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Detailed Physical Modeling Reveals the Magnetar Nature of a Transient Anomalous X-ray Pulsar

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Anomalous X-ray Pulsars (AXPs) belong to a class of neutron stars believed to harbor the strongest magnetic fields in the universe, as indicated by their energetic bursts[1] and their rapid spindowns.[2] However, a direct measurement of their surface field strengths has not been made to date. It is also not known whether AXP outbursts result from changes in the neutron star magnetic field or crust properties. Here we report the first, spectroscopic measurement of the surface magnetic field strength of an AXP, XTE J1810−197, and solidify its magnetar nature. The field strength obtained from detailed spectral analysis and modeling is remarkably close to the value inferred from the rate of spindown of this source and remains nearly constant during numerous observations spanning over two orders of magnitude in source flux. The surface temperature, on the other hand, declines steadily and dramatically following the 2003 outburst of this source. Our findings demonstrate that heating occurs in the upper neutron star crust during an outburst and sheds light on the transient behaviour of AXPs.

The X-ray pulsar XTE J1810−197 was discovered[3] in 2003 when it suddenly brightened to more than 100 times its quiescent value[4] during an outburst. The source showed a steady decline of its X-ray flux thereafter, accompanied by significant spectral changes.[5] The 5.54 s period of the source, as well as the large period derivative $\dot{P} \approx 10^{-11}$ s s^{-1} were established,[3] confirming the source as the first transient Anomalous X-ray Pulsar (AXP). The detection of characteristic X-ray bursts,[6] similar to those seen in other AXPs,[1] further strengthened this classification.

The spectra of XTE J1810−197 have so far been analyzed by fitting empirical functions such as two blackbodies or a blackbody plus a power-law to the data[7] (as with the X-ray spectra of the other known AXPs). Such analyses are typically used for providing a rough estimate of the surface temperature of AXPs, even though neutron star surfaces do not emit like blackbodies. The photon energy-dependent radiation processes in their atmospheres strongly distort the emission originating deep in the neutron stars away from a blackbody spectrum. The strong magnetic fields that the sources are thought to possess, based on the rapid spindowns,[2] also leave distinctive imprints on the spectra both by altering the radiation processes in their atmospheres[8] and by giving rise to moderate scattering optical depths in the magnetospheres.[9]

We have developed a spectral model of magnetars that for the first time takes into account all these relevant mechanisms, and depends only on four physical parameters that describe the surface magnetic field strength and temperature of the neutron star, as well as the density and the energetics of charges in its magnetosphere. We have calculated spectra spanning the range of surface magnetic field strengths $B = 5 \times 10^{13} - 5 \times 10^{15}$ G and surface temperatures $T = 0.1 - 0.6$ keV, in line with the physical processes incorporated into the calculations. In our detailed calculations, we address the polarization-mode dependent transport of radiation, treating absorption, emission, and scattering processes that take place in the fully ionized plasmas of hot ($\sim 0.1 - 0.6$ keV) magnetar atmospheres.[8] The model also incorporates the interaction of photons with the protons in the plasma that gives rise to absorption features at the proton cyclotron energy. Furthermore, we fully calculate the effects of vacuum polarization resonance, which leads to an enhanced conversion between photons of different polarization modes as they propagate outward through the atmosphere.

In the stellar magnetospheres, we include a treatment of resonant scattering.[10] The enhanced current density in the magnetosphere of a magnetar significantly increases the optical depth to electron scattering experienced by the outgoing atmospheric photons.[9] The resulting upscattering modifies both the high-energy continuum and the equivalent widths of the proton cyclotron absorption features. Finally, because the surface photons originate in the strong gravitational field of the neutron star, we follow the general relativistic propagation of the photons to an observer on Earth. This last step depends on the mass-to-radius ratio of the neutron star (for which we assume a fixed fiducial value of $z = (1 - 2M/R)^{-1/2} - 1 = 0.3$) and is necessary to make the physical models directly comparable to the observations of AXPs. Here, M and R are the mass and radius of the neutron star, respectively, given in gravitational units.

Among the dozen known magnetars whose spectra can be successfully fit with our models, XTE J1810−197 is a prime candidate for a detailed study for several reasons. This source is unique in that over its short lifetime, it has gone through extreme variations in its X-ray flux and spectrum. It is not a priori obvious that such a wide range of spectra can be fit with a model that depends only on four physical parameters. Successfully reproducing in detail the spectral characteristics of every epoch with a single physical model, while keeping consistent values for these parameters, would indicate that this model captures all the relevant physical effects that take place on a magnetar. At the same time, studying the spectra of these different epochs with a physical model allows us to understand for the first time the unknown mechanism responsible for the outburst of a transient magnetar and the cause underlying the rapid variation of the source properties.

XTE J1810−197 was observed for a total of 120 ks in seven pointings between August 9, 2003 and March 12, 2006 with EPIC-PN onboard XMM-Newton. The flux of the source varied from 26 erg s^{-1} cm^{-2} at its peak to 0.41×10^{-12} erg $s^{-1}cm^{-2}$ during the last observation. All observations were calibrated using the latest version of Science Analysis Software (SAS, v. 7.0.0) and the latest available calibration files. All the spectra were grouped so that each spectral bin has at least 25 counts. The spectra were then fit with the detailed model of magnetar emission that we discussed above, allowing for interstellar extinction from a cold medium with cosmic abundances.

Figure 1 shows the spectra observed in the seven different epochs, the best fit models, and the residuals. The model describes in detail the salient features of the spectra in the entire energy range. This is especially remarkable because the significant evolution of the spectra during the decay of the outburst can be fit with a single physical model. Even more compelling than the low χ^2 values is the flatness of residuals that demonstrate the ability of the model to reproduce the observations without the need for any additional ad hoc components such as a blackbody or a power-law function. In the analyses of all seven observations, we obtain a constant value of $N_H = 0.64 \times 10^{22}$ cm^{-2} for the equivalent hydrogen column density responsible for the interstellar extinction, even though we allow this parameter to vary between observations. This value is also in agreement with an independent study of this source.[5]

The physical model allows for a tight and unique constraint of the magnetic field strength because of the presence of significant broad features in the magnetar spectra imparted by weakened proton cyclotron lines and the vacuum polarization resonance that have a strong dependence on the magnetic field strength. Here, we detect for the first time these unique modifications in the spectra of XTE J1810−197 and obtain the first measurement of its surface magnetic field strength.

The best-fit values for the surface magnetic field and the surface temperature of the neutron star, obtained from the detailed fits, as well as the 1- and 2-sigma confidence limits are shown in Figure 2. The measured magnetic field strength remains nearly constant during the decline of the outburst. This measurement is also in good agreement with the value of the magnetic field inferred from the spindown rate of the pulsar. Such an accord is unanticipated given the numerous assumptions involved in inferring the magnetic field strength with a vacuum dipole spindown formula.[11] To our knowledge, this is the first situation where an independent, spectroscopic measurement of the magnetic field strength of a pulsar has been possible, validating the use of the dipole spindown formula.

The surface temperature is also well constrained, as can be seen in the tight confidence limits in Figure 2. The time arrow shows the monotonic decline of the temperature during the sequence of the seven XMM observations. The decay of the source flux during the same time interval can be explained entirely by the cooling of the neutron star crust, as described by the single temperature parameter, without significant changes to the emitting area on the neutron star surface. The radius of this hot region remains approximately 2.7 km, likely corresponding to the area that is heated during the outburst. The scattering optical depth τ and the velocity distribution β of electrons in the magnetosphere also remain fairly constant, around values $\tau \approx 3$ and $\beta \approx 0.24$, despite the changes in the hardness of the spectra as the source cools. Indeed, the spectral changes are best described by a change in the temperature alone, without accompanying changes to any other parameter describing the neutron star surface or its magnetosphere.

This physical model allows us to track the changes in the AXP during its decline from its outburst and probe the mechanism that produces the transient behavior. Suggested ideas for the observed flares and outbursts for the AXPs and SGRs rely either on the injection of heat deep in the crust or a sudden change in the topology of the field lines in the magnetosphere. Our analysis, which disentangles the contributions of the processes in the magnetosphere from those on the stellar surface, shows that it is the release of heat in the crust, and not changes in the magnetosphere, that is responsible for the AXP outburst.

We can identify the depth in the crust where the heat is released to produce the outburst of XTE J1810−197 by considering the energetics of the outburst and the measured evolution of the temperature. Assuming that the heat is deposited over a surface area S at a depth h, where the particle density and temperature are given by $N_{\rm d}$ and $T_{\rm d}$, respectively, we can calculate the total fluence of the outburst E as $E \approx L\Delta t \approx 3N_{\rm d}k_{\rm B}\Delta T_{\rm d}Sh$. Here, $\Delta T_{\rm d}$ is the resulting increase in the temperature in the deep layer, which is related to the change in the effective temperature by $\Delta T_{\rm d}/T_{\rm d} \approx \Delta T_{\rm eff}/T_{\rm eff}$ by the Eddington-Barbier relation. We estimate a total energy of 10^{42} erg for the outburst using the typical luminosity $L \simeq 3 \times 10^{34}$ (assuming a distance of 3.3 kpc) and a timescale of $\Delta t \simeq 1$ yr.

Finally, we calculate the particle density at a given depth using the detailed surface model of the neutron star used in fitting the spectral data. Requiring that, during the outburst, $\Delta T_{\rm eff}/T_{\rm eff}$ is larger than 0.4 keV/0.1 keV, as inferred from the temperature evolution, we find that the energy release occurred at a depth of $\simeq$ 270 cm, which corresponds to a column depth of 2×10^{11}g cm^{-2}. This shows that the currents carrying the magnetic field must be decaying in the upper crust. For the transient AXP, the lack of subsequent energy release at such depths allows the crust to cool completely, and fade out of the observable window.

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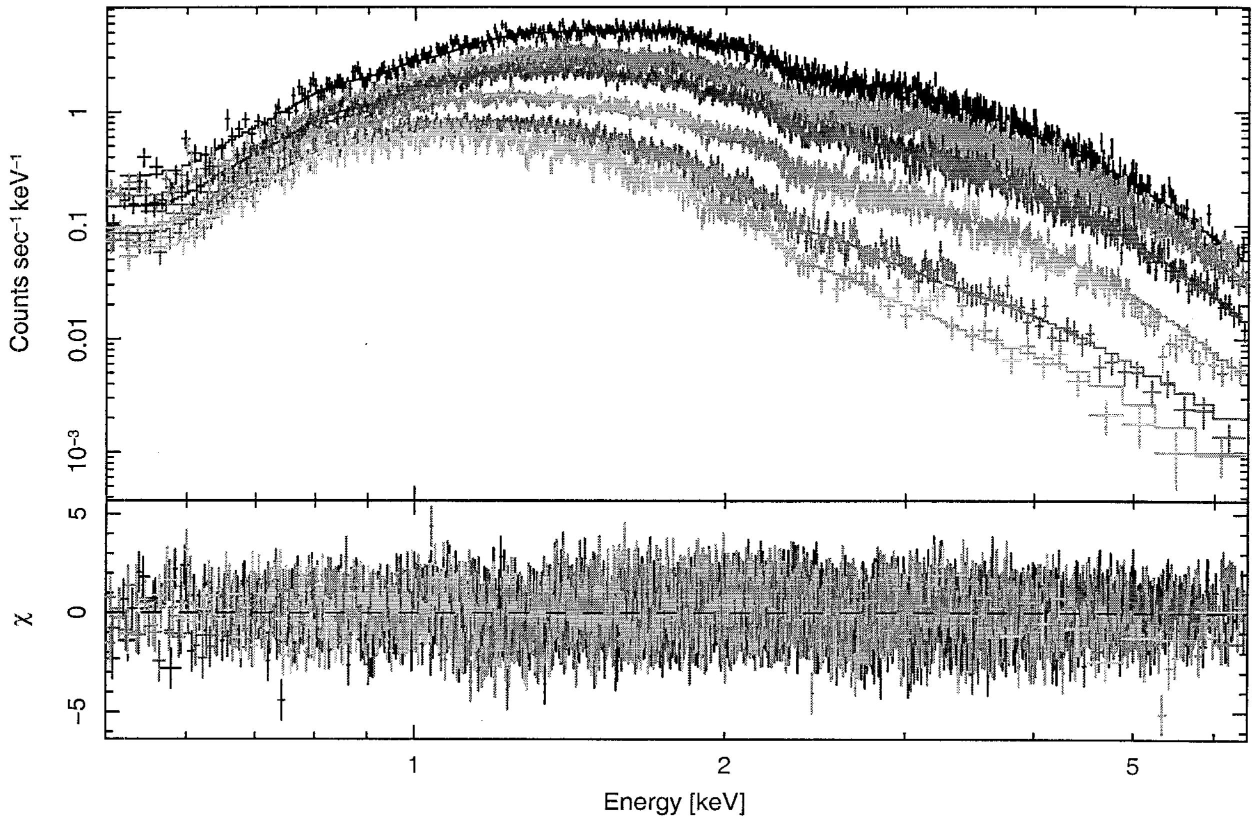

Figure 1. Comparison of theoretical magnetar spectra to XMM-Newton observations of XTE J1810−197 obtained over three years while the source was declining from its 2003 outburst. Different colors correspond to the seven different epochs of observations. Solid lines show the best-fit theoretical models that incorporate emission from the magnetar surface and its reprocessing in the magnetosphere. The lower panel shows the residuals of the fits demonstrating the ability of the model to account in detail for the observed spectra. The theoretical spectra depend only on the strength of the surface magnetic field, the surface temperature of the magnetar, and the density and velocity of the electrons in the magnetosphere. The χ^2/d.o.f. for the spectral fits, in order of decreasing source flux are 1.07/732, 0.95/548, 1.11/820, 1.10/772, 1.21/653, 1.09/424, 1.10/303.

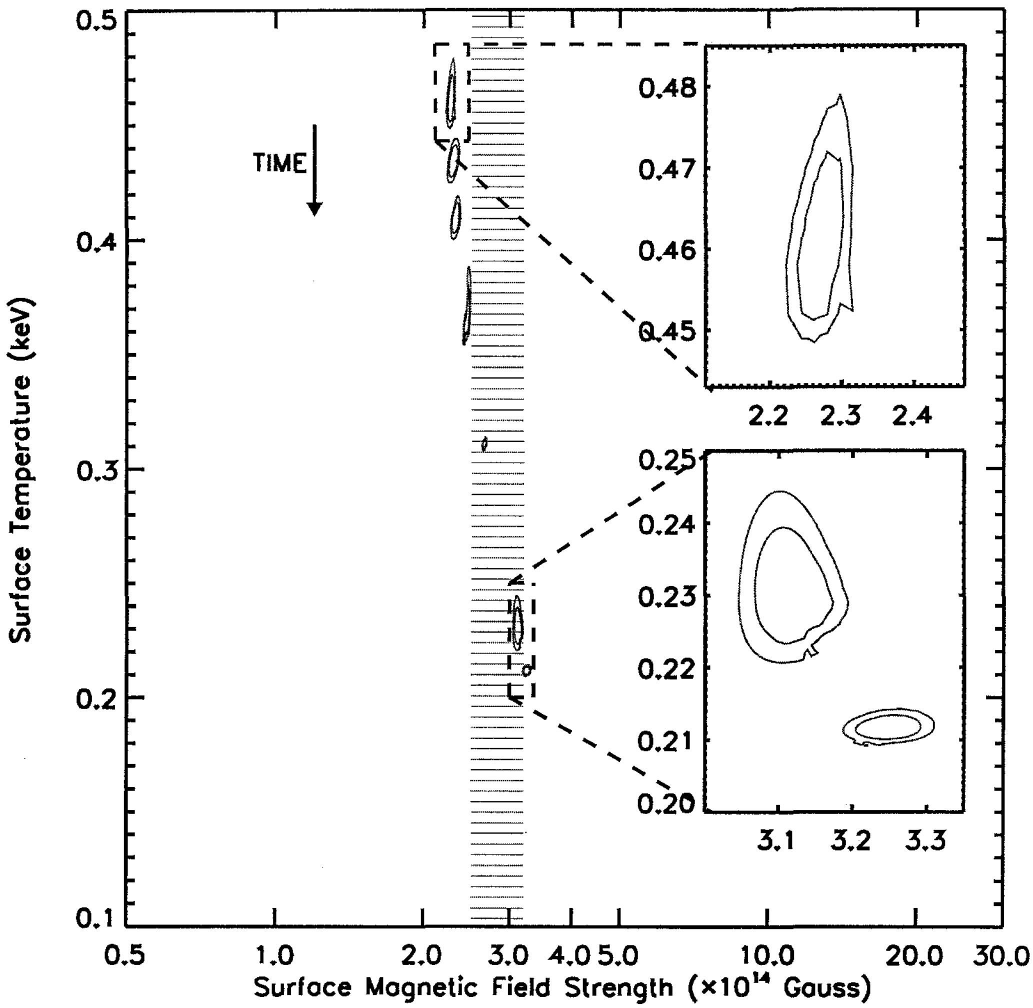

Figure 2. The spectroscopically measured surface magnetic field strength and temperature during the decline of the 2003 outburst of XTE J1810−197. The contours show the one- and two-sigma confidence limits on the parameters obtained from the individual observations. The hatch-filled area shows the magnetic field inferred from the observed rate of spindown, assuming magnetic dipole braking. The spectroscopically determined field strength is remarkably close to the value inferred from the dipole spindown formula. The monotonic and rapid decline of the measured effective temperature is the only significant change in the source properties during the outburst.