Astrophysics

Superficial resonance

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Neutron stars are the most poorly understood stellar objects in the Universe. But observations of X-rays emitted from one neutron star have now revealed a clue to the nature of its surface and composition.

Neutron stars are the remnants of massive stars. The density of their cores exceeds that of atomic nuclei, and they might contain exotic states of matter that are not found anywhere else in nature[1]. For decades astronomers have tried to 'see' the surfaces of such stars, in an effort to determine their physical properties. Space-borne telescopes have brought improved X-ray-imaging capabilities, but the first observations of neutron stars with these instruments were rather disappointing, revealing that the X-ray emission from most isolated neutron stars is remarkably featureless. But now observations of one neutron star have finally given us a glimpse of the fundamental properties of these objects: on page 725 of this issue, Bignami *et al.*[2] describe the first physical clue to the nature of this star's X-ray emission.

When massive stars — stars more than eight times heavier than the Sun — run out of thermonuclear fuel, their cores collapse. The resulting configuration typically has a mass about one-and-a half times that of the Sun, but a radius of only 10 km: the density of the material exceeds the nuclear density, and degeneracy (the quantum-mechanical restriction on the occupation of energy levels by particles) provides the support against the gravity of the star's own weight. According to simple astrophysical arguments, a young neutron star is expected to have a magnetic field of the order of 10^{12} gauss at its surface (in comparison, the Earth's field is about 0.5 gauss). It should also spin rapidly, appearing as a 'pulsar'.

The first neutron stars were discovered through their emission at radio wavelengths. Radio emission is produced in the envelope of magnetic field that surrounds a pulsar (through processes that are still poorly understood), and although it carries information about the star's magnetic field and spin period, it tells us nothing about the internal properties of the neutron star itself. If, instead, we could observe emission from the star's surface, it would tell us about the surface composition, which in turn would reveal more about how a neutron star forms, and the processes that affect the chemical composition of its atmosphere.

To 'view' the surface of hot young neutron stars requires observations of their X-ray, rather than radio, emission: the emission peaks in the 'soft' X-ray band of photon energies (0.1–1 kiloelectronvolts, or keV). But even in the X-ray band, isolated hot neutron stars are faint. The 1999 launches of NASA's Chandra X-ray Observatory and the European Space Agency's XMM-Newton observatory were eagerly awaited, but the initial observations of a handful of hot neutron stars were universally disappointing. The spectra of radiation from the stars did show the expected characteristic of thermal emission from their surfaces: a gently curving, black-body-like energy distribution. But detailed scrutiny of the X-ray spectrum failed to reveal any structure; the shape of the spectrum in all cases was very close to that of a black body, which by its very nature contains no other information than the thermodynamic temperature[3].

But last year Sanwal *et al*.[4] reported observations using Chandra of the spectrum of the young isolated neutron star 1E1207.4 − 5209. The data show two distinct dips in the energy spectrum of photons emitted from the star, centred at 0.7 and 1.4 keV. Here was the first spectral signature of an interaction of the surface radiation with something in the stellar atmosphere — but what? These features, known as absorption lines, were difficult to explain. Sanwal *et al*. speculated that they are due to absorption by singly ionized helium atoms in the stellar atmosphere; others, however, argued that transitions in highly ionized oxygen or neon atoms are the more likely explanation[5,6].

The energies at which the features appear — 0.7 and 1.4 keV — are in the ratio 1:2. That suggests another interpretation. Charged particles in a magnetic field oscillate at a particular, resonant frequency — this is called 'cyclotron resonance'. For a magnetic field strength of about 6×10^{10} gauss, the resonant frequency of electron oscillations corresponds to an absorbed-photon energy of 0.7 keV; absorption will also occur at multiples of this fundamental energy. Protons can resonantly absorb radiation in a magnetic field, but, for a given resonant frequency, the corresponding magnetic field would be 2,000 times higher than in the case of cyclotron resonance of electrons (because a proton is 2,000 times heavier than an electron).

From an accurate timing analysis of the spin behaviour of 1E1207.4 − 5209, Sanwal *et al*.[4] estimate that the star has a surface magnetic field strength of $2\text{–}3 \times 10^{12}$ gauss. But if the 0.7-keV feature in the X-ray spectrum is a cyclotron resonance, this doesn't add up — for an electron resonance, the field strength would be much lower than this value, whereas a proton resonance would require a field strength that is much higher. For this reason, the cyclotron-resonance interpretation was initially rejected.

But Bignami *et al*.[2] now report more detailed observations of the same neutron star using cameras onboard XMM-Newton, data that provide convincing proof of the cyclotron interpretation. Bignami *et al*. have found a third feature at about 2.1 keV and perhaps even a fourth feature around 2.8 keV — almost precisely three and four times 0.7 keV, respectively. What makes the identification compelling is that all of the features vary systematically in strength (and perhaps even in shape) with the spin phase of the star, ruling out the possibility of this being a chance conspiracy of noise fluctuations in the data. Cyclotron resonances have been seen before in a handful of neutron stars in binary systems, the first one being Hercules X-1 (ref. 7). But never before has a triple harmonic structure been seen so convincingly in an isolated neutron star.

The implications of this beautiful spectrum are somewhat puzzling, though. First, there is the obvious question of why only this object shows cyclotron resonances. (There is a recent report[8] of a broad feature in the spectrum of the isolated neutron star RBS1223, but even if that also turns out to be a cyclotron resonance, it still means that only a small fraction of isolated neutron stars show these kinds of spectral features.) This question translates into the equivalent statement that only a small fraction of isolated young neutron stars have a low magnetic field strength, one that is in the right range for electron cyclotron resonances to show up in the 0.1–10-keV band.

And there is the problem that the magnetic field strength estimated from the resonance energy is inconsistent with the field strength derived from the star's observed spin rate and deceleration rate. Perhaps there are additional torques on 1E1207.4 − 5209. That would clearly have implications for our understanding of the angular momentum and magnetic field strength existing at the birth of a neutron star — an understanding that is already under siege on another flank, with the discovery of 'magnetars'. These neutron stars have superstrong magnetic fields[9] that exceed a staggering 10^{14} gauss.

Whatever the answer, the fact that 1E1207.4 − 5209 shows definite structure in the spectrum of light emitted near or at its surface is an important finding. Physical clues to the fundamental properties of neutron stars are rare, and this discovery adds an important piece to the puzzle. It will be interesting to see whether the detailed shape of the spectrum can be made to fit a model for the atmosphere, and what the resulting distribution of the field, and perhaps the thermal structure of the atmosphere, looks like. And the discovery itself will undoubtedly add impetus to attempts to find spectral structure in the emissions of other neutron stars. ■

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