NEUTRON STARS

The patchy temperature map of magnetars

On a magnetar's surface, magnetic fields can create permanent sunspot-like structures. Accounting for heat diffusion and magnetic evolution in a magnetar's crust in the latest simulations improves agreement with observations.

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Astrophysicists are progressing in the understanding of how magnetic fields evolve and directly affect the properties of the X-ray radiation coming from magnetars — ultra-magnetized neutron stars with spectacular, unpredictable activity. We currently know of roughly 30 such objects in our Galaxy, often thanks to the detection of their high-energy outbursts, which can temporarily make them some of the brightest sources in the X-ray sky. Magnetars represent a unique laboratory in astrophysics because of the extreme conditions in their interior. Theories about plasma processes, general relativity, high-energy radiation and nuclear physics are tested by these city-sized compact stars containing one or two solar masses. Writing in *Nature Astronomy*, Andrei Igoshev and collaborators¹ report the first

three-dimensional (3D) simulation of the internal heat diffusion from the thin crust to the surface of a magnetar, considering at the same time the non-trivial evolution of the magnetic field and the conversion of magnetic energy into heat by the Joule effect, which regulates the dissipation of currents in any electrical conductor. Thus, they were able to compare the simulated temperature maps with observations.

X-ray observations of magnetars with satellites such as Swift, XMM-Newton and Chandra can be used to study processes inside and around these stars. The analysis of the X-ray spectra reveals that magnetars generally emit non-thermal and thermal radiation in both their quiescent and outburst states, with temperatures systematically higher than less magnetized neutron stars. This thermal emission is

compatible with the age of these objects, typically 10^3 – 10^4 years, at which a large amount of the residual heat from their formation is still trapped in their interior. At these stages, neutron stars cool down mostly due to the production of a large number of neutrinos, but in magnetars such losses are partially compensated by the additional heat deposited by the slow dissipation of their magnetic field².

The inferred surface magnetic fields in magnetars are typically about 10^{14} – 10^{15} G, at least 13 orders of magnitude stronger than in any body of the Solar System. In the Sun and in the planets, the continuous convection of electrically conducting ionized material in some layers (the outer core of the Earth, for instance) continuously feeds a kinetic-to-magnetic energy conversion, the so-called dynamo process. Neutron stars,

Fig. 1 | Hotspots on the surface of magnetars. **a**, Strong magnetic fields make the heat transport anisotropic, so that the heat from the deepest layers is released preferentially corresponding to the radially directed magnetic fields, forming localized hotspots. **b**, Since the star is rotating, such hotspots can modulate the observed light curve. Shown here is the light curve of 1E 1547.0-5408. The dashed blue lines and the error bars are observations and 1σ confidence intervals, respectively. The solid black line is the theoretical light-curve for the most favourable orientation. Panel **b** reproduced with permission from ref. ¹, Springer Nature Ltd.

instead, inherit their magnetic budget at birth, after the amplification of the magnetic fields occurring during their collapse³. After that, the dynamo mechanism stops and the magnetic fields tend to dissipate due to the Joule effect, which is especially important in the crust. But the picture is more complex than that⁴. In the crust, matter is composed of heavy-ion crystals, in which degenerate electrons move almost freely, carrying the electrical currents and giving rise to the Hall effect, similarly to conductors embedded in magnetic fields. The Hall effect can be dominant, creating small structures and thus shaping the temperature map at the surface. Moreover, it results in dynamical timescales compatible with the age of a magnetar, thus explaining the trigger to their observed activities.

Igoshev and collaborators focus precisely on the crustal magnetic dynamics. For their 3D simulations, they adapt a code that was originally designed for the geodynamo, which is an important step forward after more than a decade of studies where either the heat diffusion was not considered⁵ or simulations were restricted to axial symmetry⁶. Considering a fully 3D scenario is very important, as it is the only way to fully account for the magnetic dynamics and for the formation of a ‘patchy’ surface temperature, with the presence of small, bright hotspots. Notably, the authors are able to fit X-ray data of the quiescent emission for several magnetars, supporting the relevance of the internal heat transport in shaping the magnetar’s thermal emission. The resulting light curve depends on the surface temperature map and on the relative directions of the magnetic moment, rotational axis and the observer, as shown in Fig. 1. The success of the authors’ model relies on two key assumptions: an initial very intense, large-scale toroidal field (twisting all the magnetic lines in one direction only); and an anisotropic emission model for the surface. The latter is qualitatively consistent with the still unconfirmed presence of a centimetre-thick atmosphere. The presence of such an atmosphere would lead to

relatively large differences between the peaks (corresponding to the hot regions pointing towards us) and the minima (for which only the cold part of the surface is seen) in the magnetar light-curves.

Many open issues remain. First, the authors did not look at the long-term cooling and the dependence of the conductivity with temperature; including the relevant microphysical ingredients (neutrino emissivity, conductivity, specific heat) considering all of the particles involved and the full temperature dependence is necessary to determine a complete magneto-thermal evolution². This step is crucial if one wants simulations to explain not only the light curve, but also the age of a given source.

Second, the authors simplified the problem by confining the magnetic field to the thin crust. The core of a neutron star occupies around 80% of the star’s volume and 99% of its mass, but its composition and dynamics remain largely unknown. Matter at such high densities could include hyperons, muons and possibly heavier particles besides neutrons, protons and electrons. Our lack of theoretical knowledge is exacerbated by the fact that the core leaves much subtler imprints on the observables compared with the crust, the envelope and the magnetosphere — these external layers dominate the shape of the observed thermal radiation. Nevertheless, magnetic fields should penetrate the core even in the presence of superconductivity⁷, and their dynamics could be relatively fast⁸, thus affecting the crustal dynamics as well.

Third, the initial magnetic field is likely to be quite turbulent, rather than being described by a smooth large-scale structure (dipoles and quadrupoles), which is a numerically more stable and less costly assumption of virtually all 2D and 3D simulations. Dynamo processes should instead lead to an amplification of the magnetic energy distributed across a wide spectrum of spatial scales, as pioneering laboratory experiments have recently proved⁹. Indeed, recently, there have been

several hints pointing towards the presence of non-dipolar topologies^{10,11}.

Finally, the imprint of the magnetosphere on the thermal emission is not trivial. There are several indications that during the outbursts, when the source’s surface becomes hotter than usual, the magnetospheric contributions dominate, in the form of heating by Sun-like coronal loops formed by the twisting of the underlying magnetic field. It is unclear whether this emission component, which is likely to be responsible for the non-thermal radiation seen in soft and hard X-rays, dominates the thermal emission in quiescence as well¹².

These open questions are exciting, especially in light of the theoretical and numerical progress made in recent years and the upcoming wealth of data from the new generation of X-ray satellites such as Athena+ and eXTP, to be launched within a decade. These satellites will improve the characterization of magnetars in quiescence and outburst states and will provide additional information on the polarization of X-rays, relevant for the emission models. □

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Competing interests

The author declares no competing interests.