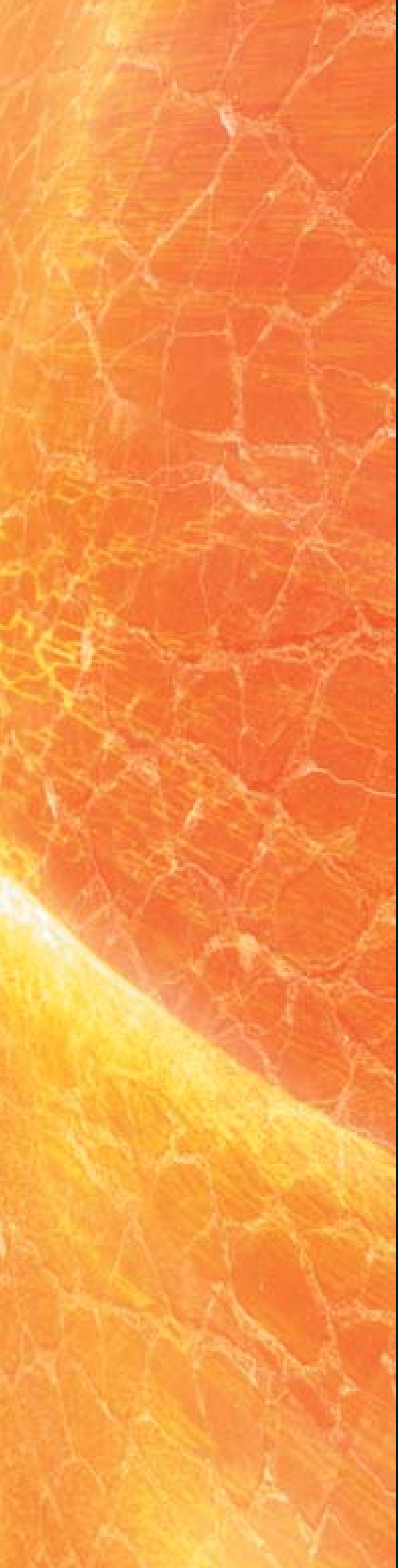
STARQUAKE ON A MAGNETAR releases a vast amount of magnetic energy—equivalent to the seismic energy of a magnitude 21 earthquake—and unleashes a fireball of plasma. The fireball gets trapped by the magnetic field.



MAGNETARS

Some stars are magnetized so intensely that they emit huge bursts of magnetic energy and alter the very nature of the quantum vacuum

By Chryssa Kouveliotou, Robert C. Duncan and Christopher Thompson

On March 5, 1979, several months after dropping probes into the toxic atmosphere of Venus, two Soviet spacecraft, Venera 11 and 12, were drifting through the inner solar system on an elliptical orbit. It had been an uneventful cruise. The radiation readings on board both probes hovered around a nominal 100 counts per second. But at 10:51 A.M. EST, a pulse of gamma radiation hit them. Within a fraction of a millisecond, the radiation level shot above 200,000 counts per second and quickly went off scale.

Eleven seconds later gamma rays swamped the NASA space probe Helios 2, also orbiting the sun. A plane wave front of high-energy radiation was evidently sweeping through the solar system. It soon reached Venus and saturated the Pioneer Venus Orbiter's detector. Within seconds the gamma rays reached Earth. They flooded detectors on three U.S. Department of Defense Vela satellites, the Soviet Prognoz 7 satellite, and the Einstein Observatory. Finally, on its way out of the solar system, the wave also blitzed the International Sun-Earth Explorer.

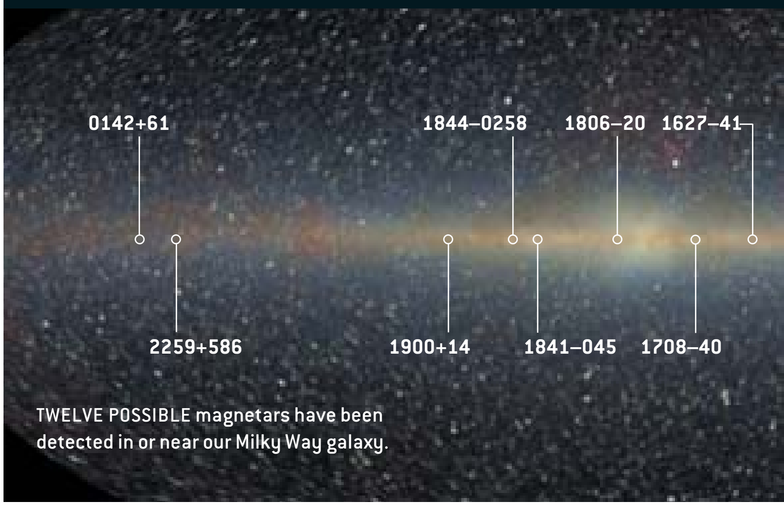
The pulse of highly energetic, or "hard," gamma rays was 100 times as intense as any previous burst of gamma rays detected from beyond the solar system, and it lasted just two tenths of a second. At the time, nobody noticed; life continued calmly beneath our planet's protective atmosphere. Fortunately, all 10 spacecraft survived the trauma without permanent damage. The hard pulse was followed by a fainter glow of lower-energy, or "soft," gamma rays, as well as x-rays, which steadily faded over the subsequent three minutes. As it faded away, the signal oscillated gently, with a period of eight seconds. Fourteen and a half hours later, at 1:17 A.M. on March 6, another, fainter burst of x-rays came from the same spot on the sky. Over the ensuing four years, Evgeny P. Mazets of the Ioffe Institute in St. Petersburg, Russia, and his collaborators detected 16 bursts coming from the same direction. They varied in intensity, but all were fainter and shorter than the March 5 burst.

Astronomers had never seen anything like this. For want of a better idea, they initially listed these bursts in catalogues alongside the better-known gamma-ray bursts (GRBs), even though they clearly differed in several ways. In the mid-1980s Kevin C. Hurley of the University of California at Berkeley realized that similar outbursts were coming from two other areas of the sky. Evidently these sources were all repeating—unlike GRBs, which are one-shot events [see "The Brightest Explosions in the Universe," by Neil Gehrels, Luigi Piro and Peter J. T. Leonard; SCIENTIFIC AMERICAN, December 2002]. At a July 1986 meeting in Toulouse, France, astronomers agreed on the approximate locations of the three sources and dubbed them "soft gamma repeaters" (SGRs). The alphabet soup of astronomy had gained a new ingredient.

Another seven years passed before two of us (Duncan and Thompson) devised an explanation for these strange objects, and only in 1998 did one of us (Kouveliotou) and her team find compelling evidence for that explanation. Recent observations connect our theory to yet another class of celestial enigmas, known as anomalous x-ray pulsars (AXPs). These developments have led to a breakthrough in our understanding of one of the most exotic members of the celestial bestiary, the neutron star.

Neutron stars are the densest material objects known, packing slightly more than the sun's mass inside a ball just 20 kilometers across. Based on the study of SGRs, it seems that some neutron stars have magnetic fields so intense that they radically alter the material within them and the state of the quantum vacuum surrounding them, leading to physical effects observed nowhere else in the universe.

MAGNETAR CANDIDATES



TWELVE POSSIBLE magnetars have been detected in or near our Milky Way galaxy.

Not Supposed to Do That

BECAUSE THE MARCH 1979 BURST was so bright, theorists at the time reckoned that its source was in our galactic neighborhood, hundreds of light-years from Earth at most. If that had been true, the intensity of the x-rays and gamma rays would have been just below the theoretical maximum steady luminosity that can be emitted by a star. That maximum, first derived in 1926 by English astrophysicist Arthur Eddington, is set by the force of radiation flowing through the hot outer layers of a star. If the radiation is any more intense, it will overpower gravity, blow away ionized matter and destabilize the star. Emission below the Eddington limit would have been fairly straightforward to explain. For example, various theorists proposed that the outburst was triggered by the impact of a chunk of matter, such as an asteroid or a comet, onto a nearby neutron star.

But observations soon confounded that hypothesis. Each spacecraft had recorded the time of arrival of the hard initial pulse. These data allowed astronomers, led by Thomas Lytton Cline of the NASA Goddard Space Flight Center, to triangulate the burst source. The researchers found that the position coincided with the Large Magellanic Cloud, a small galaxy about 170,000 light-years away. More specifically, the event's position matched that of a young supernova remnant, the glowing

Overview/*Ultramagnetic Stars*

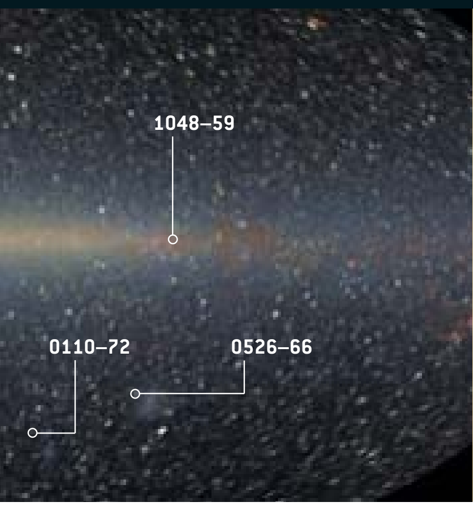
- Astronomers have seen a handful of stars that put out flares of gamma and x-radiation, which can be millions of times as bright as any other repeating outburst known. The enormous energies and pulsing signals implicate the second most extreme type of body in the universe (after the black hole): the neutron star.
- These neutron stars have the strongest magnetic fields ever measured—hence their name, magnetars. Magnetic instabilities analogous to earthquakes can account for the flares.
- Magnetars remain active for only about 10,000 years, implying that millions of them are drifting undetected through our galaxy.

DON DIXON (*preceding pages*); E. L. WRIGHT *University of California at Los Angeles,* THE COBE PROJECT, DIRBE AND NASA (*above*) remains of a star that exploded 5,000 years ago. Unless this overlap was pure coincidence, it put the source 1,000 times as far away as theorists had thought—and thus made it a million times brighter than the Eddington limit. In 0.2 second the March 1979 event released as much energy as the sun radiates in roughly 10,000 years, and it concentrated that energy in gamma rays rather than spreading it across the electromagnetic spectrum.

No ordinary star could account for such energy, so the source was almost certainly something out of the ordinary—either a black hole or a neutron star. The former was ruled out by the eight-second modulation: a black hole is a featureless object, lacking the structure needed to produce regular pulses. The association with the supernova remnant further strengthened the case for a neutron star. Neutron stars are widely believed to form when the core of a massive but otherwise ordinary star exhausts its nuclear fuel and abruptly collapses under its own weight, thereby triggering a supernova explosion.

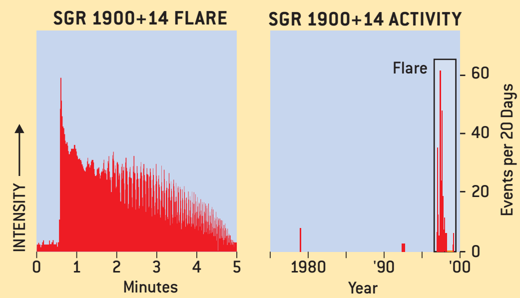
Identifying the source as a neutron star did not solve the puzzle; on the contrary, it merely heightened the mystery. Astronomers knew several examples of neutron stars that lie within supernova remnants. These stars were radio pulsars, objects that are observed to blink on and off in radio waves. Yet the March 1979 burster, with an apparent rotation period of eight seconds, was spinning much more slowly than any radio pulsar then known. Even when not bursting, the object emitted a steady glow of x-rays with more radiant power than could be supplied by the rotation of a neutron star. Oddly, the star was significantly displaced from the center of the supernova remnant. If it was born at the center, as is likely, then it must have recoiled with a velocity of about 1,000 kilometers per second at birth. Such high speed was considered unusual for a neutron star.

Finally, the outbursts themselves seemed inexplicable. X-ray flashes had previously been detected from some neutron stars, but they never exceeded the Eddington limit by very much. Astronomers ascribed them to thermonuclear fusion of hydrogen or helium or to the sudden accretion of matter onto the star. But the brightness of the SGR bursts was unprecedented, so a new physical mechanism seemed to be required.



NAME	YEAR OF DISCOVERY	ROTATION PERIOD (seconds)
SGR 0526–66	1979	8.0
SGR 1900+14	1979	5.16
SGR 1806–20	1979	7.47
SGR 1801–23*	1997	?
SGR 1627–41	1998	?
AXP 1E 2259+586	1981	6.98
AXP 1E 1048–59†	1985	6.45
AXP 4U 0142+61	1993	8.69
AXP 1RXS 1708–40†	1997	11.0
AXP 1E 1841–045	1997	11.8
AXP AXJ1844–0258	1998	6.97
AXP CXJ0110–7211†	2002	5.44

* Not shown on map; location not known precisely
† Abbreviated name



GIANT X-RAY FLARE in August 1998 confirmed the existence of magnetars. It started with a spike of radiation lasting less than a second (*left*). Then came an extended train of pulses with a period of 5.16 seconds. This event was the most powerful outburst to come from the object, designated SGR 1900+14, since its discovery in 1979 (*right*).

SOURCE FOR TABLE: CHRYSSA KOUVELIOTOU, ROBERT C. DUNCAN AND CHRISTOPHER THOMPSON

Spin Forever Down

THE FINAL BURST FROM the March 1979 source was detected in May 1983; none has been seen in the 19 years since. Two other SGRs, both within our Milky Way galaxy, went off in 1979 and have remained active, emitting hundreds of bursts in the years since. A fourth SGR was located in 1998. Three of these four objects have possible, but unproved, associations with young supernova remnants. Two also lie near very dense clusters of massive young stars, intimating that SGRs tend to form from such stars. A fifth candidate SGR has gone off only twice; its precise location is still unknown.

As Los Alamos National Laboratory scientists Baolian L. Cheng, Richard I. Epstein, Robert A. Guyer and C. Alex Young pointed out in 1996, SGR bursts are statistically similar to earthquakes. The energies have very similar mathematical distributions, with less energetic events being more common. Our graduate student Ersin Gögüs of the University of Alabama at Huntsville verified this behavior for a large sample of bursts from various sources. This and other statistical properties are a hallmark of self-organized criticality, whereby a composite system attains a critical state in which a small perturbation can trigger a chain reaction. Such behavior occurs in systems as diverse as avalanches on sandpiles and magnetic flares on the sun.

But why would a neutron star behave like this? The solution emerged from an entirely separate line of work, on radio pulsars. Pulsars are widely thought to be rapidly rotating, magnetized neutron stars. The magnetic field, which is supported by electric currents flowing deep inside the star, rotates with the star. Beams of radio waves shine outward from the star's magnetic poles and sweep through space as it rotates, like lighthouse beacons—hence the observed pulsing. The pulsar also blows out a wind of charged particles and low-frequency electromagnetic waves, which carry away energy and angular momentum, causing its rate of spin to decrease gradually.

Perhaps the most famous pulsar lies within the Crab Nebula, the remnant of a supernova explosion that was observed in 1054. The pulsar rotates once every 33 milliseconds and is currently slowing at a rate of about 1.3 millisecond every century. Extrapolating backward, it was born rotating once every 20 milliseconds. Astronomers expect it to continue to spin down, eventually reaching a point when its rotation will be too slow to power the radio pulses. The spin-down rate has been measured for almost every radio pulsar, and theory indicates that it depends on the strength of the star's magnetic field. From this, most young radio pulsars are inferred to have magnetic fields between 10^{12} and 10^{13} gauss. For comparison, a refrigerator magnet has a strength of about 100 gauss.

The Ultimate Convection Oven

THIS PICTURE LEAVES a basic question unanswered: Where did the magnetic field come from in the first place? The traditional assumption was: it is as it is, because it was as it was. That is, most astronomers supposed that the magnetic field is a relic of the time before the star went supernova. All stars have weak magnetic fields, and those fields can be amplified simply by the act of compression. According to Maxwell's equations of electromagnetism, as a magnetized object shrinks by a factor of two, its magnetic field strengthens by a factor of four. The core of a massive star collapses by a factor of 10^5 from its birth through neutron star formation, so its magnetic field should become 10^{10} times stronger.

If the core magnetic field started with sufficient strength, this compression could explain pulsar magnetism. Unfortunately, the magnetic field deep inside a star cannot be measured, so this simple hypothesis cannot be tested. There are also good reasons to believe that compression is only part of the story.

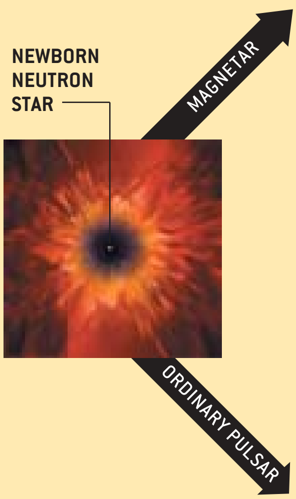
Within a star, gas can circulate by convection. Warm parcels of ionized gas rise, and cold ones sink. Because ionized gas conducts electricity well, any magnetic field lines threading the gas are dragged with it as it moves. The field can thus be reworked and sometimes amplified. This phenomenon, known as dynamo action, is thought to generate the magnetic fields of stars and planets. A dynamo might operate during each phase of the life of a massive star, as long as the turbulent core is rotating rapidly enough. Moreover, during a brief period after the core of the star turns into a neutron star, convection is especially violent.

This was first shown in computer simulations in 1986 by Adam Burrows of the University of Arizona and James M. Lattimer of the State University of New York at Stony Brook. They found that temperatures in a newborn neutron star exceed 30

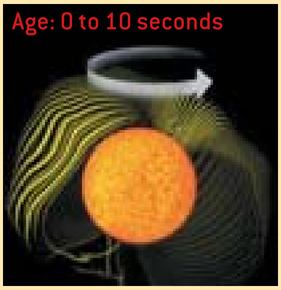
TWO TYPES OF NEUTRON STARS

1 Most neutron stars are thought to begin as massive but otherwise ordinary stars, between eight and 20 times as heavy as the sun.

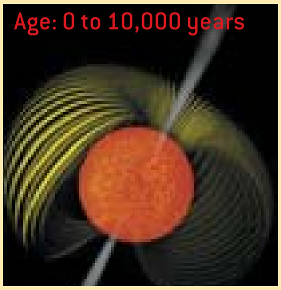
2 Massive stars die in a type II supernova explosion, as the stellar core implodes into a dense ball of subatomic particles.



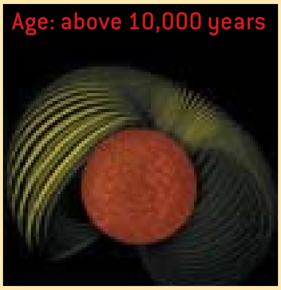
3 A: If the newborn neutron star spins fast enough, it generates an intense magnetic field. Field lines inside the star get twisted.



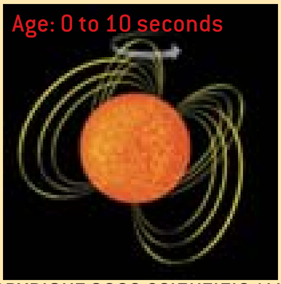
4 A: The magnetar settles into neat layers, with twisted field lines inside and smooth lines outside. It might emit a narrow radio beam.



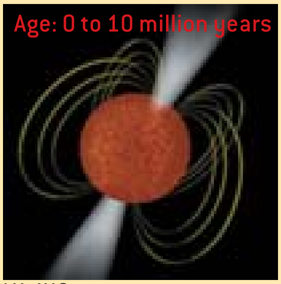
5 A: The old magnetar has cooled off, and much of its magnetism has decayed away. It emits very little energy.



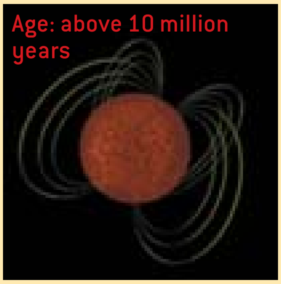
3 B: If the newborn neutron star spins slowly, its magnetic field, though strong by everyday standards, does not reach magnetar levels.



4 B: The mature pulsar is cooler than a magnetar of equal age. It emits a broad radio beam, which radio telescopes can readily detect.



5 B: The old pulsar has cooled off and no longer emits a radio beam.

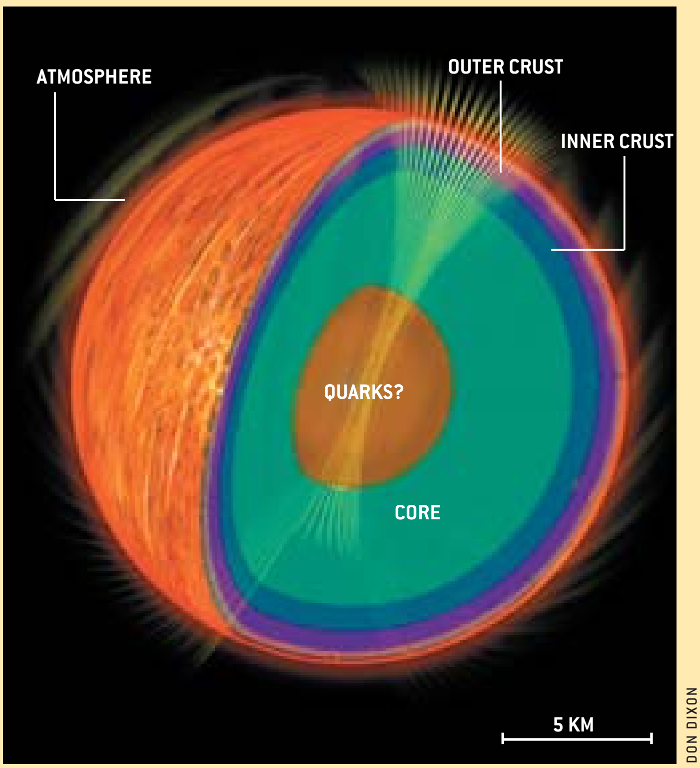


billion kelvins. Hot nuclear fluid circulates in 10 milliseconds or less, carrying enormous kinetic energy. After about 10 seconds, the convection ceases.

Not long after Burrows and Lattimer conducted their first simulations, Duncan and Thompson, then at Princeton University, estimated what this furious convection means for neutron-star magnetism. The sun, which undergoes a sedate version of the same process, can be used as a reference point. As solar fluid circulates, it drags along magnetic field lines and gives up about 10 percent of its kinetic energy to the field. If the moving fluid in a newborn neutron star also transfers a tenth of its kinetic energy to the magnetic field, then the field would grow stronger than 10^{15} gauss, which is more than 1,000 times as strong as the fields of most radio pulsars.

Whether the dynamo operates globally (rather than in limited regions) would depend on whether the star's rate of rotation was comparable to its rate of convection. Deep inside the sun, these two rates are similar, and the magnetic field is able to organize itself on large scales. By analogy, a neutron star born rotating as fast as or faster than the convective period of 10 milliseconds could develop a widespread, ultrastrong magnetic field. In 1992 we named these hypothetical neutron stars "magnetars."

An upper limit to neutron-star magnetism is about 10^{17} gauss; beyond this limit, the fluid inside the star would tend to mix and the field would dissipate. No known objects in the universe can generate and maintain fields stronger than this level. One ramification of our calculations is that radio pulsars are neutron stars in which the large-scale dynamo has *failed* to operate. In the case of the Crab pulsar, the newborn neutron star rotated once every 20 milliseconds, much slower than the rate of convection, so the dynamo never got going.



STRUCTURE OF A NEUTRON STAR can be inferred from theories of nuclear matter. Starquakes can occur in the crust, a lattice of atomic nuclei and electrons. The core consists mainly of neutrons and perhaps quarks. An atmosphere of hot plasma might extend a grand total of a few centimeters.

Crinkle Twinkle Little Magnetar

ALTHOUGH WE DID NOT develop the magnetar concept to explain SGRs, its implications soon became apparent to us. The magnetic field should act as a strong brake on a magnetar's rotation. Within 5,000 years a field of 10^{15} gauss would slow the spin rate to once every eight seconds—neatly explaining the oscillations observed during the March 1979 outburst.

As the field evolves, it changes shape, driving electric currents along the field lines outside the star. These currents, in turn, generate x-rays. Meanwhile, as the magnetic field moves through the solid crust of a magnetar, it bends and stretches the crust. This process heats the interior of the star and occasionally breaks the crust in a powerful "starquake." The accompanying release of magnetic energy creates a dense cloud of electrons and positrons, as well as a sudden burst of soft gamma rays—accounting for the fainter bursts that give SGRs their name.

More infrequently, the magnetic field becomes unstable and undergoes a large-scale rearrangement. Similar (but smaller) upheavals sometimes happen on the sun, leading to solar flares. A magnetar easily has enough energy to power a giant flare such as the March 1979 event. Theory indicates that the first half-second of that tremendous outburst came from an expanding fireball. In 1995 we suggested that part of the fireball was trapped by the magnetic field lines and held close to the star. This trapped fireball gradually shrank and then evaporated, emitting x-rays all the while. Based on the amount of energy released, we calculated the strength of the magnetic field needed to confine the enormous fireball pressure: greater than 10^{14} gauss, which agrees with the field strength inferred from the spin-down rate.

A separate estimate of the field had been given in 1992 by Bohdan Paczyński of Princeton. He noted that x-rays can slip

THE AUTHORS

CHRYSSA KOUVELIOTOU, ROBERT C. DUNCAN and *CHRISTOPHER THOMPSON* have studied magnetars for a collective 40 years and have collaborated for the past five. Kouveliotou, an observer, works at the National Space Science and Technology Center in Huntsville, Ala. Besides soft-gamma repeaters, her pets include gamma-ray bursts, x-ray binaries and her cat, Felix; her interests range from jazz to archaeology to linguistics. Duncan and Thompson are theorists, the former at the University of Texas at Austin, the latter at the Canadian Institute for Theoretical Astrophysics in Toronto. Duncan has studied supernovae, quark matter and intergalactic gas clouds. In his younger days he ran a 2:19 marathon in the 1980 U.S. Olympic trials. Thompson has worked on topics from cosmic strings to giant impacts in the early solar system. He, too, is an avid runner as well as a backpacker.

through a cloud of electrons more easily if the charged particles are immersed in a very intense magnetic field. For the x-rays during the burst to have been so bright, the magnetic field must have been stronger than 10^{14} gauss.

What makes the theory so tricky is that the fields are stronger than the quantum electrodynamic threshold of 4×10^{13} gauss. In such strong fields, bizarre things happen. X-ray photons readily split in two or merge together. The vacuum itself is polarized, becoming strongly birefringent, like a calcite crystal. Atoms are deformed into long cylinders thinner than the quantum-relativistic wavelength of an electron [*see box on opposite page*]. All these strange phenomena have observable effects on magnetars. Because this physics was so exotic, the theory attracted few researchers at the time.

Zapped Again

AS THESE THEORETICAL developments were slowly unfolding, observers were still struggling to see the objects that were the sources of the bursts. The first opportunity came when NASA's orbiting Compton Gamma Ray Observatory recorded a burst of gamma rays late one evening in October 1993. This was the break Kouveliotou had been looking for when she joined the Compton team in Huntsville. The instrument that registered the burst could determine its position only to within a fairly broad swath of sky. Kouveliotou turned for help to the Japanese ASCA satellite. Toshio Murakami of the Institute of Space and Astronautical Science in Japan and his collaborators soon found an x-ray source from the same swath of sky. The source held steady, then gave off another burst—proving beyond all doubt that it was an SGR. The same object had first been seen in 1979 and, based on its approximate celestial coordinates, was identified as SGR 1806–20. Now its position was fixed much more precisely, and it could be monitored across the electromagnetic spectrum.

The next leap forward came in 1995, when NASA launched the Rossi X-ray Timing Explorer (RXTE), a satellite designed to be highly sensitive to variations in x-ray intensity. Using this instrument, Kouveliotou found that the emission from SGR 1806–20 was oscillating with a period of 7.47 seconds—amazingly close to the 8.0-second periodicity observed in the March 1979 burst (from SGR 0526–66). Over the course of five years, the SGR slowed by nearly two parts in 1,000. Although the slowdown may seem small, it is faster than that of any radio pulsar known, and it implies a magnetic field approaching 10^{15} gauss.

More thorough tests of the magnetar model would require a second giant flare. Luckily, the heavens soon complied. In the early morning of August 27, 1998, some 19 years after the giant flare that began SGR astronomy was observed, an even more intense wave of gamma rays and x-rays reached Earth from the depths of space. It drove detectors on seven scientific spacecraft to their maximum or off scale. One interplanetary probe, NASA's Comet Rendezvous Asteroid Flyby, was forced into a protective shutdown mode. The gamma rays hit Earth on its nightside, with the source in the zenith over the mid-Pacific Ocean.

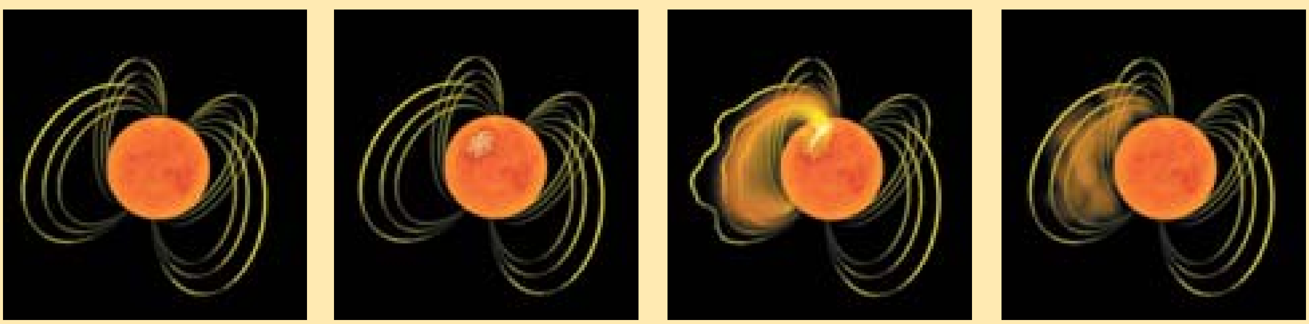
Fortuitously, in those early morning hours electrical engineer Umran S. Inan and his colleagues from Stanford University were gathering data on the propagation of very low frequency radio waves around Earth. At 3:22 A.M. PDT, they noticed an abrupt change in the ionized upper atmosphere. The inner edge of the ionosphere plunged down from 85 to 60 kilometers for five minutes. It was astonishing. This effect on our planet was caused by a neutron star far across the galaxy, 20,000 light-years away.

Another Magneto Marvel

THE AUGUST 27 FLARE was almost a carbon copy of the March 1979 event. Intrinsically, it was only one tenth as powerful, but because the source was closer to Earth it remains the most intense burst of gamma rays from beyond our solar system ever detected. The last few hundred seconds of the flare showed conspicuous pulsations, with a 5.16-second period. Kouveliotou

HOW MAGNETAR BURSTS HAPPEN

THE MAGNETIC FIELD OF THE STAR is so strong that the rigid crust sometimes breaks and crumbles, releasing a huge surge of energy.



1 Most of the time the magnetar is quiet. But magnetic stresses are slowly building up.

2 At some point the solid crust is stressed beyond its limit. It fractures, probably into many small pieces.

3 This "starquake" creates a surging electric current, which decays and leaves behind a hot fireball.

4 The fireball cools by releasing x-rays from its surface. It evaporates in minutes or less.

DON DIXON

and her team measured the spin-down rate of the star with RXTE; sure enough, it was slowing down at a rate comparable to that of SGR 1806–20, implying a similarly strong magnetic field. Another SGR was placed into the magnetar hall of fame.

The precise localizations of SGRs in x-rays have allowed them to be studied using radio and infrared telescopes (though not in visible light, which is blocked by interstellar dust). This work has been pioneered by many astronomers, notably Dale Frail of the National Radio Astronomy Observatory and Shri Kulkarni of the California Institute of Technology. Other observations have shown that all four confirmed SGRs continue to release energy, albeit faintly, even between outbursts. "Faintly" is a relative term: this x-ray glow represents 10 to 100 times as much power as the sun radiates in visible light.

By now one can say that magnetar magnetic fields are better measured than pulsar magnetic fields. In isolated pulsars, almost the only evidence for magnetic fields as strong as 10^{12} gauss comes from their measured spin-down. In contrast, the combination of rapid spin-down and bright x-ray flares provides several independent arguments for 10^{14}- to 10^{15}-gauss fields in magnetars. As this article goes to press, Alaa Ibrahim of the NASA Goddard Space Flight Center and his collaborators have reported yet another line of evidence for strong magnetic fields in magnetars: x-ray spectral lines that seem to be generated by protons gyrating in a 10^{15}-gauss field.

One intriguing question is whether magnetars are related to cosmic phenomena besides SGRs. The shortest-duration gamma-ray bursts, for example, have yet to be convincingly explained, and at least a handful of them could be flares from magnetars in other galaxies. If seen from a great distance, even a giant flare would be near the limit of telescope sensitivity. Only the brief, hard, intense pulse of gamma rays at the onset of the flare would be detected, so telescopes would register it as a GRB.

Thompson and Duncan suggested in the mid-1990s that magnetars might also explain anomalous x-ray pulsars, a class of objects that resemble SGRs in many ways. The one difficulty with this idea was that AXPs had not been observed to burst. Recently, however, Victoria M. Kaspi and Fotis P. Gavriil of McGill University and Peter M. Woods of the National Space and Technology Center in Huntsville detected bursts from two of the seven known AXPs. One of these objects is associated with a young supernova remnant in the constellation Cassiopeia.

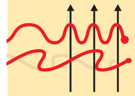
Another AXP in Cassiopeia is the first magnetar candidate to have been detected in visible light. Ferdi Hulleman and Marten van Kerkwijk of Utrecht University in the Netherlands, working with Kulkarni, spotted it three years ago, and Brian Kern and Christopher Martin of Caltech have since monitored its brightness in visible light. Though exceedingly faint, the AXP fades in and out with the x-ray period of the neutron star. These observations lend support to the idea that it is indeed a magnetar. The main alternative—that AXPs are ordinary neutron stars surrounded by disks of matter—predicts too much visible and infrared emission with too little pulsation.

In view of these recent discoveries, and the apparent silence of the Large Magellanic Cloud burster for nearly 20 years, it appears that magnetars can change their clothes. They can remain quiescent for years, even decades, before undergoing sudden periods of extreme activity. Some astronomers argue that AXPs are younger on average than SGRs, but this is still a matter of debate. If both SGRs and AXPs are magnetars, then magnetars plausibly constitute a substantial fraction of all neutron stars.

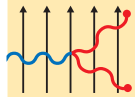
The story of magnetars is a sobering reminder of how much we have yet to understand about our universe. Thus far, we have discerned at most a dozen magnetars among the countless stars. They reveal themselves for a split second, in light that only the most sophisticated telescopes can detect. Within 10,000 years, their magnetic fields freeze and they stop emitting bright x-rays. So those dozen magnetars betray the presence of more than a million, and perhaps as many as 100 million, other objects—old magnetars that long ago went dark. Dim and dead, these strange worlds wander through interstellar space. What other phenomena, so rare and fleeting that we have not recognized them, lurk out there? SA

EXTREME MAGNETISM

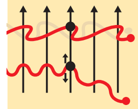
MAGNETAR FIELDS wreak havoc with radiation and matter.



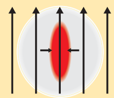
VACUUM BIREFRINGENCE
Polarized light waves (*orange*) change speed and hence wavelength when they enter a very strong magnetic field (*black lines*).



PHOTON SPLITTING
In a related effect, x-rays freely split in two or merge together. This process is important in fields stronger than 10^{14} gauss.



SCATTERING SUPPRESSION
A light wave can glide past an electron (*black circle*) with little hindrance if the field prevents the electron from vibrating with the wave.



DISTORTION OF ATOMS
Fields above 10^9 gauss squeeze electron orbitals into cigar shapes. In a 10^{14}-gauss field, a hydrogen atom becomes 200 times narrower.

MORE TO EXPLORE

Formation of Very Strongly Magnetized Neutron Stars: Implications for Gamma-Ray Bursts. Robert C. Duncan and Christopher Thompson in *Astronomical Journal,* Vol. 392, No. 1, pages L9–L13; June 10, 1992. Available at **makeashorterlink.com/?B16A425A2**

An X-ray Pulsar with a Superstrong Magnetic Field in the Soft Gamma-Ray Repeater SGR1806–20. C. Kouveliotou, S. Dieters, T. Strohmayer, J. Von Paradijs, G. J. Fishman, C. A. Meegan, K. Hurley, J. Kommers, I. Smith, D. Frail and T. Murakami in *Nature,* Vol. 393, pages 235–237; May 21, 1998.

The Life of a Neutron Star. Joshua N. Winn in *Sky & Telescope,* Vol. 98, No. 1, pages 30–38; July 1999.

Physics in Ultra-strong Magnetic Fields. Robert C. Duncan. Fifth Huntsville Gamma-Ray Burst Symposium, February 23, 2002. Available at **arXiv.org/abs/astro-ph/0002442**

Flash! The Hunt for the Biggest Explosions in the Universe. Govert Schilling. Cambridge University Press, 2002.

More information can be found at Robert C. Duncan's Web site: **solomon.as.utexas.edu/magnetar.html**

BRYAN CHRISTIE DESIGN