation force to exactly cancel out gravity everywhere in the atmosphere: either the radiation force is too strong far out, blowing part of the atmosphere away, or it is too weak close to the star, so that the atmosphere is not supported at the bottom. Thus, magnetars cannot have the large atmospheres supported by radiation force required for PRE.

This conclusion throws up a new question: what does happen when a magnetar emits enough radiation for the radiation force to overcome gravity? The answer is that the magnetar must blow away part of its atmosphere, creating an outflow. In Chapter 3 I have modelled outflows from magnetars, to try to predict the properties of such outflows, and see if they might be observable. These are models of stationary radiation driven winds, which means that the velocity at a single point in the model does not change over time, and the force driving the outflow is the radiation force. These models again consist of numerically solving the differential equations describing the structure of the atmosphere, which now has an outwards velocity throughout. These solutions are complicated by the existence of a so-called critical point. This is the point where the velocity of the outflow crosses the speed of sound, and this point has to be treated with special care in solving the structure equations.

My outflow models have three types of solution. The first type of solution crosses the critical point, but then becomes unphysical, as the temperature crosses absolute zero. This is a mathematically correct solution to the problem, but one that does not make physical sense. The second type also crosses the critical point, but then slows down, crosses the critical point again, and continues to slow down outwards. This outwards decrease of the velocity also causes an unphysical situation, because the rate at which it decreases causes the density to become a high constant value all the way out to infinity. In reality, the density should drop to the near-zero density of interstellar space. The third type of solution never crosses the critical point as the outflow velocity already starts to decrease down before it gets to the speed of sound. Once the velocity starts to decrease this type of solution has the same problem of constant density as the second type. These types of solution that are unphysical because the density becomes constant were already known from outflows on other types of stars.

Because I do not find any physically sensible solutions, I conclude that magnetars cannot have stationary radiation driven outflows. Instead, outflows from magnetars have to be non-stationary, meaning that they accelerate and slow down on short timescales, and thus have to be modelled in a fully time dependent manner. This intrinsic variability will also make it difficult to use observations of outflows to study the properties of these stars.

Having looked at how a magnetar's emission alters its atmosphere in Chapters 2 and 3, I have studied the opposite effect in Chapter 4, modelling how the atmosphere affects the properties of the emission. In particular, I have simulated the beaming of magnetar emission during the last phase of a giant flare. Beaming means that the emitted radiation is stronger in some directions than in others. We know that this beaming exists, as observations of giant flares show that the intensity of the observed emission varies strongly in a repeating pulse pattern, and that the duration of this pattern equals the rotation period of the magnetar. As the magnetar rotates we see it from different directions, and because the radiation is beamed we receive a different amount of radiation.

This beaming was already described qualitatively, but my model makes these predictions quantitative for the first time. I set up a simple atmosphere structure, following the fireball model for magnetar flares as described in the literature, and used a Monte Carlo radiation transfer method to calculate the properties of the radiation escaping this atmosphere. In a Monte Carlo method, instead of trying to describe all the properties of the escaping radiation at once, you simply simulate a single photon as it scatters through the model atmosphere. Any time there are multiple options for what happens to this photon an option is chosen at random, taking into account the probability for that option to happen. When this photon escapes the atmosphere, you start again with another photon, in the end simulating millions of photons. This way, the overall properties of the escaping radiation can be calculated statistically from the properties of the escaped photons.

The fireball model for magnetar flares predicts that during a magnetar burst, a large volume of electrons and positrons will be created, and these will become trapped in the magnetic field, forming a fireball. This fireball then gradually shrinks, as it loses its energy by emitting radiation. This radiation mostly escapes at the base of the fireball, close to the surface of the magnetar. Outside this fireball the strong radiation will cause an outflow, and the escaping radiation scatters through this outflow on its way out of the atmosphere. I find that a simple model for the structure of the fireball and the properties of the outflow is enough to recreate the observed amount of beaming, with the exact amount of beaming depending mostly on the magnetic field structure, and the shape and the velocity of the assumed outflow. This makes this model a promising way to fit observations of giant flares, and to use these observations to learn more about the objects that emitted them.