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ON THE SPIN HISTORY OF THE X-RAY PULSAR IN KES 73: FURTHER EVIDENCE FOR AN ULTRAMAGNETIZED NEUTRON STAR

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ABSTRACT

In previous papers, we presented the discovery of a 12 s X-ray pulsar in the supernova remnant Kes 73, providing the first direct evidence for an ultramagnetized neutron star, a magnetar, with an equivalent dipole field of nearly 20 times the quantum critical magnetic field ($m_e^2c^3/e\hbar$). Our conclusions were based on two epochs of the measurement of the spin, along with an age estimate of the host supernova remnant. Herein, we present a spin chronology of the pulsar using additional *Ginga*, *ASCA*, *RXTE*, and *BeppoSAX* data sets spanning over a decade. The timing and spectral analyses confirm our initial results and severely limit an accretion origin for the observed flux. Over the 10 yr baseline, the pulsar is found to undergo a rapid, constant spin-down while maintaining a steady flux and an invariant pulse profile. Within the measurement uncertainties, no systematic departures from a linear spin-down are found—departures as in the case of glitches or simply stochastic fluctuations in the pulse times of arrival (e.g., red timing noise). We suggest that this pulsar is akin to the soft γ-ray repeaters; however, it is remarkably stable and has yet to display similar outbursts. Future γ-ray activity from this object is likely.

Subject headings: stars: individual (Kes 73, 1E 1841−045) — stars: neutron — supernova remnants — X-rays: stars

1. INTRODUCTION

The discovery of 12 s pulsed X-ray emission from the central compact source in Kes 73 (Vasisht & Gotthelf 1997, hereafter VG97; Gotthelf & Vasisht 1997) came somewhat as a surprise since this Einstein source (1E 1841−045) had been studied for some time (Kriss et al. 1985; Helfand, Becker, & White 1994). The pulsar was initially detected in an archived *ASCA* observation (1993) of Kes 73 (also supernova remnant G27.4+0.0) and was soon confirmed in an archived *ROSAT* data set. The measured spin-down from these detections indicated rapid braking on a timescale of $\tau_s \sim 4 \times 10^3$ yr. This is entirely consistent with the inferred age of the supernova remnant, $t_{\rm snr} \sim 2 \times 10^3$ yr, based on analysis of its X-ray spectrum (Helfand et al. 1994; see Gotthelf & Vasisht 1997 for details), given the model dependence in τ_s and measurement uncertainties in $t_{\rm snr}$. The geometric location of the pulsar, in the center of a symmetric and well-defined supernova remnant of similar age, strongly suggests that the two objects are related.

The observed characteristics of the new X-ray pulsar and its associated remnant lead us to present 1E 1841−045 as a new member of the rare class of "anomalous" X-ray pulsars (Duncan & Thomson 1995; Mereghetti & Stella 1995; van Paradijs, Taam, & van den Heuvel 1995). We further argued that 1E 1841−045 could not be an accreting neutron star (NS) based on the lack of observational evidence indicative of accretion and on evolutionary considerations. Instead, we proposed that the X-ray pulsar is powered by an ultramagnetized NS with a dipole field of $B_s \simeq 7 \times 10^{14}$ G; magnetic braking was assumed to be the predominant spin-down mechanism, with $B_s \propto (P\dot{P})^{1/2}$. Since then, such large magnetic fields have also been inferred for the soft γ-ray repeaters 1806−20 and 1900+14 (see Kouveliotou et al. 1998, 1999) via measurement of their spins and spin-down with *RXTE* and *ASCA*.

In this Letter, we present a long-term spin history of the X-ray pulsar. We reinforce our original *ASCA* and *ROSAT* data sets with new *ASCA*, *RXTE*, and *BeppoSAX* pointings and 10 yr old *Ginga* archival data sets, bringing the total number of timing observations of Kes 73 to seven. We show that the spin evolution obeys a steady linear spin-down at a rate consistent, within errors, with our original estimate, reaffirming our somewhat marginal *ROSAT* detection (VG97).

2. OBSERVATIONS

2.1. *ASCA and BeppoSAX Data Sets*

Kes 73 was reobserved with *ASCA* (Tanaka, Inoue, & Holt 1994) in 1998 March 27–28 using an observing plan identical to the original 1993 *ASCA* plan. A complete description of the observing modes can be found in VG97. Here we concentrate on the high temporal resolution data (62 μs or 48.8 ms depending on data mode) acquired with the two gas-imaging spectrometers (GIS2 and GIS3) on board *ASCA*. The data sets were edited using the standard Revision 2 screening criteria, which resulted in an effective exposure time of 39 ks per GIS sensor. Photons from the two GISs were merged, and arrival times corrected to the solar system barycenter. A log of all observations presented herein are given in Table 1.

We also acquired a 1.5 day *BeppoSAX* (Boella et al. 1997) observation of Kes 73 in 1999 March 8–9 using the three operational narrow field instruments, the low-energy concentrator spectrometer (LECS) and two medium-energy concentrator spectrometers (MECS2 and MECS3). These gas-imaging scintillation counters are similar to the GIS detectors, providing arcminute imaging over an ~40′ field of view in a broad energy bandpass of 0.1–12 keV (LECS) and 1–12 keV (MECS), with similar energy resolution; the data consist of photon arrival times tagged with 16 μs precision. All data were prescreened during the standard SAX pipeline processing to remove times of enhanced background, resulting in usable exposure times of 57.9 ks for each of the MECSs and 26.5 ks for the LECS. Here

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TABLE 1
OBSERVATION LOG FOR THE KES 73 PULSAR

Start Date (UT)	Mission	Exposure (ks)	Epoch[a] (MJD)	Period (s)	Uncertainty[b] (μs)
1987 May 08 (06:28)	*Ginga*	37.6	46924.5142361	11.758320	7
1991 Apr 24 (17:27)	*Ginga*	11.6	48371.2447166	11.76346	23
1992 Mar 16 (04:30)	*ROSAT*	25.1	48698.1946593	11.7645	...
1993 Oct 11 (14:56)	*ASCA*	39.6	49272.0820309	11.76676	45
1996 Aug 31 (14:21)	*RXTE*	5.9	50326.6953400	11.7707	375
1998 Mar 27 (22:30)	*ASCA*	38.7	50900.4509668	11.77248	50
1999 Apr 08 (03:41)	*BeppoSAX*	57.8	51276.8889120	11.77387	34

[a] Epochs are given for the midobservation, with time in MJD.
[b] Period uncertainties quoted as 1 σ (see text for method).

we concentrate exclusively on photons obtained with the two MECS detectors, which make up the bulk of the data. Data from the two MECS were merged and barycentered by the SAX team.

For all data sets, we extracted barycenter-corrected arrival times from a $\simeq 4'$ radius aperture centered on the central object in Kes 73, and we restricted the energy range to 2–10 keV. We then searched these time series for coherent pulsation by folding the data about the expected periods derived from the ephemeris of VG97. In each case, highly significant power is detected in the resulting periodograms, corresponding to the central pulsar's pulse period at the specific epoch. Figure 1 compares periodograms of the *ASCA* data of 1993 and 1998 produced in the manner described above. We plot these on the same scale to emphasize both the significance of the detection and the unambiguous change in period between the two epochs.

2.2. *Ginga and RXTE Data Sets*

With a period detection in hand, we reanalyzed archival data from the *Ginga* (Makino 1987) and *RXTE* (Bradt, Rothschild, & Swank 1993) missions. The main instrument on board *Ginga* is the nonimaging large-area counter (LAC) that covers an energy range of 1–37 keV with an effective area of 4000 cm^2 over its $\sim 1° \times 2°$ field of view (FWHM). *Ginga* observed

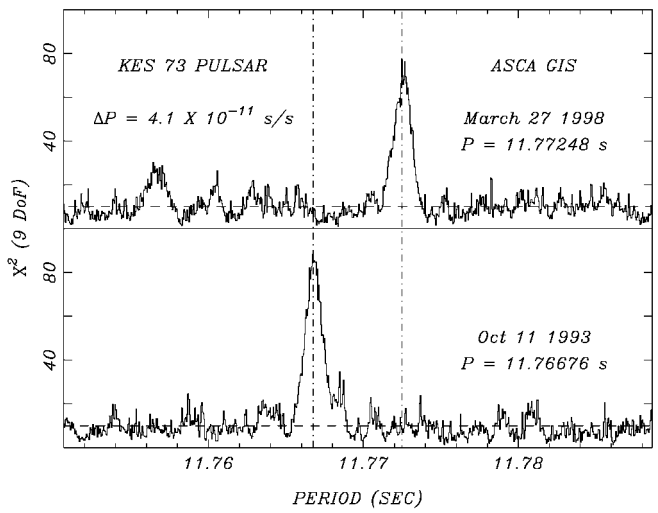

FIG. 1.—The *ASCA* detections of the Kes 73 pulsar at two epochs. These periodograms depict the χ^2 of the light curve folded into 10 phase bins and tested against a null-hypothesis as a function of trial fold periods. *Bottom*: Discovery detection of 1993 October 11. *Top*: Follow-up 1998 March 27 observation. The change in period is highly significant and clearly resolvable; the period derivative, assuming a linear trend, is $\simeq 4.1 \times 10^{-11}$ s s^{-1}. The dashed horizontal lines represent the expected 1 σ noise levels.

Kes 73 twice in data modes with sufficient temporal resolution (2 ms or 16 ms depending on the telemetry rate) and exposure to carry out the present analysis (see Table 1). These data were screened using the following criteria: (1) an Earth-limb elevation angle of greater than 5°, (2) a cutoff rigidity of greater than greater than 8 GeV/c, and (3) South Atlantic Anomaly avoidance. The LAC light curves were collected in the fixed $\sim$1–17 keV energy band and corrected to the solar heliocenter using the available software.[4]

Kes 73 was observed for 5 ks by *RXTE* during 1996 as part of the Guest Observer program. We analyzed archive data acquired with the proportional counter array (PCA) in "good xenon" data mode at 0.9 μs time resolution. The PCA instrument is similar to the LAC, with a smaller field of view ($\sim 1° \times 1°$ FWHM) and a greater effective area of 6500 cm^2. The two *RXTE* observation windows were scheduled so that no additional time filtering was required. After processing and barycentering the good xenon data according to standard methods, we selected events from layer 1 only and applied an energy cut of $\lesssim$10 keV.

As found with the imaging data, epoch folding around the anticipated period produced a highly significant period detection. These periods are consistent with the extrapolated *ASCA*-derived ephemeris. In Figure 2, we display pulse profiles of Kes 73 at two epochs separated by over a decade in order to look for possible long-term changes. To improve the signal-to-noise ratio in the latter observation, we have co-added phased-aligned profiles from the 1998 *ASCA* and the 1999 *BeppoSAX* observations. No significant differences were found between the two pulse profiles, which are identical to the 1993 *ASCA* and 1996 *RXTE* profiles, to within statistical uncertainties.

2.3. *Timing Characteristics of 1E 1841−045*

In order to accurately determine the detected period, each light curve (binned at 1 s resolution) was zero-padded to 2^{20} samples and Fourier transformed. The best period was then determined from a fit to the centroid of the peak signal. There is some evidence for a peak in the fast Fourier transform corresponding to the second harmonic, which is consistent with the roughly double-humped shape of the pulsar's profile.

To estimate the uncertainty in the period measurements, we carried out extensive Monte Carlo simulations. For each data set, we generated a set of simulated time series whose periodicity, total count rate, noise properties, and observation gap are consistent with the actual data. We used the normalized profile folded into 10 bins, to compute the probability of a photon arriving in a given phase bin. Each realization of the

[4] The barycentric correction to these periods is small and has been added in, along with the statistical error in the periods.

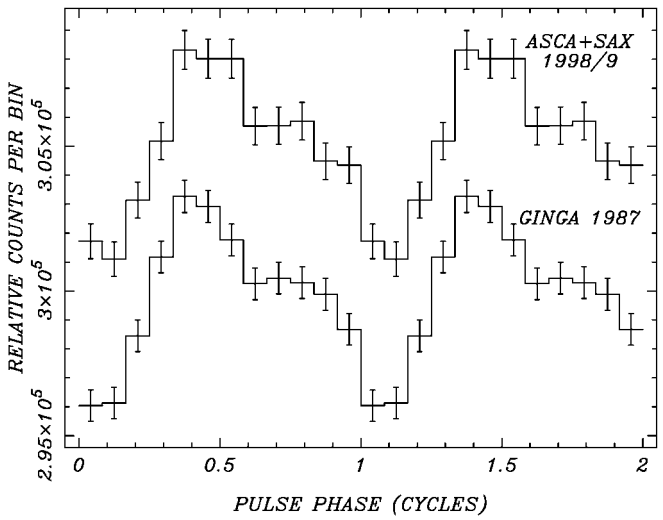

FIG. 2.—The pulse profiles of the Kes 73 pulsar at two epochs aligned in phase: the 1987 *Ginga* data (*bottom*) and the 1998 *ASCA* and 1999 *BeppoSAX* data (*top*) phased and co-added to give an increased signal-to-noise ratio. An invariant, Bactrian camel–like profile is observed in both cases. Two cycles are shown for clarity.

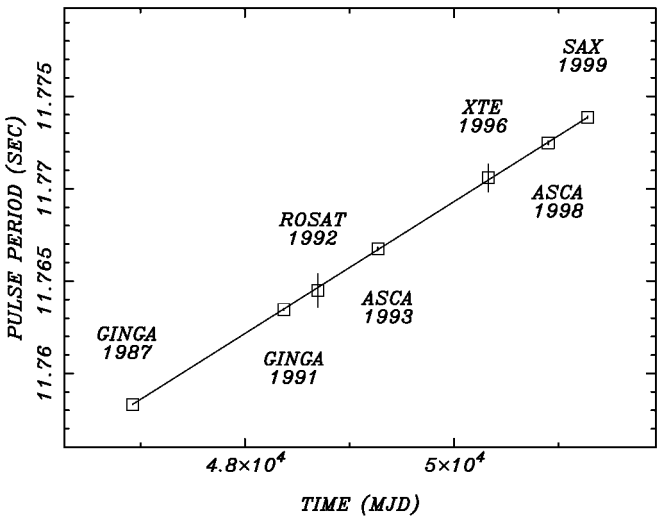

FIG. 3.—The long-term spin-down history of the Kes 73 pulsar. The square markers denote the spin period vs. epoch; the solid line follows the best-fit linear model (model parameters in § 2). The data points are depicted with 1 σ error bars that are smaller than the model line for most points (see Table 1).

simulated data was subjected to the same analysis as the actual data sets in order to obtain a period measurement. After 500 trials, we accumulated a range of measured periods that was well represented by a normal distribution. The resulting standard deviation of this function, after normalization, is taken as the 1 σ uncertainty in the period and is presented in Table 1. The errors in the period are roughly consistent with the size of a period element divided by the signal-to-noise ratio of each detection.

The period measurements and their uncertainties were then fitted with simple linear and quadratic models in order to evaluate the spin-down characteristics. The parameters were P_s, $\dot{P}_s$, and the addition of the second derivative $\ddot{P}_s$ for the second-order fit, with the spin history written as a Taylor expansion. The best fit to the linear model (shown in Fig. 3) gives the following period ephemeris (epoch MJD 49,000): $P = 11.765732 \pm 0.000024$ s; $\dot{P} = 4.133 \times 10^{-11} \pm 1.4 \times 10^{-13}$ s s^{-1}.

The linear spin-down model was consistent with the data with fit residuals at the 10^{-4} s level. We found that these residual were not sensitive to a second derivative of the period. An upper limit on $\ddot{P}_s$, allowed by the available data sets and their associated errors, is more than an order of magnitude larger than expected from classic vacuum dipole spin-down energy losses alone; for a vacuum dipole rotator, one expects $\ddot{P}_s \simeq (2 - n)\dot{P}_s^2/P_s$, where $n = 3$ is the braking index in the vacuum dipole formalism.

3. DISCUSSION

In its observed characteristics, 1E 1841−045 most resembles the anomalous X-ray pulsars (AXPs), with its slow, ~10 s pulse period, steep X-ray spectral signature, inferred luminosity of $\sim 4 \times 10^{35}$ ergs s^{-1} cm^{-2}, and lack of counterpart at any wavelength. It is, however, unique among these objects in its apparent temporal and spectral stability. The two AXPs for which sufficient monitoring data are available, 2259+586 and 1E 1048−59, show large excursions in flux ($\gtrsim$3) and significant irregularities in their spin-down [$\log(|\delta P/P|) \sim -4$]. Compared with these objects, the spin-down of 1E 1841−045 suggests a lower level of torque fluctuations; the magnitude of timing irregularities, given by the timing residuals after subtracting the linear model, is $\log(|\sigma/P|) < -5$, where $\sigma \sim 10^{-4}$ s is the typical size of the measurement error (Table 1). The spin-down of this object is apparently quieter than that observed in some middle-aged pulsars, which have red noise fluctuations in the pulse times of arrival on the order of −3 to −4 (e.g., Arzoumanian et al. 1994).

There is mounting evidence that, as a class, AXPs are related to the soft γ-ray repeaters (SGRs), given their similar X-ray spectral and timing properties; indeed, prior to the discovery of 1E 1841−045, Thomson & Duncan (1996) had already considered an earlier set of four designated AXPs in the context of their magnetar theory of SGRs. However, these AXPs show systematic long-term departures from linear spin-down, which, along with their advanced ages (~10^5 yr; therefore, except for 1E 2259+586, no host supernova remnants), has always kept the debate on the accretion from a fossil disk or a binary companion alive. For 1E 1841−045, the timing measurements, along with the consistency in age with its supernova remnant, imply an isolated ultramagnetized NS with a magnetic field strength of a magnitude predicted (and eventually implied) for the SGRs themselves (e.g., Duncan & Thomson 1992). Curiously, no bursting activity is observed from 1E 1841−045, as would be expected for an ultramagnetized NS; nor is such activity reflected in its spin history as systematic departures from linearity as in the case of glitches, which might be accompanied by bursting activity. Note that the glitch observed from SGR 1900+14 resulted in a period change an order of magnitude larger, $\log(|\delta P/P|) \simeq -4.3$ (Kouveliotou et al. 1999).

In the context of an evolutionary link between the SGRs and the AXPs, the timing and spectral stability of 1E 1841−045 suggest a quiescent state either pre- or post-SGR activity. The relative age of 1E 1841−045 argues for an early state, possibly preceding γ-ray activity, since there is some evidence that 1E 1841−045 is the youngest among the currently recognized AXPs and SGRs. Half the AXPs are known to be associated with supernova remnants, while, of the four known soft re-

peaters, two have host remnants while another, SGR 1806−20, has associated plerion-like emission but no discernible supernova shell. All these objects are thought be at least $\gtrsim 10^4$ yr old, with the oldest AXPs having been around for a few times 10^5 yr (the spin-down on timescales of a few hundred years that is observed in SGRs is no reflection of their true ages).

Rotational energy loss is insufficient to power the inferred luminosity of 1E 1841−045, unlike in the usual radio pulsar. In the SGRs, the ultimate mechanism for powering particle acceleration is naturally the release of magnetic-free energy (both steady and episodic-seismic) rather than rotation (see Thompson & Duncan 1996). The episodic emission of γ-ray bursts is thought to be due to starquakes in the NS crust. This could suggest a future "turning on" of 1E 1841−045 as a γ-ray repeater on a several thousand year timescale, presumably resulting from a slow buildup of stress/strain between the core and the surface of the NS that is due to an as yet unknown state transition in the stellar crust.

The blackbody spectrum suggests a radiating surface of size $R_\infty \simeq 8 d_7^2$ km, were d_7 is the distance to Kes 73 in units of 7 kpc (Sanbonmatsu & Helfand 1992), which is consistent with neutron stellar dimensions (assuming an isotropic emitter and ignoring surface redshift and photospheric corrections to the observed spectral energy distribution). This rough estimate suggests low surface temperature anisotropies (as opposed to small hot spots) and is in agreement with the low-modulation, broad pulse originating from near the stellar surface. In an ultramagnetized NS, outward-energy transport from a decaying magnetic field can keep the surface at elevated temperatures, with high thermal luminosities ($\sim 10^{35}$ ergs s^{-1}), that are not observed in a normal NS at age $\sim 10^3$ yr. In contrast, researchers have argued (Heyl & Hernquist 1998) that the X-ray luminosities in such stars may be driven by the cooling of the NS through a strongly magnetized, light-element envelope without the need for appreciable field decay (see also Heyl & Kulkarni 1998). Along with these cooling emissions from the surface, the star may have a magnetically-driven, charged-particle outflow as is suggested by VLA observations of SGR 1806−20 (Frail, Vasisht, & Kulkarni 1997) via the energetics and small-scale structure of its plerion. Evidence of a more episodic particle ejection, rather than a steady wind, is inferred from the recent radio flare observations of SGR 1900+14, taken during a period of high activity (Frail, Kulkarni, & Bloom 1999).

For 1E 1841−045, we can only attempt to place limits on a steady pair-wind luminosity: the upper limits to radio emission from a putative plerionic structure surrounding the pulsar suggest an averaged pair luminosity of less than 10^{36} ergs s^{-1}. Similarly, limits on a hard X-ray tail suggest a present-day wind luminosity of less than 5×10^{35} ergs s^{-1}; the latter condition assumes a tail with a photon index of 2, which is quite typical of plerions, and a soft X-ray radiation conversion efficiency of 10%. These bounds are well within the energy budget available from field decay, $L_B \simeq (1/6)\dot{B}BR^3$, which is expected to power a bolometric luminosity of $\lesssim 10^{36}$ ergs s^{-1}; the fastest avenue for stellar field decay would be the modes of ambipolar diffusion for which theoretical arguments suggest a timescale of decay ($B/\dot{B}$) of $\sim 3 B_{15}^2$ kyr (Goldreich & Reisenegger 1992). Note that these upper limits are a factor of $\sim 10^2$ larger than the star's dipole luminosity of $4\pi^2 I\dot{P}/P^3 \sim 10^{33}$ ergs s^{-1}. This suggests that spin-down torques on the star could conceivably be dominated by wind torques, although such a wind would have to be remarkably steady so as not to produce timing residuals larger than those observed (Thompson & Blaes 1998). Alternatively, if classical dipole radiation is the primary spin-down mechanism, then the expected field is $B \simeq 0.75 B_{15}$ G.

To conclude, ongoing X-ray–timing monitoring of the spin period is underway by independent groups, including ours, that will provide an accurate measurement of the braking index of this pulsar. As previously mentioned, a large braking index may reflect directly on active field decay or field realignment inside the star. The observed braking index in a pure dipole rotator, with the loss of torque due to field decay, may be written as

$$n_{\rm obv} = 3 - 2\left(\frac{P}{\dot{P}}\right)\left(\frac{\dot{B}}{B}\right).$$

Given that the spin-down timescale for this pulsar is about 9 kyr, a field decay time of about $\lesssim 3 B_{15}^2$ kyr could impose a fairly large curvature on the spin-down. Perversely, the situation may be far more complicated with the different factors such as dipole radiation, winds driven by magnetic activity, and field decay all competing for torque evolution. This, however, remains to be tested through accurate long-term timing.

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