Way too cool
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Created in a recent supernova explosion, a young neutron star reveals secrets of nuclear matter. BY DAVID HELFAND

"a guest star appeared in Kui lunar lodge. It was trespassing against Chuanshe. According to the divination, the guest star was a star of ill omen." So begins a story that in 2001 led to newspaper headlines around the country: "Weird Stars Show Evidence of a New Form of Matter" and "X ray Telescope Finds Stars That May Defy Current Physics." I'm happy to report that current physics remains comfortably intact. But close examination of the detritus left behind by the celestial visitor of 1181 is providing some tantalizing clues about the structure of the subatomic world.

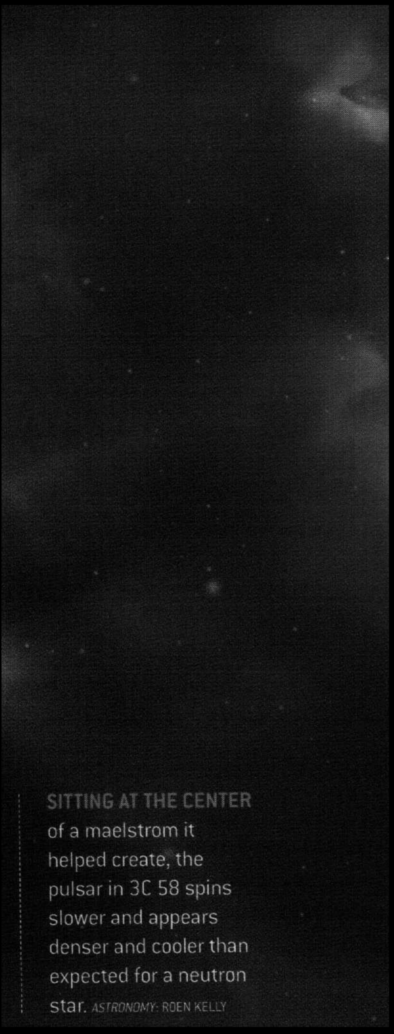
Astronomers from the Song dynasty in southern China were not the only ones watching the sky for portents in the 12th century. Observers from the Kamakura Shogunate in Japan left two records of the new guest star, dating its appearance to August 7. One record compares its brightness to Saturn and states that it is the first brilliant "guest" since one recorded 175 years earlier. In a Jin dynasty report from northern China, we read that the new star was visible for 156 days, "... *then it was extinguished.*"

Extinguished to the naked eye perhaps, but hardly gone. At the site of the explosion, the collapsed core of the parent star was spinning rapidly, pumping out enormous amounts of energy to build a surrounding nebula. Meanwhile, under the surface of the stellar core, forms of matter never seen on Earth were taking shape.

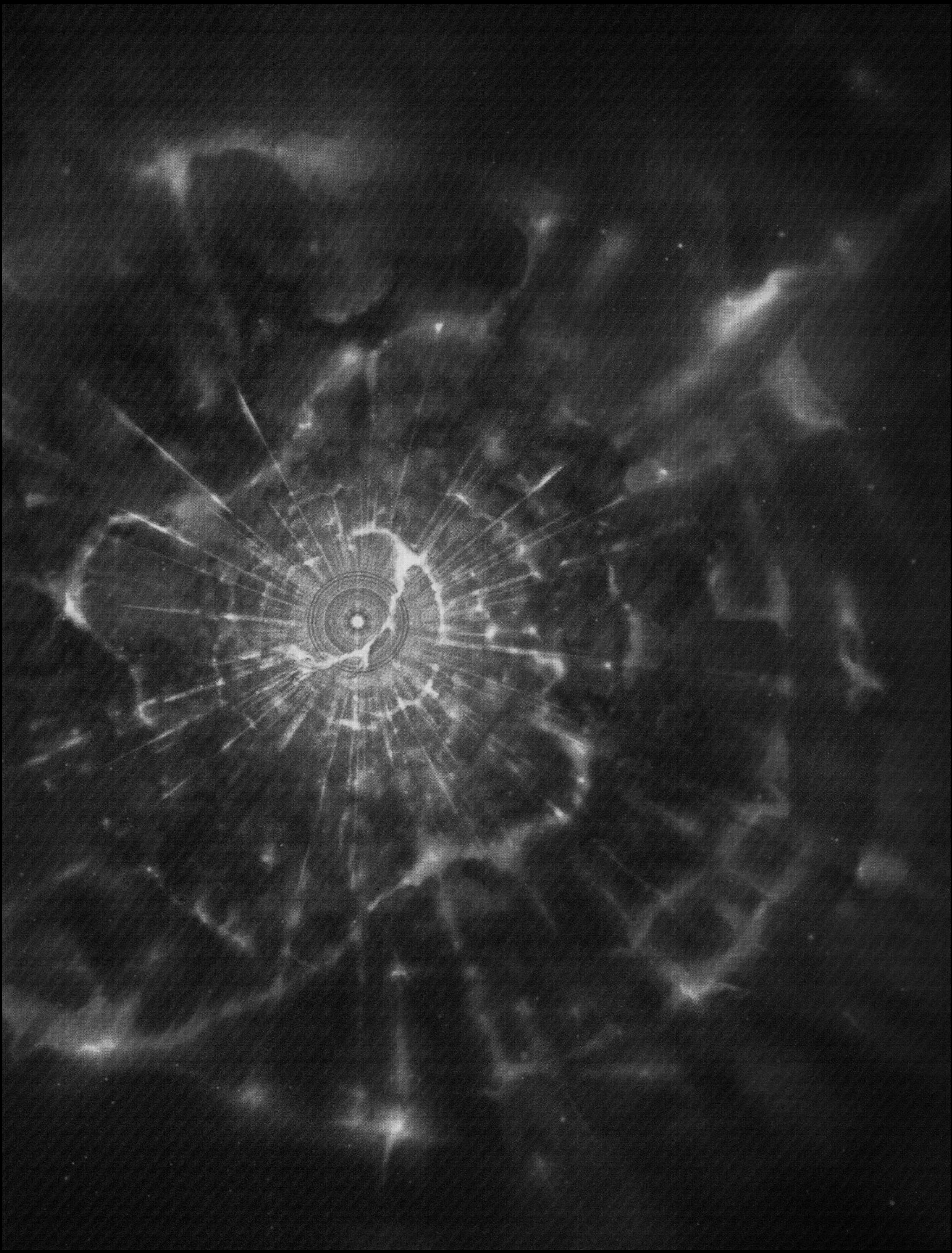
Eight hundred and twenty years later, the secrets of this matter are beginning to be told.

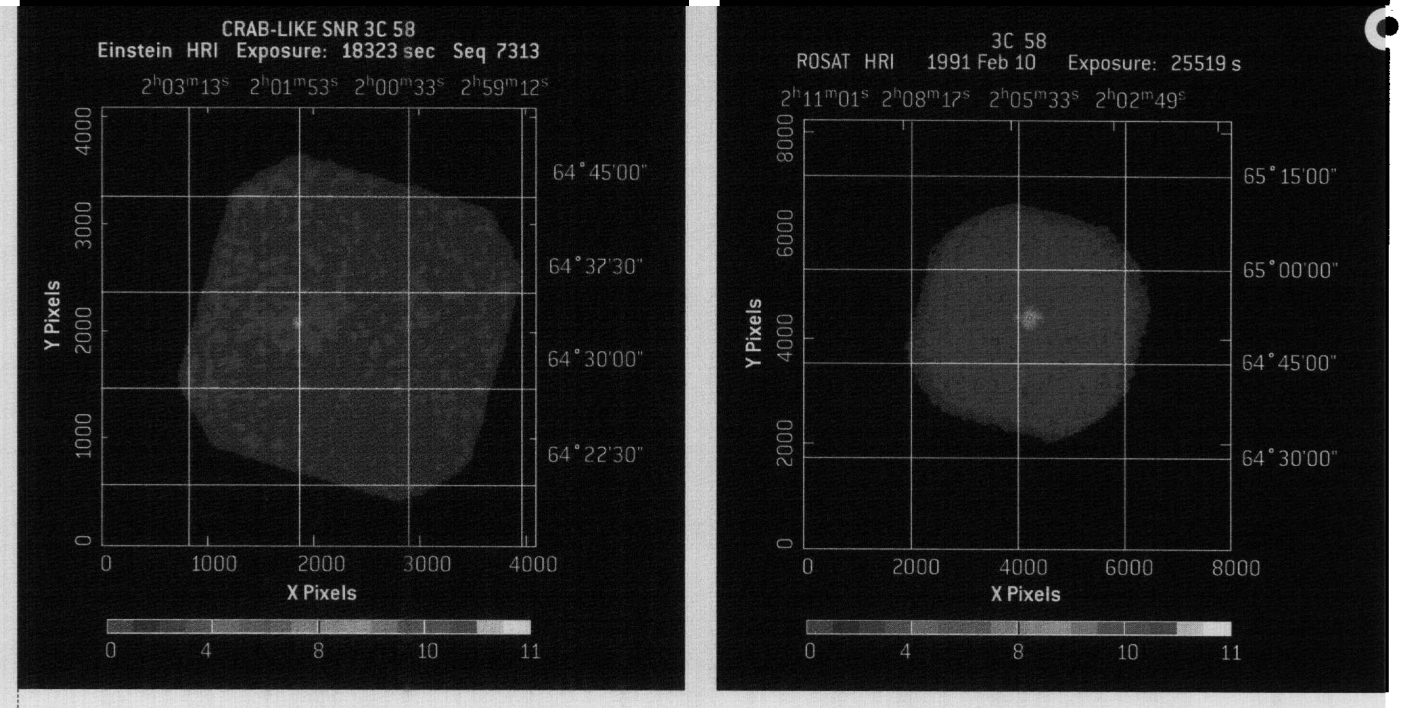
Radio astronomers were the first to record a signal from the guest star's location when they listed it as the 58th entry in the *Third Cambridge Catalogue* of radio sources in 1959. Nearly two decades later, Andrew Wilson and Kurt Weiler studied 3C 58 in detail. They suggested it shared several properties with the most famous guest-star remnant — the Crab Nebula — which formed after the destruction of a massive star in a supernova explosion witnessed around the world on July 4, 1054.

The Crab is one of the most studied objects in the sky — the subject of more than 2,000 research papers since 1950 — and is the Rosetta Stone for decrypting



SITTING AT THE CENTER of a maelstrom it helped create, the pulsar in 3C 58 spins slower and appears denser and cooler than expected for a neutron star. ASTRONOMY: ROEN KELLY





OUR FIRST DECENT LOOK AT 3C 58 (left) came from the Einstein Observatory, although it couldn't resolve the central pulsar. NASA/GSFC
ROSAT YIELDED BETTER RESOLUTION and much higher sensitivity (right), yet the pulsar remained tantalizingly out of reach. ROSAT DATA CENTER

the fate of massive stars. Briefly, the standard story goes like this:

Having run out of nuclear fuel, the core of a massive star suddenly implodes, creating a dense, spinning neutron star. The energy released in the collapse causes a titanic explosion, hurling the star's outer layers into space. The rapidly rotating neutron star has a huge magnetic field and acts like a giant generator, pouring a current of particles traveling at nearly the speed of light into the surrounding nebula, making it glow. The star itself flashes a lighthouse-like beacon in our direction with each rotation, justifying its name — a pulsar.

As astronomers find more remnants of massive stars, the details of the picture are changing. Moreover, the prototype object, as often happens in astronomy, is turning out to be less and less typical of the class. But the basic picture remains unchanged and provides a useful outline for the story of 3C 58.

Cousin to the Crab?

My own involvement with the Guest Star of 1181 began more than twenty years ago, around its 800th birthday. Using the first x-ray telescope, the orbiting Einstein Observatory, we targeted 3C 58 with the observatory's cameras and spectrographs to test the hypothesis that it was a twin of the Crab Nebula. We also looked for its central neutron star.

The x-ray spectrum of 3C 58 showed lots of high-energy photons compared to low-energy ones and an absence of features expected from hot x-ray gas. These were just the characteristics expected for a Crab-like emission of electrons spiraling in nebular magnetic fields almost at lightspeed. Furthermore, the x-ray brightness peaked at the center of the remnant, suggesting a central power source. Kinship with the Crab looked promising.

There were two striking differences, however. The total x-ray luminosity was 2,000 times weaker, and the x-ray nebula extended several times larger. In addition, our search for a central pulsar was unsuccessful. The highest quality camera on Einstein had a resolution equivalent only to binoculars, so we couldn't resolve the central star from the surrounding nebula.

Ten years passed. In 1991, we used the German x-ray satellite, ROSAT, in another attempt to find 3C 58's pulsar. ROSAT's High Resolution Imager had slightly better resolution and considerably higher sensitivity than Einstein's. But the result of a seven-hour exposure was again somewhat unsatisfying. In the remnant's core we found a bright concentration of x-ray emission, but it appeared extended north to south. Unfortunately, a small fraction of ROSAT observations were plagued by an error in the star-tracking cameras that turned point sources into blobs just like this. Because we couldn't rule out this explanation, we were left with an ambiguous result. We tried searching for a period in the arrival times of the 352 x-ray photons making up the blob, but found nothing significant.

Another decade passed. Then the Chandra X-ray Observatory, x-ray astronomy's equivalent of the Hubble Space Telescope, was launched. On September 4, 2000, my colleague Pat Slane at the Harvard-Smithsonian Center for Astrophysics slipped our previously approved observation of 3C 58 into the Chandra schedule. That day we collected nearly ten hours of good data with Chandra's Advanced CCD Imaging Spectrometer camera. Nine months earlier, Pat's colleague at CfA, Steve Murray, had used Chandra's other camera (which he had built) to observe 3C 58. But in the flood of data pouring in daily, the dataset remained unanalyzed.

And we weren't much faster. Then on March 28, 2001, I got an e-mail from Pat:

"I finally got a bit of time to get back to the 3C 58 data. I'm working on it now, and plan on spending more time tomorrow. An encouraging result from today, that I need to quantify, is that there definitely seems to be a point-like source in the compact inner nebula (by which I

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THE RAPIDLY ROTATING PULSAR IN 3C 58 came into view as the bright spot in the center of this Chandra X-ray Observatory image. It lies embedded in extended emission produced by energetic particles accelerated to nearly the speed of light by the pulsar's enormous magnetic field. NASA/CXC/CFA/P. SLANE ET AL.

mean the extended object that we used to consider a point source — but that you concluded *might* be extended based on the ROSAT data). Have a look."

It took me three seconds to download the image from his website, five seconds to run down the hall to the printer, and less than a minute to show it to colleagues at Columbia who share my interest in dead stars. All agreed it was a good bet that the pulsar in 3C 58 had at last been found. Unfortunately, this Chandra camera takes three-second-long exposures, so there was no chance to look for the pulsar's spin period (which was expected to be much less than one second).

But Steve Murray's camera records the arrival time of each x ray to an accuracy of millionths of a second, and as soon as Pat showed him our picture, their analysis sprung into high gear. Within days, they found an x-ray pulse with a period of 65.7 milliseconds, roughly twice that of the Crab pulsar. A comparison with data obtained earlier by the Rossi X-ray Timing Explorer mission showed that, like all pulsars, this period was slowly lengthening as the star lost energy to the surrounding nebula. This stellar dynamo was pumping out energy at a rate nearly 100,000 times that of the Sun. The inferred magnetic field strength, roughly 10 trillion times that of Earth's, was very similar to that of the Crab pulsar.

> We got interested in the Guest Star of 1181 around the time of its 800th birthday.

The match to our standard supernova story was nearly perfect. 3C 58's only major difference from the Crab was the initial spin rate of the star. Knowing the age, the current period, and the rate at which the period is slowing, we can calculate the spin period at birth. For the Crab, it is 19 milliseconds, while for 3C 58 it is closer to 60 milliseconds. Now, the shorter the period, the higher the spin rate. And the higher the spin rate, the more energy is available for powering the nebula — in fact, every factor of two increase in the initial spin rate raises the power by a factor of 16. Thus the slower initial spin of 3C 58 goes a long way toward explaining why it's so faint in x rays compared with its Crab cousin.

The whole picture was coming together nicely.

Although the data were of no use in finding a pulse period, they did record the energy of each arriving x ray. This let us construct a spectrum of the pulsar and its surrounding nebula. And that's where the fun began.

Weird starlight

Astronomers don't "see" most pulsars the way they do other stars — by detecting thermal radiation produced by atoms jiggling on their surfaces. For example, the Sun produces predominantly yellow light because its surface temperature is roughly 5800 kelvins. This means its surface atoms are rushing around at a speed such that collisions between them produce electromagnetic energy at a wavelength of 500 nanometers ("yellow" to our eyes). The atoms on hotter stars move quicker and collide more violently, and produce higher-energy (to us, bluer) light. Similarly, cooler stars have more sluggish atoms and produce low-energy red photons. Astrophysicists have a general rule: The amount of energy a star radiates is proportional to its surface area, and to the fourth power of its surface temperature. Decoded, this means that if two stars have the same surface area, but one is twice as hot, the hotter star radiates 16 times more energy.

But neutron stars aren't directly comparable to ordinary ones. Although they are hotter than the Sun, neutron stars are *tiny*, with surface areas only one ten-billionth that of the Sun. The fact that we can see them shining brightly across thousands of light-years, at wavelengths from radio to gamma rays, tells us that they use a totally different radiation process than what makes the Sun shine.

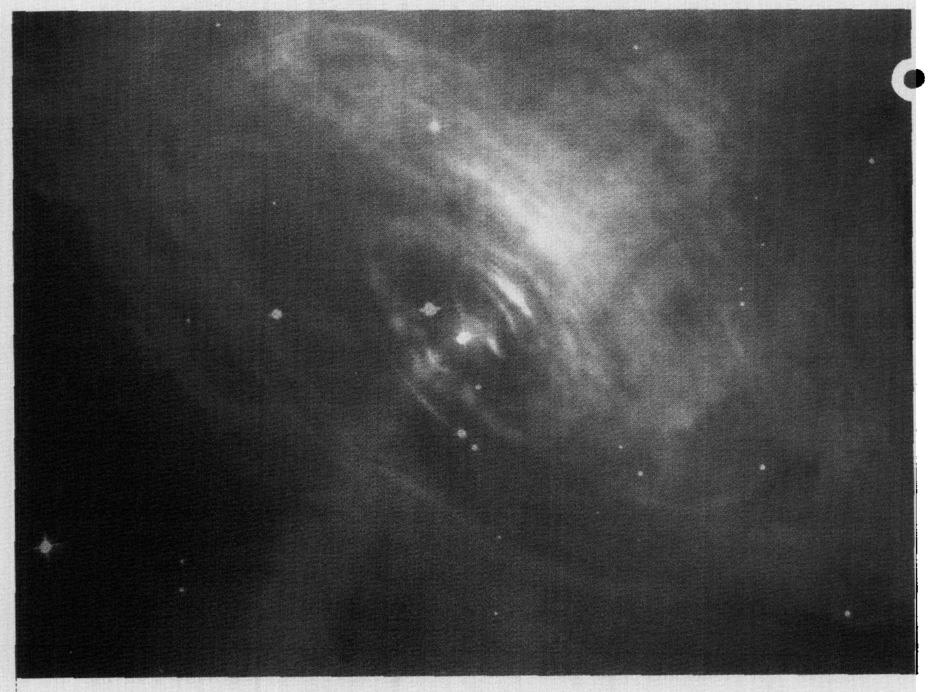
Neutron stars are huge spinning magnets that produce enormous electric fields near their surfaces: 1,000 trillion volts is typical at the magnetic poles. Just as voltage differences between the ground and thunderclouds can produce sudden discharges of lightning on Earth, titanic energy releases on a neutron star's surface rip out particles and accelerate them to nearly the speed of light. These particles (primarily electrons and their sister antiparticles, positrons) spiral around the huge magnetic field of the star, generating continuous radiation that spans the spectrum. It is x rays from this process that Chandra detects as pulses when a pulsar's poles sweep in and out of view with each rotation.

Tiny as they are, neutron stars still have a surface and they are born in a very hot place (a supernova explosion). Thus, we thought, it might not be crazy to look for surface thermal emission — that is, to try to see them as we see other stars.

A newborn neutron star is expected to be hotter than a billion kelvins, and it takes a year or so to cool enough for its surface to solidify. Then, since it lacks any internal heat-producing source (such as the nuclear reactions that drive normal stars), it just continues to cool off, independent of the magnetic and electrical pyrotechnics playing out above its surface. Most of the energy is lost directly from the deep interior, carried away by neutrinos — wraith-like subatomic particles that can travel through a million miles of lead without slowing. Because interacting particles in the neutron star's core produce neutrinos, the rate at which they carry energy away from the star gives us a window on the core.

After 100 years or so, such a star will have cooled to about 3 million kelvins. At this temperature, the surface radiates primarily low-energy x rays at roughly ten times the rate at which the Sun emits yellow light. So despite being small, fresh neutron stars should be detectable at considerable distances. The only problem is, we don't know of any 100-year-old neutron stars. Astronomers expect supernova explosions to create one or two each century in the Milky Way, but we haven't seen a supernova in our galaxy since Johannes Kepler recorded one in 1604. Any that have exploded since then did so far from the Sun, hidden by clouds of dust that block the view of the central Milky Way. Thus, we don't know where to look for hot, young neutron stars. (And even if we did, intervening gas and dust absorb low-energy x rays as efficiently as they do light, so the neutron stars would likely be invisible anyway.)

> **While exotic particles** have been produced in atom smashers for fleeting moments, they could live forever in the core of a neutron star.



THE CRAB NEBULA'S VIOLENT INTERIOR features shock waves and high-speed winds in this composite combining an optical image from Hubble (seen in red) with an x-ray image from Chandra (in blue). The Crab pulsar is the white dot at the center of the image. NASA/HST/CXC/ASU/J. HESTER ET AL.

Neither Kepler's supernova nor one observed by Tycho in 1572 were of a type that leaves behind a neutron star. That makes 3C 58 the youngest known remnant likely to house a hot object. So one of the first things Pat and I did was to look up the expected temperature for an 820-year-old neutron star. The answer was 1.4 million kelvins. We plugged this into software that calculated a likely spectrum and compared that to our data.

The mismatch was absolutely terrible. We were delighted.

Extreme matter

The calculated spectrum (see page 59) showed that, sitting on top of a smooth curve of x-ray photons from the magnetospheric light-show, Chandra should see significant additional emission at wavelengths longer than 1 nanometer. And it simply wasn't in the data. The real star was significantly cooler, less than one million kelvins — in fact, we couldn't detect it at all. Conclusion: The theory that predicted temperatures was wrong.

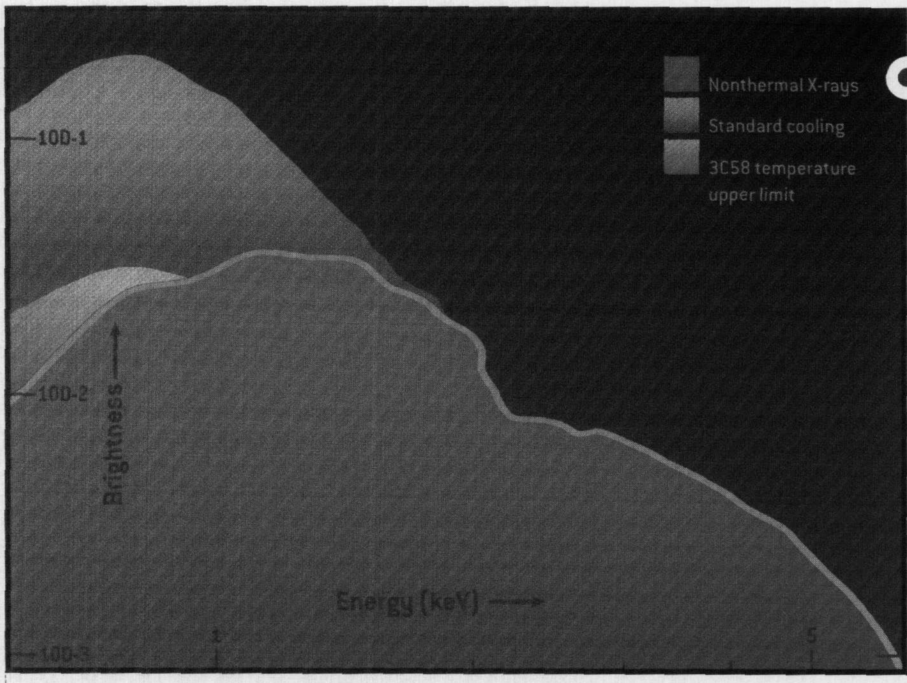
Predicting a temperature for a neutron star of a given age is no easy task. The only things on Earth that even approach a neutron star's density are the individual nuclei of atoms — tiny packages of tightly bound protons and neutrons. The largest of these has 238 nuclear particles packed into a space a trillionth of a centimeter in diameter. That's a density of about a billion tons per teaspoon. Imagine every car and truck on Earth squeezed into a single sugar cube or the entire Earth compressed into a city block.

We don't experience nuclear densities directly because of the enormous distances at which electrons, the third component of atoms, orbit their nuclei. Textbooks commonly show a "planetary atom" as a pea-sized nucleus with electrons spinning around it a few inches away. A real scale-model atom has a nuclear pea orbited by rings of electrons starting 200 feet away. It's atoms like this — 99.9999999999 percent empty space — that make up everything around us.

Nonetheless, by smashing nuclei together, physicists have modeled their internal structure and can predict how they would behave if they were packed together so they touched, with the orbiting electrons out of the way. This is what happens in a neutron star when the enormous pressure of the collapsing stellar core squeezes the electrons right into the nucleus, where they combine with protons to create neutrons. The conversion isn't total, however; depending on the star's mass, up to 20 percent of the matter can remain as protons and electrons, swimming around in a sea of neutrons.

In this environment, when a proton and electron encounter each other, they can merge to form a neutron. Likewise, neutrons can fall apart into an electron plus a proton. In each such transformation, a neutrino (or its antimatter equivalent) is emitted. Undaunted by passing through the equivalent of fifty Earths'-worth of matter, the neutrinos zip out of the star, carrying away energy and cooling the interior.

Using knowledge of atomic nuclei, we can calculate the energy loss rate and estimate the falling temperature of the star's surface. It is this calculation that led to the conclusion 3C 58 should be significantly hotter than it is.



3C 58'S NEUTRON STAR ISN'T SO HOT. The x-ray brightness of 3C 58's central region (orange curve) matches that expected from non-thermal x rays, those produced by electrons spiraling in an intense magnetic field. An 820-year-old neutron star should generate far more emission at wavelengths longer than 1 nanometer, corresponding to energies less than about 1.25 keV (blue). Even a one-million-kelvin neutron star should create more low-energy photons (green). NASA/SAO/CXC/P. SLANE ET AL.

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So what's happening? Several possibilities emerge. If the central density of the star exceeds that of normal atomic nuclei, its protons and neutrons can be squeezed so hard they start to rupture, spilling out their fundamental building blocks — quarks. Six types of quarks are found in nature, with the whimsical names of *up*, *down*, *strange*, *charm*, *top*, and *bottom*. Protons and neutrons are made of triplets of up and down quarks only. But at high enough pressures, the triplets can break, and strange cousins can pop into existence. The particle called lambda, for example, includes one strange quark in its triplet. While physicists have fleetingly produced such peculiar entities in atom smashers, they live at most a tiny fraction of a microsecond under laboratory conditions. But in the core of a neutron star, they could live forever.

Even simple pairs of quarks can form stable particles under these conditions — an up plus an antimatter down makes a pion, and an up paired with an anti-strange makes a kaon. Both of these two-quark particles behave very differently from normal nuclear matter — rather than constantly elbowing their neighbors away, they happily settle into a tightly packed crystalline form at the star's center. Should the density go even higher, the nuclei may dissolve completely into a formless sea of quarks. And all of these exotic species boost the neutrino rate enormously, leading to cool young neutron stars like 3C 58.

We found our answer.

Staring at a dead star the size of Manhattan across 10,000 light-years may not seem the best way to study the basics of matter. But the Chandra observations of 3C 58 and a handful of other young neutron stars are giving us looks at matter under conditions never achievable on Earth. At Brookhaven National Laboratory on Long Island, the Relativistic Heavy Ion Collider smashes single gold nuclei into each other to liberate quarks for a fraction of a microsecond. Neutron stars like 3C 58 routinely accomplish this trick on vastly larger and longer scales.

Contrary to what Chinese astrologers thought, guest stars provide no "ill omens." Indeed, throughout modern science, astronomical observations have played a key part in advancing our understanding of the universe. Astronomy is now extending its reach deep into the realms of nuclear and particle physics. Who knows what wonders lie ahead? ■