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THE DISCOVERY OF AN ANOMALOUS X-RAY PULSAR IN THE SUPERNOVA REMNANT Kes 73

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ABSTRACT

We report the discovery of pulsed X-ray emission from the compact source 1E 1841−045, using data obtained with the *Advanced Satellite for Cosmology and Astrophysics*. The X-ray source is located in the center of the small-diameter supernova remnant (SNR) Kes 73 and is very likely to be the compact stellar remnant of the supernova that formed Kes 73. The X-rays are pulsed with a period of ≃11.8 s and a sinusoidal modulation of roughly 30%. We interpret this modulation to be the rotation period of an embedded neutron star, and as such it would be the longest spin period for an isolated neutron star to date. This is especially remarkable since the surrounding SNR is very young, ∼2000 yr old. We suggest that the observed characteristics of this object are best understood within the framework of a neutron star with an enormous dipolar magnetic field, $B \simeq 8 \times 10^{14}$ G.

Subject headings: ISM: individual (Kesteven 73) — pulsars: individual (1E 1841−045) — stars: magnetic fields — stars: neutron — supernova remnants

1. INTRODUCTION

In 1934, Baade & Zwicky published a prophetic paper making a phenomenological connection between supernovae (SNs), the core collapse of massive stars, and the formation of neutron stars (then hypothetical)—all purely on grounds of energetics. Decades later, their conjecture was first vindicated by the discoveries of young pulsars in the Crab and Vela supernova remnants (SNRs) and now in a handful of other Galactic SNRs.

Supernova remnants come in at least two distinct morphological types, i.e., shells and plerions (Weiler & Sramek 1988), and a majority are the result of core collapse in massive progenitors (the non-Type Ia SNs; van den Bergh & Tammann 1991). The Baade-Zwicky picture, in its simplest interpretation, is somewhat problematic. A majority of SNRs appear not to contain either central pulsars or pulsar plerions (because pulsars are beamed, plerions ought to be more commonplace than pulsars in the interiors of shells). The predominant "hollowness" of shell remnants is ill understood and raises questions about the fate of most core collapses of massive stars. This conundrum is nowhere more apparent than in the studies of the youngest SNRs, especially those of the historical SNs (Strom 1994). Of the eight historical SNs that have expanded into full-blown SNRs, only the Crab Nebula has a pulsar. There is weak plerionic activity (but no beamed pulsars) in two others (SN 386 and SN 1181; see Vasisht et al. 1996). It follows, therefore, that there is a need to give up our notions about the birth properties of young neutron stars, best typified by the Crab pulsar: fast rotation ($\lesssim$0.1 s) and a dipole field strength clustered around 3×10^{12} G. That neutron stars may be born in a fashion drastically different from the Crab has become increasingly evident via recent X-ray studies. Preliminary evidence of this kind includes the discovery of radio-quiet, cooling neutron stars (Vasisht et al. 1997 and references therein; Gotthelf, Petre, & Hwang 1997) in SNRs, the association of the exotic soft gamma-ray repeaters with young (∼10^4 yr old) SNRs (see Thompson & Duncan 1996, ereafter TD96), and observations of magnetically dominated plerions (Vasisht et al. 1996). Also, the slowly spinning ($P \approx 7$ s) anomalous X-ray pulsar (AXP) in the ∼10^4 yr old SNR CTB 109 has been known for several years (Gregory & Fahlman 1980), although its nature is still widely debated (Mereghetti & Stella 1995; van Paradijs, Taam, & van den Heuvel 1995; TD96).

This Letter discusses 1E 1841−045, an unresolved *Einstein* point source discovered near the geometrical center of the shell-type SNR Kes 73 (Kriss et al. 1985). The refined *ROSAT* HRI location of the object is $\alpha_{J2000} = 18^h41^m19^s.2$ and $\delta_{J2000} = -04°56'12''.5$ (∼3″ at 90% confidence; Helfand et al. 1994). The SNR shows no evidence for an extended plerionic core from radio brightness morphology, polarization properties, or spectral index distribution. This suggests that Kes 73, in spite its inferred youth, lacks a bright radio plerion. To date, no optical counterpart to the central X-ray source has been identified for 1E 1841−045. Herein, we present the discovery of ∼12 s pulsed X-rays from 1E 1841−045 and argue that the source is young and unusual. In our companion Letter (Gotthelf & Vasisht 1997; hereafter GV97) we present the results of imaging spectroscopy of Kes 73 and the compact source.

2. OBSERVATIONS

Kes 73 was observed with the *ASCA Observatory* (Tanaka, Inoue, & Holt 1994) on 1993 October 11–12, as a performance and verification target. Data were acquired by the two gas-imaging spectrometers (GIS-2 and GIS-3) and collected with a photon time-of-arrival resolution of 488 μs in medium bit-rate mode and 64 μs in high bit-rate mode. We used data made available in the *ASCA* public archive, screened with the standard REV1 processing to exclude time intervals corresponding to high background contamination, i.e., from Earth block, bright Earth, and SAA passages. An effective exposure of ≃3.5×10^4 s was achieved with each detector, and the

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on-source measured count rates for the GIS-2 and GIS-3 instruments were 1.55 and 1.66 counts s^{-1}, respectively. Here, we concentrate on the GIS data exclusively and present data from the two solid-state imaging spectrometers (SISs) on board *ASCA* in our companion Letter (GV97), which reports on spectral and imaging results. We summarize the spectra pertinent to this Letter below.

The spectrum of 1E 1841−045 is fitted by an absorbed, soft power law of photon index $\Gamma \simeq 3.0 \pm 0.2$ ($S_\nu \propto \nu^{-\Gamma}$; 95% confidence). The foreground absorption toward Kes 73 is found to be $N_H \simeq 2 \times 10^{22}$ cm^{-2} and is consistent with the kinematic distance estimate of 7 kpc (Sanbonmatsu & Helfand 1992). The power-law spectral normalization is found to be consistent with no long-term spectral variation when compared to the count rates observed by *ROSAT* HRI, $\simeq$0.02 counts s^{-1} (Helfand et al. 1994). We deduce an unabsorbed model flux of 6.3×10^{-11} ergs cm^{-2} s^{-1} (0.5–10.0 keV), yielding a source luminosity $L_X \simeq 3.5 \times 10^{35} d_7^2$ ergs s^{-1}; the SNR distance is $7.0d_7$ kpc.

The long-term temporal variability of 1E 1841−045 has been examined by Helfand et al. (1994), who found no concrete evidence for flux changes on the 10 yr baseline between *Einstein* and *ROSAT*. We examined the *ASCA* data for aperiodic variability by selecting source photons from a 5′ radius aperture and binning them on ~96 min (*ASCA* orbital period), 10 min, and 1 min durations. The light curves obtained were χ^2 tested against a uniform model, but no evidence for significant variations on these timescales was found.

A search for coherent pulsation from the central object was made by combining the two GIS high–time-resolution data sets (t_s = 488 μs). Photons were selected from the entire SNR region of $\simeq$5′, centered on the compact object from (i) the entire energy band (0.5–10.0 keV) and (ii) the hard band (2.5–10.0 keV). The photon times of arrival were barycentered and binned with resolutions of 488 μs, 32 ms, and 0.5 s. The barycentering and binning procedures were tested on a series of data sets of the Crab pulsar and PSR 0540−69. Fourier transforms on the entire data sets were performed at each time resolution; interesting periodicities were harmonically summed and later folded at the period of interest.

A significant high-*Q* X-ray modulation (17 σ) with no overtones is seen at a period $P \simeq 11.766684$ s ($f = 0.08498571 \pm 0.00000004$ Hz; see Figs. 1 and 2). The modulation is obvious in all the above data sets and separately in both GIS on-source time series; it is not observed in off-source GIS data, which makes it unlikely to be an instrumental artifact. The period emerges with greatest significance in time series that contain emission mainly from the central source (hard band, 2.5–10.0 keV) and is not significant in the soft energy band between 0.5–2.5 keV, where the nebula is dominant. No other significant pulsations were found in up to 1 ms periods. We suggest that the central object is weakly pulsed at 11.7667 s, possibly a neutron star spin period. The pulsed luminosity is $L_X \approx 5 \times 10^{34} d_7^2$ ergs s^{-1}, and the modulation level is about 35% of the steady flux from the compact source after subtraction of the estimated contribution of the background and the SNR thermal component above 2.5 keV.

With a period in hand, we have reanalyzed the 18 ks of *ROSAT* HRI data obtained 1992 March 16–18 (Helfand et al. 1994), selecting the few ($\simeq$650) source and background photons available from the vicinity of 1E 1841−045. We performed a conditional search in a small range of periods around

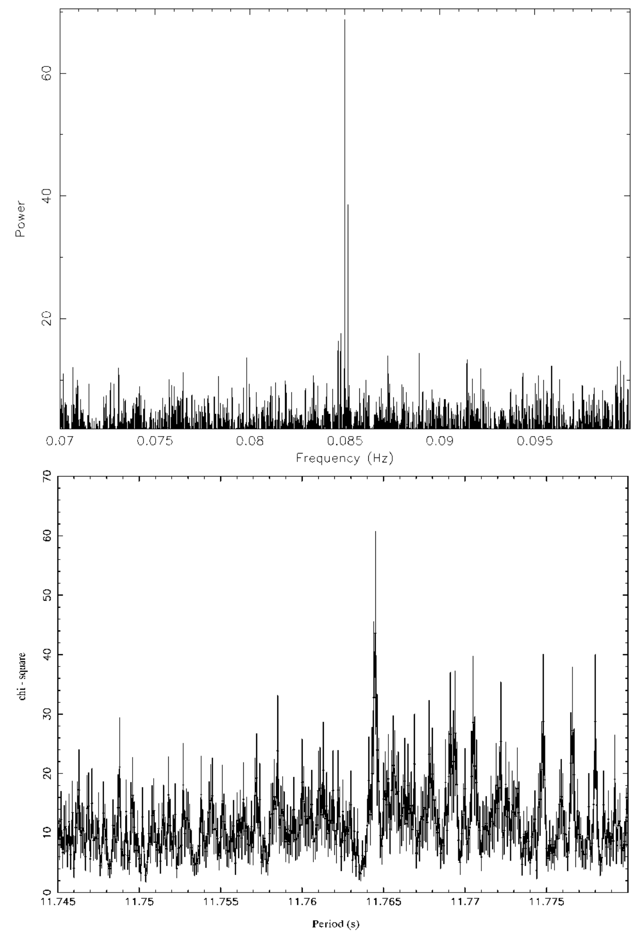

FIG. 1.—*Top*: A power spectrum of photons from both GIS cameras displayed in the range 11.75–11.78 s. Photons were selected from the hard band (2.5–10.0 keV). The main peak near 11.766684 s is the putative pulsar period. The powerful side-lobe peaks are separated from the main peak by 0.00017 Hz, the *ASCA* orbital period. *Bottom*: A periodogram of χ^2 vs. period of the HRI data, which peaks up at roughly 4 σ as is expected from the GIS profile (even though the energy range is different). The peak-up period is 11.7645 s. The total number of HRI counts for this was ~800. The search was done with 12 bins across the folding period.

11.76 s using the folding technique (12 phase bins per fold); the resulting periodogram is displayed in Figure 1 (*bottom panel*). We cautiously forward the suggestion of a peak-up at a barycentered period of 11.7645 s (4.0 σ, which is the expected significance given the HRI count rate and the *ASCA*-derived modulation); the observed FWHM of the periodogram excess of $\lesssim 10^{-3}$ s is consistent with expectations, given the period and the time span of the HRI observations. Also, the crest and trough in the HRI profile (Fig. 2, *bottom panel*) match those of the GIS profile quite well. A linear interpolation, assuming steady spin-down, gives a period derivative of $\dot{P} \simeq 4.73 \times 10^{-11}$ s^{-1}.

3. DISCUSSION

Our interpretation of 1E 1841−045 is that of a young neutron star that was born during an SN that now forms the SNR Kes 73. The kinematic distance to the SNR of 6.7–7.5 kpc is consistent with its high-foreground X-ray absorption, $N_H \simeq 2 \times 10^{22}$ cm^{-2}. The small-shell radius ($R_s \simeq 4.7d_7$ pc), along with intense radio and X-ray shell emission are characteristics of a young SNR. This notion is supported by our detection of

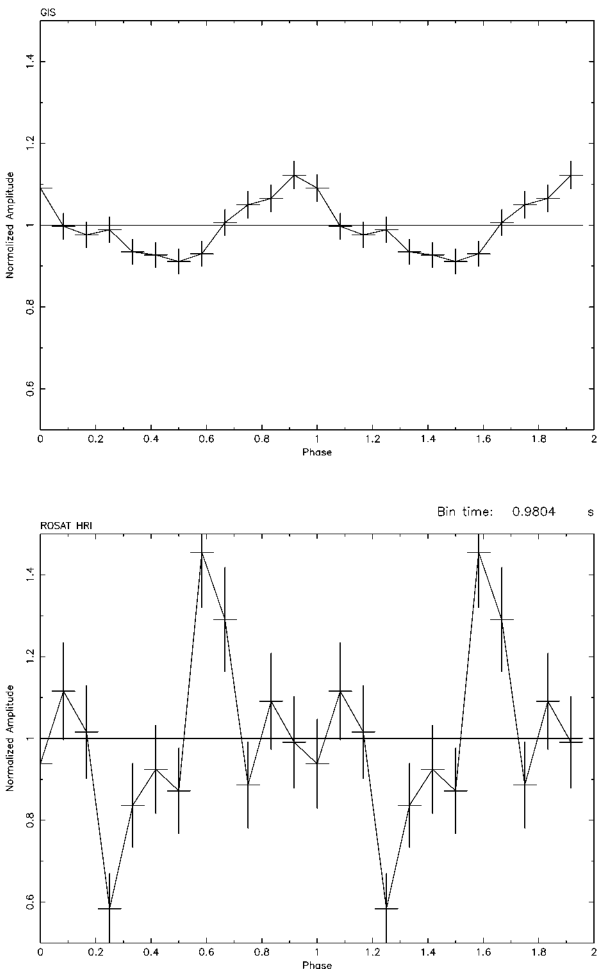

FIG. 2.—*Top*: A normalized folded profile of the GIS data (including background) with 12 bins of resolution and a folding period of 11.7667 s. The profile is roughly sinusoidal, with $\sim$35% modulation (after accounting for the background). The start epoch of folding is MJD 4.9271609362 $\times 10^4$. *Bottom*: A normalized folded profile of *ROSAT* HRI data, with 12 bins of resolution, at a folding period of 11.7645 s. The start epoch of folding is MJD 4.8697189 $\times 10^4$.

a hot thermal ($kT \simeq 0.8$ keV) X-ray continuum in the shocked gas. Helfand et al. (1994) have argued that the SNR is likely to be in transition between free expansion and the adiabatic phases, whereby the Sedov age of $\tau_S < 2500$ yr must be an upper bound. The SIS spectra show the enhancement of Mg over the species S, Si, and Fe, along with possible evidence for highly absorbed emission from O and Ne in the 0.5–0.9 keV range (see GV97). During the course of their evolution, massive stars produce large quantities of O group elements (O, Ne, and Mg), which are ejected during the SN explosion (see Hughes et al. 1994). Hence, there is spectral evidence that Kes 73 is young and still ejecta dominated. On spectral grounds we also favor a Type II or Ib origin for Kes 73, i.e., a massive progenitor. We consider it unlikely that the neutron star was born in an accretion-induced collapse of a heavy white dwarf (Lipunov & Postnov 1985).

The pulsar in 1E 1841−045 has properties in common with the peculiar X-ray pulsar, 1E 2259+586 (Gregory & Fahlman 1980; Corbet et al. 1995) and the soft gamma-ray repeaters (TD96). 1E 2259+586 is a 7 s spin rotator and coincides with a $\gtrsim 10^4$ yr old SNR (CTB 109). Much like 1E 1841−045, it has a soft X-ray spectrum best represented by a blackbody at 0.45 keV with a nonthermal tail with $S_\nu \propto \nu^{-3}$, and $L_X \simeq 0.5$–1×10^{35} ergs s^{-1}. It has a history of nearly steady spin-down and no detected binary modulation (Iwasawa, Koyama, & Halpern 1992), optical companion, or quiescent radio emission. There are four other X-ray pulsars, 4U 0142+614 (Hellier 1994; Israel, Mereghetti, & Stella 1994), 1E 1048.1−5937 (Seward, Charles, & Smale 1986), RXJ 1838−0301 (Schwentker 1994; possibly also associated with a $\gtrsim 10^4$ yr old SNR), and 1RXS J170849.0−400910 (Sugizaki et al. 1997) that have low luminosities ($L_X \sim 10^{35}$–10^{36} ergs s^{-1}), periods of order 10 s that are steadily increasing, soft spectra, and no detected companions or accretion disks. In all the above cases, spectra can be fitted with soft power laws with indices in the range 2.3–3.5 (Corbet et al. 1995). Collectively, these have been grouped into a class called breaking X-ray pulsars (Mereghetti & Stella 1995) or, alternatively, AXPs (van Paradijs et al. 1995). We observe AXPs through a substantial distance in the Galactic disk (with foreground columns densities of $\sim 10^{22}$ cm^{-2}), which suggests that they are not commonplace.

The rotational energy of 1E 1841−045 is far too small to power its total X-ray emission of $L_X \sim 4 \times 10^{35} d_7^2$. The maximum luminosity derivable just from spin-down is

$$L_X \approx 4\pi^2 I \frac{\dot{P}}{P^3} \sim \frac{1}{2\tau_s} I \left(\frac{2\pi}{P}\right)^2 \sim 10^{33} \text{ ergs s}^{-1},$$

where I is the moment of inertial of the neutron star and $\tau_s \sim 2 \times 10^3$ yr is the SNR age. The mechanisms for powering the X-rays could then be either (i) accretion from a high-mass X-ray binary (Helfand et al. 1994), a low mass companion (Mereghetti & Stella 1995), or a fossil disk (van Paradijs et al. 1995) or a merged white dwarf (Paczynski 1990) or (ii) intrinsic energy loss, such as initial cooling or the decay of magnetic fields in a magnetic neutron star (TD96).

The strongest argument for accretion as the source of energy is that the inferred accretion rate is just that required if the neutron star is close to its equilibrium spin period $P_{\rm eq}$, with a field $B \sim 10^{12}$ G, which is typical for young pulsars (see Bhattacharya & van den Heuvel 1991):

$$P_{\rm eq} \simeq 10 \text{ s} \left(\frac{B_d}{5 \times 10^{11} \text{ G}}\right)^{6/7} \left(\frac{L_X}{10^{35} \text{ ergs s}^{-1}}\right)^{-3/7} .$$

However, only a pathological evolution scenario involving accretion could bring an energetic dipole rotator to its present rotation rate within $\simeq 2 \times 10^3$ yr. The strongest support for 1E 1841−045 as an accretor will be from future identification of an infrared (large foreground $A_V \simeq 10$ mag) companion or an accretion disk. As in the case of other AXPs, an infrared counterpart may not be easily identified (Coe, Jones, & Lehto 1994, and references therein). The pulsar has properties that may already preclude accretion as a power source. (i) High-mass neutron star binaries with an NS accreting from the companion wind sometimes go into low-luminosity states with $L_X \sim 10^{35}$ ergs s^{-1} and have periods in the range 0.07–900 s. However, in general they display hard spectra ($0.8 < \Gamma < 1.5$) and strong aperiodic variability on all timescales (Nagase 1989). If the X-ray source is indeed a high-mass X-ray binary, then the inferred $\dot{P}$ could be the result of orbital Doppler effects. (ii) Neutron stars with disk accretion from a low-mass companion or a fossil disk, with the latter having formed from SN debris or a Thorne-Zytkow phase (van Paradijs et al. 1995), should display similar accretion noise in the light curve. (iii)

Other AXPs show near-steady spin-down on timescales of 10^4–10^5 yr, although this is controversial (Baykal & Swank 1996; Corbet & Mihara 1997). The long-term torque behavior of 1E 1841−045 will be evident only with future observations. (iv) Finally, accretion models would have to be stretched in order to explain the slow rotation period (inside a young SNR) and its associated spin-down timescale of $\lesssim$2500 yr. First, it is difficult for accretion torques to spin down a pulsar to 12 s in $\sim 10^3$ yr from initial periods of $P_i \lesssim 10^2$ ms unless, of course, the pulsar were born a very slow rotator, which is quite interesting in its own right. Second, if the pulsar were rotating near its equilibrium period, as in the Ghosh & Lamb (1979) scenario, the spin-down time of $P/2\dot{P} \sim 3900$ yr is inconsistent with the implied accretion rate, $\dot{M} \simeq 10^{-11}\ M_\odot\ \mathrm{yr}^{-1}$ (assuming the pulsar has a normal dipolar field of $\simeq 10^{12}$ G); these usually lie in range 10^4–10^5 yr.

A dipolar magnetic field versus period scaling can also be obtained under the assumption that the neutron star is isolated and has undergone conventional pulsar spin-down from torques provided by a relativistic wind, as in the Crab. For dipolar secular spin-down, the implied B_{dipole} is enormous,

$$P = 10\ \mathrm{s}\left(\frac{t}{3\times 10^3\ \mathrm{yr}}\right)^{1/2}\left(\frac{B_{\mathrm{dipole}}}{10^{15}\ \mathrm{G}}\right)\left(\frac{R}{15\ \mathrm{km}}\right)^{2}\left(\frac{M}{1.4\ M_\odot}\right)^{-1/2}.$$

Such highly magnetized neutron stars (with dipolar field strengths $B \approx 10^{14}$–10^{15} G), or "magnetars," have been postulated by TD96 (and references therein) to explain the action of soft gamma-ray repeaters. Magnetars have magnetic flux densities that are larger by a factor of $\gtrsim 10^2$ than the typical $B \sim 10^{12}$ G fields supported by radio or X-ray pulsars and perhaps represent a tail of B-field distribution in neutron stars. After birth, they spin down too rapidly to be easily detectable as radio pulsars, assuming that they are capable of radio pulsar action at all. The dipole energy in the star's exterior, a small fraction of the total magnetic energy, exceeds the rotational energy of the neutron star after roughly $2B_{15}^{-4}$ yr, where $B = 10^{15}B_{15}$ G. Magnetism then quickly becomes the dominant source of free energy in an isolated magnetar.

The derived spin-down age of the pulsar, $\sim$3900 yr, is consistent with SNR age (ages inferred from the estimator $P/2\dot{P}$ are larger than the true age, as they measure linear spin-down). The equivalent dipolar field is $B_{\mathrm{dipole}} \simeq 3.2\times 10^{19}\ (P\dot{P})^{1/2} \approx 8\times 10^{14}$ G. There is an intriguing possibility that the pulsar in Kes 73 was born as a magnetar $\sim 2\times 10^3$ yr ago and has since spun down to the long period of 11.7 s as a result of rapid dipole radiation losses. It could be unobservable as a radio pulsar because of period dependence of beaming (Kulkarni 1992); it is also possible the radio pulsar mechanism may operate differently or not at all above the quantum critical field, $B_{\mathrm{cr}} \simeq 4.4\times 10^{13}$ G. In a magnetar, the observed X-ray luminosity would be driven by the decay of the stellar B field via diffusive processes, which set in at an age of $\sim 10^3$–10^4 yr (TD96; we assume that diffusion of field lines through the crust by Hall drift and through the core by ambipolar diffusion occur on timescales $\tau_{\mathrm{Hall}} \simeq 5\times 10^8 B_{12}^{-1}$ yr and $\tau_{\mathrm{amb}} \simeq 3\times 10^9 B_{12}^{-2}$ yr, respectively; Goldreich & Reisenegger 1992). Magnetic field decay powers the star, on average, at a steady rate of $(1/6t_d)R^3B_{\mathrm{dipole}}^2 \sim 10^{36}$ ergs s^{-1} for the first decay time, $t_d \sim 10^3$ yr. Decay in the core is likely to keep the stellar surface hot via release of internal magnetic free energy, while crustal decay is likely to set up a steady spectrum of Alfvén waves in the magnetosphere, which can accelerate particles to produce the soft nonthermal tail observed in the pulsar spectrum (GV97). Such a neutron star may in time ($\sim 10^4$ yr) display the soft gamma-ray repeater phenomenon (TD96).

In conclusion, we reiterate that 1E 1841−045 is in our estimation a young ($\sim$2000 yr old) neutron star spinning at an anomalously slow rate of $\simeq$11.8 s, possibly with very strong torques on its rotation. The claim of rapid spin-down is based on a weak detection of periodicity in the archival *ROSAT* HRI data and urgently needs to be tested in future observations. Whatever the final consensus on 1E 1841−045, it is a most unusual and exciting object, the understanding of whose nature should make us rethink important aspects about the birth process of neutron stars as a whole.

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