Evidence for Heating of Neutron Stars by Magnetic Field Decay

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(Dated: June 12, 2018)

We show the existence of a strong trend between neutron star (NS) surface temperature and the dipolar component of the magnetic field extending through three orders of magnitude, a range that includes magnetars, radio-quiet isolated neutron stars, and many ordinary radio pulsars. We suggest that this trend can be explained by the decay of currents in the crust over a time scale of $\sim 10^5$ yr. We estimate the minimum temperature that a NS with a given magnetic field can reach in this interpretation.

A question of fundamental importance in subatomic physics concerns the ground state and emissivity of dense matter in beta equilibrium. In this connection, the manner in which a neutron star (NS) cools after its birth has been an active area of research since the discovery of NSs as pulsars four decades ago. Cooling occurs through neutrino emission for the first $\sim 10^5$ yr of its life, and later by surface thermal emission (see, e.g., [1] for a review). As the star loses its residual heat, any internal heat sources would affect, and possibly control, the star’s thermal evolution. One important heat source could be decay of the star’s magnetic field if it occurs over a sufficiently rapid time scale. The field could decay directly as a consequence of Hall drift that produces a cascade of the field to high wave number components that decay rapidly through Ohmic decay [2, 3]. The possibility of field decay has motivated extensive work to assess how the thermal evolution would be affected (see, e.g., [4, 5] and references therein). Ohmic decay is expected to proceed most rapidly in the crust, where the conductivity is determined primarily by electrons colliding with phonons and impurities [6]. With considerable uncertainties in conductivities and transport coefficients, clear conclusions as to the effects of Ohmic decay have not been reached, though it appears likely that it could play some role in the thermal evolution of NSs. Magnetic field evolution is, however, expected to play a key role in the evolution of magnetars, NSs with fields $\gtrsim 10^{14}$ G. Magnetars are remarkable in the sense that their magnetic energy exceeds their rotational energy, in contrast to the lower-field rotation-powered pulsars. In magnetars, dissipative field evolution is expected to occur, and the magnetic energy available is so great that substantial energy can be dissipated, contributing to the star’s heat budget.

In this Letter, we present observational evidence for a strong correlation between stellar magnetic field and surface temperature. We suggest that this trend can be simply explained by energy dissipation from field decay in the crust over a time scale of $\sim 10^5$ yr. We argue that NSs with fields $\gtrsim 10^{13}$ G begin to have their thermal evolution controlled by field decay about when they enter the photon cooling era at $\sim 10^5$ yr, and that magnetars, which have more magnetic energy available, are dominated by field decay even earlier. Our conclusions are essentially independent of the uncertainties concerning stellar structure and the state of matter above nuclear saturation.

To evaluate the extent to which the magnetic field of a star determines its temperature, we show in Fig. 1 the effective surface temperature $T_{\text{eff}}$ vs. the dipole component of the magnetic field $B_d$ estimated for 27 NSs (Tab. 1). We note a striking trend of $T_{\text{eff}}$ with $B_d$ well approximated by $T_{\text{eff}} \propto B_d^{1/2}$. This trend holds over three orders of magnitude in $B_d$, encompassing much of the observed range of magnetic fields. Fig. 1 suggests that the thermal evolution of NSs with $B \gtrsim 10^{13}$ is largely determined by the strength of the magnetic field.

The spectra of some stars are well-described by a simple blackbody (BB) associated with thermal surface emission. In many stars, however, the spectrum comprises both a magnetospheric component and one or two BB components. Two-component BB spectra are indicative of temperature anisotropy over the stellar surface, presumably smooth, but modeled as being relatively cold with small hot spots around the magnetic poles. For pure BB stars, we took $T_{\text{eff}}$ to be the measured temperature of an unknown area $A_{\text{eff}}$ of the stellar surface. For stars with spectra that include two BB components, we used the temperature of the component which dominates the spectrum obtained from the references cited in Tab. 1. Some reported temperatures are not BB temperatures, but were obtained with specific atmospheric models (mainly H atmospheres); atmospheric compositional uncertainties introduce an uncertainty of a factor of $\sim 2$ in $T_{\text{eff}}$, which is unimportant for our purposes. Fig. 1 contains a point for every star from which thermal emission has been observed with reasonable confidence. These include: ordinary radio pulsars; isolated NSs which show no radio emission but thermal X-ray emission, and magnetars.

We consider it highly unlikely that the observed distribution of $T_{\text{eff}}$ along a narrow diagonal band is a selection effect. If there were no relationship between $T_{\text{eff}}$ and $B_d$, we would expect to see many examples of stars in the
from the spin-down luminosity required to power its H band between 0.03-0.2 keV with low fields (\(\sim\) \(10^{12}\) G), where \(P\) is the spin period and \(\dot{P}\) is its time derivative. Except for RX J1856.4–3754 (see footnote), \(B_d\) was estimated assuming observed x-ray absorption features are proton cyclotron lines. Ages are spin-down ages \((P/2\dot{P})\) except for RX J1856.4–3754.

### TABLE I: Properties of NSs with reported thermal emission.

| Source   | \(kT\) (keV) | \(B_d\) (B\(_d\)) | Age (kyr) | Ref. |
|----------|-------------|------------------|-----------|------|
| Magnetars |             |                  |           |      |
| SGR 0526-66 | 0.53        | 74               | 1.9       | [8]  |
| SGR 1000+14 | 0.43        | 57               | 1.3       | [8]  |
| CXOU J0100-7211 | 0.38   | 39               | 6.8       | [9]  |
| 4U0142+61 | 0.46        | 13               | 70        | [8]  |
| 1E 1048.1-5937 | 0.63   | 39               | 1-8       | [8]  |
| 1RXS J1708-4009 | 0.44  | 47               | 9.0       | [8]  |
| XTE J1810-197 | 0.67     | 29               | 5.7       | [8]  |
| 1E 1841-045 | 0.44        | 71               | 4.5       | [8]  |
| 1E 2259+586 | 0.41        | 6                | 220       | [8]  |

\(P > 3\) s

| Source   | \(kT\) (keV) | \(B_d\) (B\(_d\)) | Age (kyr) | Ref. |
|----------|-------------|------------------|-----------|------|
| RX J0420.0–5022 | 0.044    | < 18 (6.6)  |           | [10] |
| RX J0720.4–3125 | 0.090    | 2.4 (5.6)   | 1900      | [10] |
| RX J0806.4–4123 | 0.096    | < 14 (6.1)  |           | [10] |
| RBS1223 | 0.086      | 3.4 (4.6)    | 1461      | [10] |
| RX J1605.3+3249 | 0.096    | (8.0)        |           | [10] |
| RX J1856.4–3754 | 0.062    | (1) \(^*\)  | (500)     | [10, 11] |
| RBS1774 | 0.102      | < 24 (15)    |           | [10] |
| CXOU J1819-1458 | 0.120    | 5.0          | 117       | [12] |
| PSR J1718-3718 | 0.145    | 7.4          | 34        | [13] |
| PSR B2233+61 | 0.056    | 1.0          | 41        | [14] |

\(P < 0.5\) s

| Source   | \(kT\) (keV) | \(B_d\) (B\(_d\)) | Age (kyr) | Ref. |
|----------|-------------|------------------|-----------|------|
| Geminga  | 0.03-0.04   | 0.16             | 340       | [15, 16] |
| PSR B1055-52 | \(\approx\) 0.06 | 0.11           | 530       | [16] |
| PSR B0656+14 | 0.059-0.12 | 0.467           | 110       | [16] |
| PSR J1119-6127 | 0.207   | 4.1            | 1.6       | [17] |
| Vela     | 0.056-0.061 | 0.34           | 11        | [18] |
| PSR B1706-44 | 0.04-0.07 | 0.3            | 17        | [19] |
| PSR J0205+6449 | < 0.094 | 0.36          | 5         | [20] |
| Crab     | < 0.17     | 0.38           | 1.2       | [21] |

\(^*\)In the case of RX J1856.4–3754 the magnetic field was estimated from the spin-down luminosity required to power its \(H_\alpha\) emission nebula [13].

true that very high-field stars are rare and therefore more distant on average, giving a preference to seeing objects with high \(T_{\text{eff}}\), continuing surveys of higher sensitivity have failed to reveal sources cooler than shown in Fig. 1 above \(10^{13}\) G after years of observation. Taken together, these facts strongly suggest that the trend we are seeing is real, though population simulations might be able to provide a definite answer. The natural interpretation of this diagram is that stars with fields of \(\sim 10^{12}\) G cool much more rapidly than stars with fields of \(\sim 10^{13}\) G and higher. It is generally believed that magnetars are kept hot by decay of their strong magnetic fields. We propose that the same is happening in NSs with fields down to \(\sim 10^{13}\) G.

Aside from the interpretation of bursts in magnetars as representing large-scale field evolution and decay, there is no convincing observational evidence for magnetic field decay in the NS population as a whole. Statistical studies of the entire NS population have generally found that continuous exponential decay of the dipole component of NS magnetic fields, if it occurs, cannot happen over time scales shorter than \(\sim 10^8\) yr (e.g., [24], but see [25]). We suggest that the general trend of Fig. 1 can be explained by the decay of crust currents in stars with \(B_d \gtrsim 10^{13}\); these stars constitute only \(\sim 5\%\) of the stellar population, so there is no obvious conflict with the conclusions cited above against field decay in the stellar population as a whole. Moreover, we do not claim that \(B_d\) decays

FIG. 1: \(T_{\text{eff}}\) vs. \(B_d\) of isolated NSs. Represented with different symbols are SGRs (stars), AXPs (diamonds), slowly-rotating \((P > 3\) s) NSs (squares) and rapidly-rotating \((P < 0.5\) s) NSs (triangles). Red symbols correspond to young \((< 10^4\) yr) NSs. Symbols with arrows indicate upper limits. The blue squares are isolated NSs for which the magnetic field was estimated from the association of a spectral feature with a proton cyclotron resonance. We show how two of these (RX J0720.4–3125 and RBS1223) move to the left if their fields inferred from cyclotron lines are replaced by \(B_d\). The solid line is the is an illustration of heating balanced by cooling, for \(b = 100\) (see eq. 3).
indefinitely, the hypothesis those studies considered. If heating by decay of crust currents is relevant in the more strongly-magnetized stars, a NS of some initial magnetic field will initially cool through neutrino emission, but eventually crustal field decay will dissipate enough energy to contribute significantly to the star’s photon emission. When this happens depends on the strength of the initial field; the stronger the field, the earlier its decay begins to control the surface emission. Eventually, dissipation of the field will nearly balance loss to surface thermal emission, and the thermal evolution will be subsequently determined by this balance. For illustration, we suppose that the hot spot of area $A$ and temperature $T_{\text{eff}}$ is kept hot by the dissipation of magnetic energy in a volume $A \Delta R$ directly below it, where $\Delta R \simeq 1$ km is the crust thickness. The near balance between heating and cooling is expressed by

$$- A \Delta R \frac{dE_m}{dt} = A \sigma T_{\text{eff}}^4,$$

where $E_m = B^2/8\pi$ is the magnetic energy density in the crust, $B$ is the field strength there and $\sigma$ is the Stefan-Boltzmann constant. The unknown $A_{\text{eff}}$ does not determine equilibrium in this simple model. We expect that the basic energy scale of the magnetic energy available in the crust for dissipation is set by the dipole field, and we parameterize the crust field strength as $B^2 = b B_d^2$; $b$ is the ratio of magnetic energy density due to currents in the crust to the dipole energy density. The crust field, which presumably includes multipole and toroidal contributions, is not directly observable, but modeling of the thermal spectra of strongly magnetized NSs that show only thermal emission indicate $b \approx 100$. These objects show a time-dependent flux, due to spin modulation of emission from a hot spot, and an optical excess interpreted as the tail of a much softer thermal emission. This interpretation of the X-ray and optical data implies the existence of a large degree of anisotropy in the surface temperature, due to a magnetic field in the crust that is large compared to $B_d$ and has significant toroidal components.

In heating-cooling equilibrium, the cooling history of the star will be simply coupled to the decay of the magnetic field. Different processes, such as Ohmic decay and Hall drift, can contribute to field decay in crust. For purposes of illustration, we assume simple exponential decay of the magnetic field over a time scale $\tau_D$,

$$\frac{dB}{dt} = - \frac{B}{\tau_D},$$

which is equivalent to assuming that the magnetic energy density $E_m$ decays at a rate proportional to $E_m$. Combining eqs. [1] and [2]:

$$\Delta R b B_d^2 = 4\pi \tau_D \sigma T_{\text{eff}}^4.$$  

This simple model accounts for the trend $T_{\text{eff}} \propto B_d^{1/2}$ shown in Fig. 1; it gives a heating balance line (HBL), along which older NSs should cluster. The location of the HBL on Fig. 1 is determined by the product $\tau_D^{-1} b$. Each star will have it’s own HBL to the extent that $b$ varies among different stars. In Fig. 1 we show an example of one possible HBL that approximately follows the data, corresponding to $\tau_D \simeq 5 \times 10^8$ yr. For $b = 100$ for example, we estimate $\tau_D \simeq 10^8$ yr as the characteristic decay time. This time scale is comparable to the Ohmic decay time estimated for an impure crust.

We now discuss how a NS reaches its HBL in this picture. A NS will begin its life high on Fig. 1 with some $B_d$. As it cools it moves vertically downward, until decay of its field causes the trajectory to bend to the left. The star eventually reaches its HBL, and then continues moving down it. This model predicts that no object will be found below its HBL. Well above the line, we should see only young hot NSs following their respective cooling trajectories which are not yet affected by heating from field decay. Cooling simulations without heating predict that the principal energy loss changes from neutrinos to surface photon emission at an age of $\sim 10^7$ yr, independent of the birth temperature (e.g., [1]). Most stars will not reach their HBLs until about this age, though very high-field objects can reach their HBLs earlier as they have more magnetic energy to dissipate. We have therefore plotted with red symbols those objects with ages under $10^4$ yr for reference. It is remarkable that slowly rotating NSs as well as most magnetars all fall close to the representative HBL. Rapidly rotating NSs (such as PSR B1055) were probably born with initially lower fields which implies a less efficient spin down. They are still moving vertically in this diagram because, due to their weaker field, heating from field decay is only relevant at later times. According to this picture, some old NSs could be former magnetars, whose magnetic fields have decayed by a factor of $\sim 10$. This evolutionary path was proposed for RX J0720.4–3125 [29], but we suggest that it is more general and applies to many other objects.

In our simple energy balance argument, we ignored the fact that some of the dissipated energy will flow into the core and be lost to neutrino emission. Kaminker et al. [30], for example, find that continuous heat deposition in 1-d simulations without a magnetic field is largely lost to neutrinos if the energy is deposited at densities above neutron drip (the beginning of the inner crust). The strong crustal fields we are proposing, however, will greatly suppress heat transport into the core, while allowing efficient transport along the field lines, which go almost directly to the surface. This effect will be investigated further in future work.

Some of the stars do fall slightly below our representative HBL, but this is not surprising since $b$ should vary among stars and we show here only one example. There are also uncertainties in $T_{\text{eff}}$ and $B_d$. Some of the ob-
jects in Fig. 1, the blue squares, have magnetic fields determined under the (not generally accepted) assumption that the absorption lines in their spectra are proton cyclotron lines, which should give estimates of the field larger than the dipolar component. For two cases in which $B_d$ is also known from $P\dot{P}$ (RX J0720.4–3125 and RBS1223), use of $B_d$ brings these objects onto our example HBL (see Fig. 1). We also note that two magnetars, 1E 2259+586 and 4U 0142+61, while following the general trend of Fig. 1, lie above our representative HBL. These objects show frequent burst activity and complex evolution of their light curves. If these objects are releasing magnetic energy episodically there would be additional heating occurring, increasing $T_{\text{eff}}$ above what we would expect in our scenario of gradual field decay.

We have argued that the strong dependence of $T_{\text{eff}}$ on $B_d$ for stars with $B \gtrsim 10^{13}$ G (Fig. 1) indicates that the thermal evolution is almost completely controlled by the amount of magnetic energy the star has stored in its crust by the time the star has reached an age of $\sim 10^8$ yr (earlier, for magnetars). This conclusion is insensitive to uncertainties about the state of the stellar core, its structure and the rates of neutrino processes that take place there. The specific heat and thermal conductivity through the star are also unimportant, provided that field decay does occur, and that the energy liberated emerges primarily at the stellar surface. The data are consistent with the decay of crustal fields about an order of magnitude stronger than the dipole component, over $\sim 10^8$ yr in all stars. It appears that the effects of strong crust fields, heat generation from their decay, and modified heat transport in the crust should all be considered towards obtaining a more complete understanding of NS cooling. The evidence for crustal field decay presented here also has implications for estimates of the ages of pulsars older than $\tau_p$; the standard spin-down age, $P/2\dot{P}$, then significantly overestimates the star’s true age.

We thank A. Cumming for interesting discussions. This work has been supported by the Spanish MEC grant AYA 2004-08067-C03-02. JAP is supported by a Ramón y Cajal contract. B. L. acknowledges support from U. S. NSF grant AST-0406832. U.G. acknowledges support from the Spanish MEC program SAB-2005-0122.

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