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Magnetars

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ABSTRACT

A neutron star is one possible end point of stellar evolution, and many of them have been observed, both in our galaxy and in nearby galaxies. One manifestation of a neutron star is a magnetar, whose surface magnetic field strength exceeds the quantum-critical limit of 4.4×10^{13} G. About a dozen of these unusual objects has been identified now via their X- and gamma-radiation. Their properties are reviewed briefly.

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1. Introduction

When a massive, but otherwise normal star runs out of nuclear fuel, it may end its life in a supernova explosion, in which 90% of the matter is expelled, and about 10% falls back in a gravitational collapse to form a 10 km radius neutron star, with a mass slightly larger than the mass of our Sun. A neutron star has a solid crust, composed mainly of iron, and an interior with a density approaching that of nuclear matter. While the exact composition and nature of neutron stars are an active area of research today, it is not too important for the purposes of this review. Neutron stars are, however, the starting point of the magnetar story. They were first mentioned in a theoretical context by Walter Baade and Fritz Zwicky. In a Physical Review paper in 1934, they said: "We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star…. We are fully aware that our suggestion carries with it grave implications regarding the ordinary views about the constitution of stars and will require further careful studies." [1]. It was not until 1968 that firm observational evidence was found for the existence of such stars. Hewish, writing about the discovery of what are today called radio pulsars, said [2]: "If the radiation is to be associated with the radial pulsation of a …neutron star there seem to be several mechanisms which could account for the radio emission." (Today we know that it is the *rotation* of a neutron star that powers radio pulsars.)

Between 1968 and the present, thousands of galactic neutron stars have been discovered via their electromagnetic emissions in the radio through gamma-ray ranges; it is estimated that there are 10^8–10^9 such objects in our Milky Way galaxy. The vast majority are undetectable and rather boring by almost any standards. They do not shine by the nuclear reactions which power our Sun; they are thought to have weak magnetic fields, and their emissions are powered mostly by thermal radiation from their surfaces. However, the ones that we *can* detect are fascinating objects. The first clue that some neutron stars might be magnetars came in 1979. On March 5, a giant gamma-ray flare was detected from a neutron star in a supernova remnant, and measured by its peak flux at Earth, it was the most intense cosmic event discovered up to that time. In 1992, Duncan and Thompson [3] proposed their magnetar model to explain the March 5, 1979 event, and Paczyński [4] also considered the role of super-strong fields.

In the magnetar model, it is the energy of the neutron star's magnetic field (specifically, its decay) which powers all the observable phenomena. This is in contrast to many other neutron stars, such as radio pulsars, whose emissions are rotation-powered, or, in some cases, accretion-powered. This definition leads to an estimate of $B\sim10^{15}$ G, the strongest known fields in the Universe. Today, we have detected well over a dozen objects which are probably magnetars, and we suspect that magnetars also play a role in explaining the nature of a few other strange objects and phenomena. More comprehensive reviews may be found in Mereghetti [5] and Woods and Thompson [6].

2. Magnetar phenomenology

Magnetars can remain dormant for many years; during these periods, they do not emit detectable bursts of radiation, but they do emit a steady flux of X- and gamma-rays. At unpredictable intervals, they become burst-active and emit anywhere from a few to several thousand bursts of X- and gamma-rays. There are various types of bursts. The most common ones have a short-duration (100 ms), and their energy spectra have been measured from ~1 keV to the soft gamma-ray range (~150 keV). Fig. 1 shows an example. This is the reason that one type of magnetar is also known as a "soft gamma repeater" or SGR. The rarest bursts are classified as *giant flares*. They last several hundred seconds,

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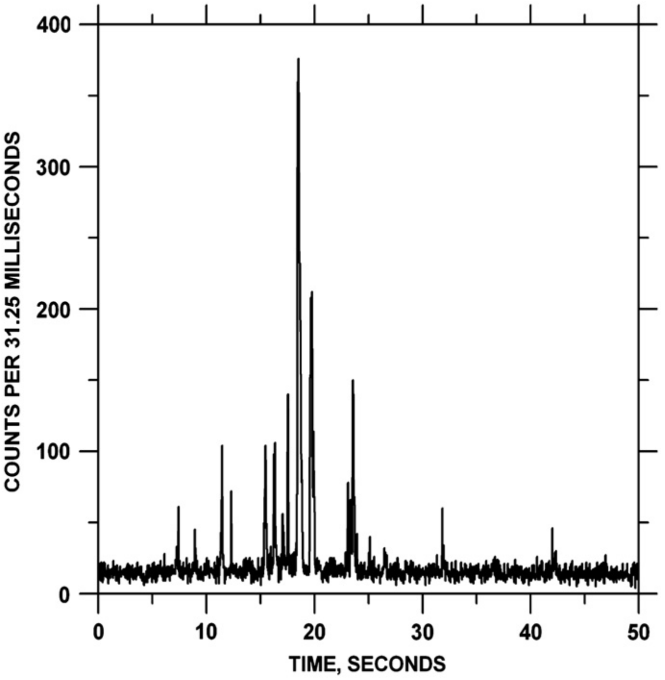

Fig. 1. A series of short bursts from SGR1900+14 in May 1998, observed by a detector aboard the *Ulysses* spacecraft. The energy spectra of these short bursts have been measured up to about 150 keV.

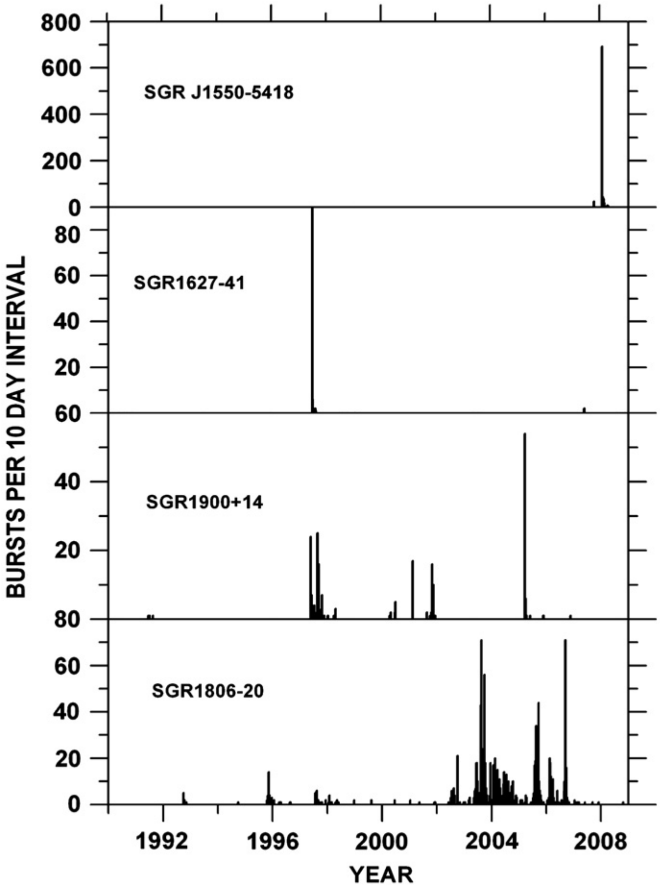

Fig. 2. The bursting activity of four magnetars over a 20 year period. Note the long quiescent periods, punctuated by intense bursting activity at random intervals. These bursts are the short, ~ 100 ms long, variety.

and their energy spectra have been measured well into the MeV range. Magnetars are named for their celestial coordinates, e.g. SGR1806-20, where 18:06 is the right ascension in hours and minutes and -20 is the declination in degrees. Fig. 2 shows the bursting activity of four magnetars over a period of about 20 years.

SGR giant flares are the most spectacular manifestations of magnetars. Fig. 3 shows an example. They are third only to supernovae and cosmic gamma-ray bursts in intensity. They emit $\sim 10^{46}$ erg (compared to $\sim 10^{41}$ erg for the short SGR bursts, and up to $\sim 10^{52}$ erg for some gamma-ray bursts). The flux at the Earth is ~ 1 erg cm^{-2}, which is enough to create dramatic ionospheric disturbances that can be detected by VLF receivers. These flares last about 5 min, and their energy spectra have so far been measured to about 10 MeV; this is an instrumental limit, and there are no obvious signs that the spectrum falls off above this energy.

As Fig. 3 shows, giant flare time histories are modulated with the neutron star periodicity-in this case, about 7.5 s. Only three giant flares have been observed to date, each from a different magnetar. In all cases, the initial spike saturated the gamma-ray detectors which observed it, but in two cases, a careful study of the responses by particle detectors have resolved it [7,8], and have found that the peak luminosity is $\sim 5 \times 10^{47}$ erg s^{-1}. No magnetar has yet been observed to emit more than one giant flare, but assuming that they do repeat, simple statistical arguments indicate that the interval between such events is perhaps 30 years or more.

Giant magnetar flares are interesting for a number of other reasons, in addition to their intensities. They create transient radio nebulae, which have been observed for weeks with radiotelescopes. These are thought to be created by relativistic electrons, accelerated in the magnetosphere of the neutron star, and expelled from it [9,10]. Their gamma-ray light curves also display fast oscillations (at the several millisecond level), which may be due to torsional vibrations of the neutron star, and provide a clue to the structure of its interior [11]. Giant flares, as well as short bursts, may also excite gravitational radiation from

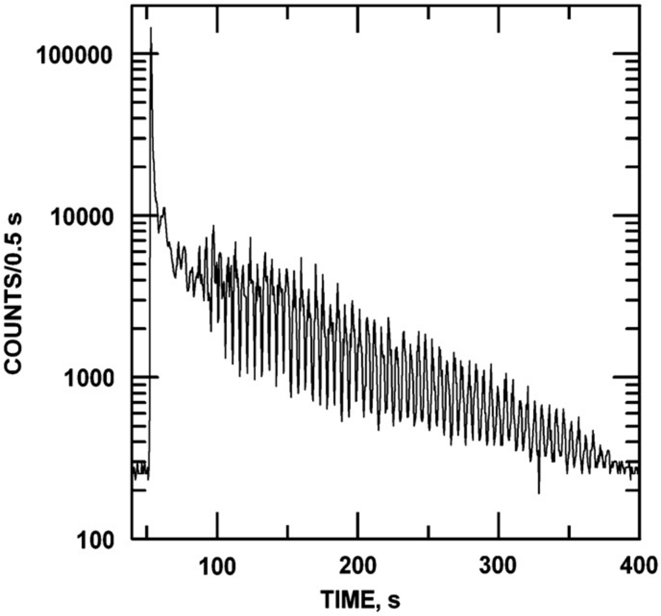

Fig. 3. A giant flare from the magnetar SGR1806-20 on December 27, 2004. The data are from the RHESSI spacecraft [21]. Note the periodic component, which reflects the rotation of the neutron star. The initial spike saturated the detectors.

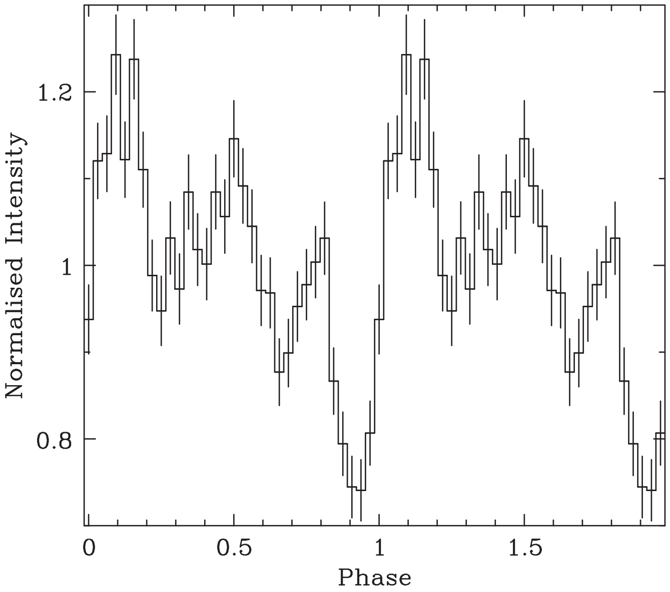

Fig. 4. From Hurley et al. [20]. The 2–10 keV light curve of the quiescent X-ray emission from SGR1900+14, folded modulo 5.16 s. The periodic modulation is due to hot spots on the neutron star surface. Reproduced by permission of the AAS.

the neutron star, which has been searched for with LIGO [12,13]. And finally, they are intense enough to be detected in nearby galaxies out to $\sim 10^7$ light-years, and there is indeed evidence that such events have been observed (e.g. Hurley et al. [14]).

3. Magnetar quiescent X-ray emission

Regardless of whether a magnetar is burst-active or not, it emits a continuous flux of X-radiation which is easily detectable in most cases by X-ray satellites. This is the key to the magnetar model. This X-radiation has a periodic component which is due to the rotation of the neutron star. Fig. 4 shows an example. Magnetar periods increase with time at a rate of $\sim 10^{-10}$ s/s. Making reasonable assumptions about the radii and moments of inertia of neutron stars, the spin-down power, $IP\dot{P}$, where I is the moment of inertia, P is the period, and $\dot{P}$ is the period derivative, is too small by one or two orders of magnitude to account for the quiescent X-ray emission, as first pointed out by Kouveliotou et al. [15]. Again, this is the opposite of the case of, say, a radio pulsar. The decay of a strong magnetic field, however, can provide this energy [3,16,17].

The period and period derivative can also provide an estimate of the magnetar's age. This turns out to be of the order of 10^3 years in most cases, which is quite young by astronomical standards.

4. Some basic problems posed, and solved, by magnetar observations

Observations provide us with the following properties of magnetars: their periods, their period derivatives, the energy that they radiate in X-rays, and the energy released in small bursts and giant flares. (The energies depend on the distances, which are notoriously difficult to measure or infer, but even with these uncertainties, we can obtain reasonable estimates.) Several questions arise immediately from these observations.

- Neutron stars are thought to be born with periods as small as several milliseconds; how do they spin down to periods of ~ 5 s in the short time implied by their ages?
- The electromagnetic energy emitted by a magnetar is much greater than its spin-down energy; where does the extra energy come from?
- What powers short bursts and giant magnetar flares?

The answers to these questions, and others, involve a very strong magnetic field, and its decay. The definition of a magnetar is a neutron star in which the magnetic field, rather than rotation, provides the main source of free energy; the decaying field powers the electromagnetic radiation [3,16,17]. Note that this definition does not specify the magnetic field strength. To explain the observations, however, B must be greater than the quantum critical value 4.4×10^{13} G, where the energy between electron Landau levels equals the electron rest mass. In fact, some magnetar observations require $B \sim 10^{15}$ G, so magnetars have the strongest magnetic fields that we know of in the universe.

The origin of this field is not known for certain, but there are two main hypotheses. The first is that it is a fossil field. That is, the magnetic field of a massive progenitor star (10^4 G or more) is amplified during core collapse in the supernova explosion, and frozen into a highly conducting compact remnant (the neutron star). The second relies on dynamo amplification: the field is generated by a convective dynamo in the rapidly spinning (1–3 ms period) proto-neutron star. These two hypotheses are not mutually exclusive. In principle, $B \sim 3 \times 10^{17}$ G can be generated. However, the magnetic field energy probably cannot exceed the binding energy of the neutron star, which limits it to $B < 5 \times 10^{18}$ G.

Differential rotation in the newly formed neutron star, and magnetic braking, will quickly reduce the period down to the 5–10 s range we observe today. Magnetic diffusion and dissipation create hot spots on the neutron star surface, which cause the star to be a quiescent, periodic X-ray source, as observed.

The bursting behavior was initially explained as follows. The strong magnetic field stresses the iron surface of the neutron star, to which it is anchored. The surface undergoes localized cracking, shaking the field lines and creating Alfvén waves, which accelerate electrons to ~ 100 keV; they radiate their energy in short (100 ms) bursts with energies of 10^{40}–10^{41} erg. (This would be the equivalent of a magnitude 19.5 crustquake on the Richter scale). There is enough magnetic field energy to power this kind of bursting activity for 10^4 years. However, localized cracking on the neutron star surface cannot relieve all the stresses exerted by the magnetic field, so it continues to build. After a few decades, the built-up stress ruptures the surface of the star profoundly, producing a giant flare (equivalent to a magnitude 23.2 starquake). The magnetic field lines, anchored to the moving surface, annihilate as they encounter other field lines, liberating energy which accelerates electrons to MeV energies and fills the magnetosphere with them. The initial, intense spike in the giant flare is radiation from the entire magnetosphere. Since a field strength $B > 10^{14}$ G is required to contain these electrons, this constitutes a consistency check of the field strength derived from spin-down considerations. The periodic component observed in the giant flare comes from the surface of the neutron star, and the transient radio nebula is attributed to radiation from escaping electrons, which cool over a period of weeks.

More recently, the role of helicity in magnetars has been studied [18]. A twisted magnetic field is created in the interior of the neutron star by a dynamo as the star is born, and the field is anchored to the crust. The field unwinds by deforming the crust.

5. Should you buy a magnetar shelter?

Cosmic gamma-ray bursts emit 10^{51}–10^{52} erg of energy. All the bursts that have been observed to date originate in distant galaxies, but the possible role that galactic gamma-ray bursts may have played in mass extinctions has been considered by numerous authors (a popular account was given in Leonard and Bonnell [19]). It is thought that a gamma-ray flux of $\sim 10^6\,\mathrm{erg\,cm^{-2}}$ absorbed in the Earth's upper atmosphere would cause an effect similar to a "nuclear winter" (ozone depletion, followed by the destruction of the food chain). This is the flux that would be emitted by a magnetar giant flare at a distance of about 50 light-years, assuming that a giant flare releases 3×10^{46} erg. If we assume that 10 magnetars are active at any given time, and that they are distributed uniformly throughout the disk of the Milky Way galaxy, the probability is $\sim 10^{-6}$ that we are living nearer than this to one of them, from simple geometrical arguments. Assuming that each magnetar emits a giant flare every 30 years leads to an estimate of the interval between nearby giant flares of 30 million years. This can be compared to a mass extinction rate of roughly one every 100 million years, although this number depends on the exact definition. The observational evidence strongly implies that all the known magnetars today are far more distant than 50 light-years. Another fact to consider is that the nearest site of massive star formation in our galaxy is the Orion nebula, which is over 1000 light-years from Earth. All these arguments suggest that the role of magnetars in past or future extinctions is a negligible one.

Acknowledgment

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