Proc. Natl. Acad. Sci. USA
Vol. 96, pp. 5351–5352, May 1999

Perspective

Magnetars

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Recent x-ray observations have shown that a substantial fraction of newly born neutron stars have magnetic fields of several 10^{14} G. They reveal themselves as soft gamma repeaters and anomalous x-ray pulsars and may account for the missing radio pulsars in young supernova remnants.

During the last year, it has become clear that a substantial fraction of neutron stars have magnetic field strengths in excess of the critical value, $B_{cr} = 4.4 \times 10^{13}$ G, above which quantum electrodynamic effects become important (for example, photon splitting, leading to a quenching of radio emission). Several soft gamma repeaters (SGRs), long suspected to be young neutron stars (1), were found (2, 3) to have B fields more than 10^{14} G, confirming the idea that in neutron stars born with high rotational velocities (>300 revolutions per second), a dynamo could develop that can produce an extremely high magnetic field. The idea was put forward in 1992 (4), and such stars were named magnetars. Magnetars, which also include the so-called anomalous x-ray pulsars, (AXPs; possibly a later phase in the evolution of SGRs) comprise perhaps as much as 10% of the total population of recently formed neutron stars. One result of the explosion of a massive stellar object is a rapidly rotating neutron star that is detected as a radio pulsar for up to several millions of years after the event; the magnetic fields of radio pulsars are typically of order 10^{12} G. In the cases where an original binary system remained bound together after the supernova explosion, the neutron star can also be detected as an x-ray pulsar, whereby the x-rays are emitted from the material accreted on the surface of the neutron star from its companion.

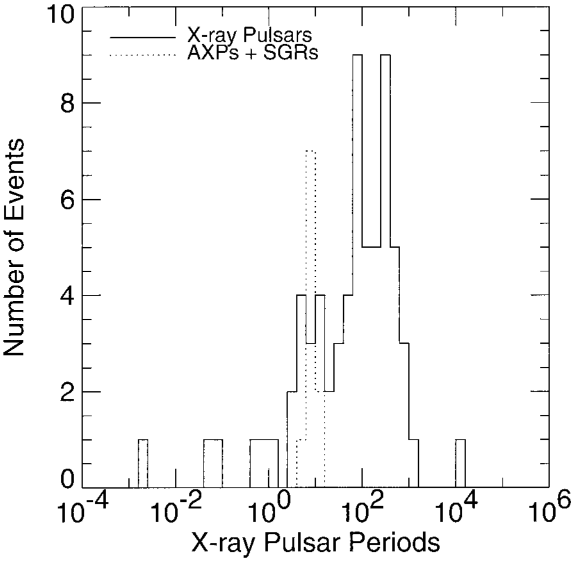

FIG. 1. The distribution of periods of x-ray pulsars (solid line). The periods of the SGRs and AXPs mentioned in the text are shown with a dashed line.

Anomalous X-Ray Pulsars

The nature of AXPs as a "special" class of x-ray pulsars was established in 1995 (5), when it was realized that a handful of x-ray pulsars share a set of common characteristics that differed strongly from the average binary x-ray pulsar, which is powered by accretion of matter from a companion star. Their x-ray spectra are much softer than those of normal x-ray pulsars, their periods are in a very narrow range (6–11 seconds, see also Fig. 1), their x-ray luminosities are $\approx 10^{35}$ erg·s^{-1} (1 erg = 0.1 μJ), and they exhibit a secular spin-down of their periods; no indication of their binary nature has ever been found, neither from orbital Doppler shifts of the pulse arrival times nor from the optical signature of a companion star. Several AXPs seemed to be correlated with young supernova remnants.

Several models have been put forward to explain the properties of AXPs: accreting neutron stars in binary systems with a very low mass companion (5); isolated accreting neutron stars that evolved from Thorne–Zytkov objects (stars that are the result of a merger of a neutron star and a high mass companion—the neutron star settles in the center of mass of the object, which leads to an apparent supergiant star with very nonstandard internal structure) (6); and magnetars (7). The first model is inconsistent with the spatial distribution of the AXPs, which are all very close to the plane of our galaxy. This observation indicates that they are young objects, unlike the evolved binary systems. The other two models could be neither confirmed nor rejected with the existing observational data.

Soft Gamma Repeaters

SGRs were discovered in 1979, but only in 1986 was it realized (8–10) that they were a class of objects separate from the sources of "classical" gamma ray bursts. The sources were singled out because of their common properties, which were significantly different than those of gamma ray bursts. The most important difference is the recurrence of the SGR events, which excluded a catastrophic destruction of their parent object population (as is conjectured for gamma ray bursts). Other differences were the softness of the SGR spectra (typical bremsstrahlung temperatures of 30 keV as opposed to 300 keV for gamma ray bursts), and the very short durations of their outbursts. In addition, SGRs are persistent sources of weak x-ray emission, with luminosities of order 10^{35} erg·s^{-1}. Until 1998, only three SGR sources were identified; two are in the galactic plane and one is in the Large Magellanic Cloud, a companion of our Milky Way system.

The light curve of the extraordinarily bright outburst of March 5, 1979 from the Large Magellanic Cloud source (11) provided a very important piece of information regarding the nature of SGRs. During the decay of this event, a coherent modulation of the brightness was seen, with a period of 8.0 s, lasting for about 3 min. This observation pointed directly to a neutron star as the source of the radiation, which typically have

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Abbreviations: SGR, soft gamma repeater; AXP, anomalous x-ray pulsar.
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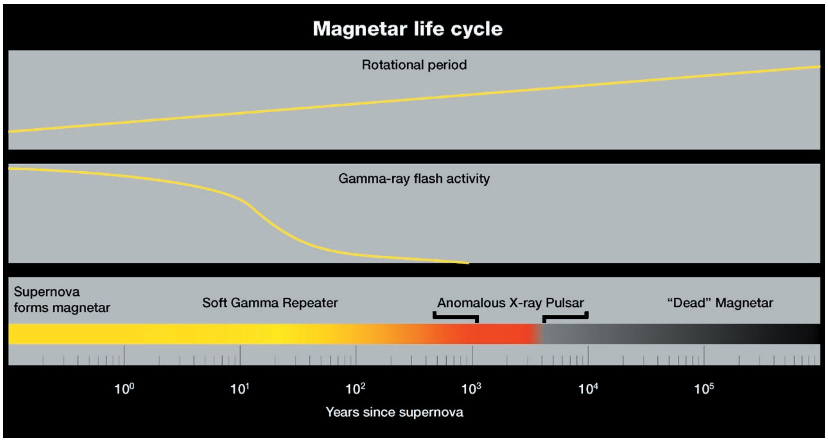

FIG. 2. A schematic diagram of the life cycle of magnetars, indicating the trends of their periods to increase and their activity to decrease as their magnetic field decays rapidly.

periods in this range. The energetics of the event led several scientists (4, 12–14) to suggest that the only force that could constrain this luminous source of gamma rays (peak power 10^{44} erg·s^{-1}) for over 100 s would be a very strong magnetic field of the order of several 10^{14} G. In 1992, The term magnetar was coined (4) to describe such highly magnetized neutron stars, and it was suggested (4) that crust quakes on their surface were the energy source of the SGR bursts. Strong support for the idea that SGRs are neutron stars came from their apparent association with supernova remnants.

Compelling evidence for the magnetar model was obtained in 1998 (2). The high-quality timing data of the Rossi X-ray Timing Explorer enabled the detection of a pulsar in the persistent x-ray emission of SGR 1806-20. The period, 7.47 s, was very similar to the 8-s period seen during the decay of the March 5, 1979 event from the Large Magellanic Cloud source and within the AXP period range. Furthermore, a spin-down was measured from the Rossi X-ray Timing Explorer data alone, as well as from archival data on this source, recorded in 1993 and 1995 with the Japanese satellite ASCA (Advanced Satellite for Cosmology and Astrophysics).

Magnetars

In principle, the steady emission of x-rays can be connected with three possible sources of energy: rotational energy loss, accretion, or magnetic field decay. Rotational energy loss, as measured by the spin-down rate, is insufficient by several orders of magnitude to sustain the persistent x-ray luminosity. In the case of SGR 1806-20, accretion could be excluded, since a strong relativistic wind emanating from the neutron star [as detected (15) in radio wavelengths through a compact plerion around the SGR] prevents matter from reaching the neutron star surface—even in the case where it would be in a binary orbit around the very luminous star with which it coincides to within one arcsecond (16). This left magnetic field decay as the remaining option. Assuming that the spindown of the 7.47-s spin period is due to magnetic dipole radiation (as is the case for radio pulsars), one can find a surface magnetic field of 8×10^{14} G.

In May 1998, measurements (3, 17) with ASCA and Rossi X-ray Timing Explorer of the persistent x-ray emission of SGR 1900+14 revealed pulsations with a period of 5.2 s from the source. Again, the spin-down rate of the neutron star was measured (3), and a magnetic field of roughly 2×10^{14} G was estimated, supporting the magnetar idea. This measurement was independently confirmed (18) with a huge flare emitted by the star on August 27, 1998, a simile of the March 5 event, only this time with a period of 5.2 s seen in a 5-min tail. Also, this time a temporary particle wind associated with the flare was detected with the VLA (Very Large Array) (19), providing additional evidence of the super-strong magnetic field of the SGR. Finally, in June 1998 a new SGR was discovered (20); this was the first discovered in ≈20 years, and was named SGR 1627-41. No definite pulsations have yet been detected from this source, but there is a weak indication in the x-ray data from the BeppoSAX satellite of a period around 6.5 s, which fits well within the SGR period range (21).

What is the relation between SGRs and AXPs? We believe that both are a new manifestation of young neutron stars. From estimates (22) of the total number of SGRs in our galaxy and their active lifetime one finds an SGR birth rate of about one per millennium, that is, of order 10% of the total birth rate of neutron stars: about 10% of the supernovae explosions lead to a magnetar. The remainders are the well known radio pulsars [recent theoretical work (23) indicates that pulsar radio emission is suppressed when the neutron star field is $B > B_{cr}$]. The ages of the supernova remnants identified with SGRs and AXPs indicate that the former are younger than the latter. The natural sequence would then be that a magnetar spends the first stage of its life as an SGR (for roughly 10,000 years) and the next 30,000–40,000 years as an AXP (see Fig. 2). The last stage of a magnetar may be what has been observed in x-rays as a solitary neutron star: a cool neutron star with very low luminosity and no evidence for a companion.

There are several unanswered questions still to be resolved: can we exclude that magnetars are binary systems? If the flashes and flares from the sources are indeed due to crustquakes, should we be able to detect aftershocks in the light curves of the magnetar bursts? What mechanism produces the giant flares and how often should we expect them? A wealth of high-sensitivity data lies ahead with the upcoming launching of NASA's Chandra and ESA's XMM observatories, together with more observations with CGRO/BATSE, ASCA, Rossi X-ray Timing Explorer, and BeppoSAX. As is often the case in astrophysics, unexpected results may come from a "solved" mystery, providing the excitement and anticipation that feeds the field.

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