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DISCOVERY OF A NEW 89 SECOND X-RAY PULSAR: XTE J1906+09

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ABSTRACT

We report on the discovery of a new pulsating X-ray source during *Rossi X-ray Timing Explorer* (*RXTE*) observations of a low galactic latitude field centered at R.A. (J2000) = $19^h05^m43^s$, decl. (J2000) = +08°58′48″. Significant pulsations were detected by both the Proportional Counter Array and the High Energy X-ray Timing Experiment instruments aboard *RXTE* at a fundamental period of 89.17 ± 0.02 s, with higher harmonics also visible in the 2–10 keV power spectrum. The folded light curve from the source is multiply peaked at lower energies and changes to a single-peaked morphology above ~20 keV. The phase-averaged spectrum from the source is well fit by strongly absorbed power-law or thermal bremsstrahlung spectral models of photon index 1.9 ± 0.1 or temperature 19.5 ± 4.6 keV, respectively. The mean neutral hydrogen column density is $N_H \approx 10^{23}$ cm^{-2}, suggesting a distance of greater than 10 kpc to the source and a minimum 2–10 keV X-ray luminosity of 2×10^{35} ergs s^{-1}. By comparison with other pulsars with similar periods and luminosities, we suggest that XTE J1906+09 has a supergiant companion with an underfilled Roche lobe. We speculate further that one of the M stars in a peculiar M star binary system may be the companion.

Subject headings: gamma rays: bursts — pulsars: individual (XTE J1906+09) — stars: neutron

1. INTRODUCTION

The discovery of a new member of a small class of astrophysical sources is important because each source has the potential to constrain theoretical models of the source physics. Neutron star binary systems are an example of a small class of X-ray sources, with numbers presently totaling ~200. Accretion-powered pulsars can be divided into two broad classes based on their X-ray luminosities and spectra (White, Swank, & Holt 1983). The X-ray spectra of the higher luminosity sources ($L_X \sim 10^{36}$–10^{37} ergs s^{-1}) are typically characterized by a hard power law of photon index $1 < \Gamma < 2$ out to an energy of 10–20 keV, above which the spectrum "breaks" to a much steeper index ($\Gamma > 3$). The lower luminosity accreting X-ray pulsars tend not to have this broken power-law shape and instead have a softer spectral shape ($\Gamma > 2$) over a broad range of X-ray energies. Furthermore, observations of low-luminosity burst sources have revealed weak power-law components ($\Gamma \sim 2$) when the inferred accretion rate drops below a critical value (Barret & Vedrenne 1994). In this Letter, we present the detection of a new source that appears to be a low-luminosity accreting X-ray source.

2. DATA

The 1° (FWHM) field of view centered at the point R.A. (J2000) = 286°.43, decl. (J2000) = 8°.98 was observed by the High Energy X-ray Timing Experiment (HEXTE) and the Proportional Counter Array (PCA) instruments aboard the *Rossi X-ray Timing Explorer* (*RXTE*) satellite on a number of occasions between 1996 August 16 and 19, with a total live time of ~25 ks. The target of the observations was the Interplanetary Network error box from the soft gamma-ray repeater SGR 1900+14 (Hurley et al. 1994), and the pointing was offset to avoid the bright confusing source 4U 1907+097, which is ~0°.7 away.

The HEXTE instrument consists of two clusters of collimated NaI/CsI phoswich detectors with a total net area of ~1600 cm^2 and an effective energy range of ~15–250 keV (Rothschild et al. 1998). HEXTE background estimation utilizes near–real time observations of off-source viewing directions. The PCA instrument consists of five collimated Xenon proportional counter detectors with a total net area of 7000 cm^2 and an effective energy range of 2–60 keV (Jahoda et al. 1996). For the PCA instrument, the instrumental background estimate is determined from modeling blank sky observations to estimate both the internal background of the detectors and the background due to cosmic X-ray flux.

3. RESULTS

3.1. *Timing Analysis*

Photon event times from the PCA in the energy range 2–10 keV were extracted and binned into light curves of 1 s bin size, after correcting the times to the solar system barycenter using the JPL DE200 ephemeris and the *RXTE* pointing coordinates. The process was repeated for background data generated with the PCA background model, which was then subtracted from the on-source light curve. A Lomb-Scargle periodogram (Press & Rybicki 1989) was then formed from the data, resulting in the power spectrum shown in Figure 1 (*top*). Two harmonically spaced frequencies were detected at frequencies $f_2 \sim 0.0224$ and $f_3 \sim 0.0336$ Hz. The probability that each of these peaks is a random fluctuation is $\sim 10^{-21}$, given the number of frequencies examined and the exponential probability distribution of the Lomb-Scargle periodogram. The presence of peaks corresponding to f_5 and f_6 is also suggested by the periodogram, but at a marginal significance. Periodogram and fast Fourier transform analyses using different time bin sizes, no background subtraction, individual PCA detector units, and time interval subsets all show evidence for of one or two harmonic peaks in the power spectra.

The harmonically spaced frequencies f_2 and f_3 imply a fundamental frequency of $f_1 \sim 0.0112$, corresponding to a period of ~89 s. To search for the fundamental period, we performed a χ^2 folding analysis on 128 frequencies corresponding to periods about 89 s, with a frequency resolution equal to the independent Fourier spacing implied by the total duration of the data. The result, shown in Figure 1 (*bottom*), indicates a fun-

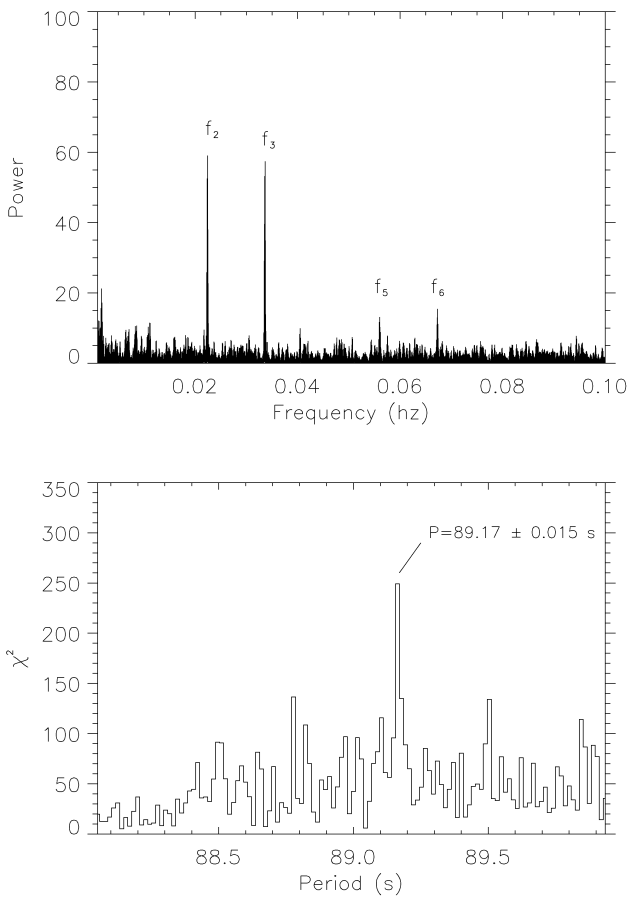

FIG. 1.—Detection of periodicity. *Top:* Lomb periodogram of 2–10 keV binned time series data from the PCA, with the harmonics labeled. *Bottom:* Results of a χ^2 folding search for the fundamental period (89 s) of the pulsations using the same data.

damental period of 89.17 ± 0.015 s. We then searched the HEXTE event data for this periodicity using the Z_n^2 test (Buccheri et al. 1983). HEXTE on-source event times in the energy range 15–50 keV were accumulated and corrected to the solar system barycenter using the JPL DE200 ephemeris and *RXTE* pointing coordinates (as before). The 4×10^5 event times yielded a Z_1^2 value of 75.3 using the single frequency corresponding to the period 89.17 s. This corresponds to a random probability of 5×10^{-17}, given the probability distribution of Z_n^2. As a check, the 15–50 keV HEXTE *off-source* events were analyzed in an identical manner, and a value of $Z_1^2 = 0.3$ was obtained—consistent with no periodicity.

The barycenter-corrected PCA and HEXTE event times were extracted for various energy ranges and folded on the fundamental period $P = 89.17$ s (Fig. 2). The corrected event times were normalized to MJD 50342.0 (TDB) before folding. The folded light curve appears to change at energies between 20 and 30 keV, with the pulse profile becoming more singly peaked and possibly shifting in phase. In addition, the pulsed emission for energies above ~20 keV peaks at a different phase than the emission at lower energies. Given the contributions from instrumental, cosmic X-ray, and Galactic ridge fluxes implied by the spectral fits (discussed below), we derive pulsed fractions of 16%, 6%, and ~4% in the energy ranges 2–10, 10–20, and 20–200 keV, respectively.

We have searched for evidence of Doppler shifts associated with possible binary motion in the observed periodicities from XTE J1906+09. Barycenter-corrected 2–60 keV PCA event times were collected for seven observation intervals throughout the observing period. The frequencies f_2 and f_3 were determined for each time interval via fitting of the peak in the Z_1^2 distribution, taken from small frequency ranges about $f_2 = 0.0224$ and $f_3 = 0.0336$, with a Gaussian. The fundamental frequency f_1 (corresponding to the 89.17 s period) was then obtained for each data set by the relation $f_1 = 1/5(f_2 + f_3)$. We find that the fundamental frequency obtained in this manner is consistent with a constant frequency over the 3 day observation period. Because of the limited (seven) number of observations and the limited temporal coverage of the observations, however, the nondetection of significant Doppler shifts poses no serious constraint on the possible binary orbital parameters of the system. For secular period changes, we fitted a model to the data in which the period changes linearly with time and obtained a 2 σ upper limit of $|\dot{P}| < 2 \times 10^{-6}$.

3.2. *Spectral Analysis*

Spectral analysis of relatively faint X-ray sources at low Galactic latitudes is complicated by the presence of diffuse emission from the Galactic ridge. Recent work by Valinia & Marshall (1998) indicates that the pointing direction of XTE J1906+09 is outside the bright, thin component of the ridge emission but inside the broader (FWHM ~ 4°) region. Only one of the HEXTE background positions is centered on a region of significantly higher Galactic X-ray flux $(l, b) = (39.^\circ6, 0.^\circ3)$, and this background is excluded from the analysis. Following Valinia & Marshall (1998), we model the Galactic ridge emission in the PCA with thermal and nonthermal components consisting of Raymond-Smith plasma (with solar elemental abundances and zero redshift) and power-law spectral shapes, respectively, multiplied by a neutral hydrogen absorption factor.

The phase-averaged PCA and HEXTE data were fitted simultaneously to various continuum spectral models using XSPEC 10.0 and assuming that XTE J1906+09 was at the center of the field of view. For the spectral fits, PCA and HEXTE data in the energy ranges 2.5–30 and 15–250 keV, respectively, were used. To account for uncertainties in the effective open area of the two instruments, the relative normalization was treated as a free parameter in the spectral fits. The plasma temperature, spectral index, and N_H values of the Galactic ridge spectrum (PCA only) were held fixed at values appropriate for the "central ridge" (see Table 3 from Valinia & Marshall 1998), but the normalizations were allowed to vary to account for the fact that the *RXTE* pointing position is displaced from the Galactic plane by 1°. The results for a power-law model for the XTE J1906+09 emission is given in Table 1. A thermal bremsstrahlung spectral shape of temperature 19.5 ± 4.6 keV and $N_H = (7.7 \pm 5.2) \times 10^{22}$ cm^{-2} fits the data equally well. More complicated spectral models (such as broken power laws) were not fitted to the data because of insufficient counts above ~20 keV. The reduced χ^2 values for both the power-law and thermal bremsstrahlung spectral fits were 1.0 for 523 degrees of freedom. As expected, for both fits the Galactic ridge normalization values were lower than the values given in Valinia & Marshall (1998)—consistent with the 1° offset from the Galactic plane—and the relative normalization factor between the PCA and HEXTE was consistent with previous fits to other sources (Marsden et al. 1997). In the spectral fitting, we have assumed that all the observed iron line emission is from the Galactic ridge (Raymond-Smith

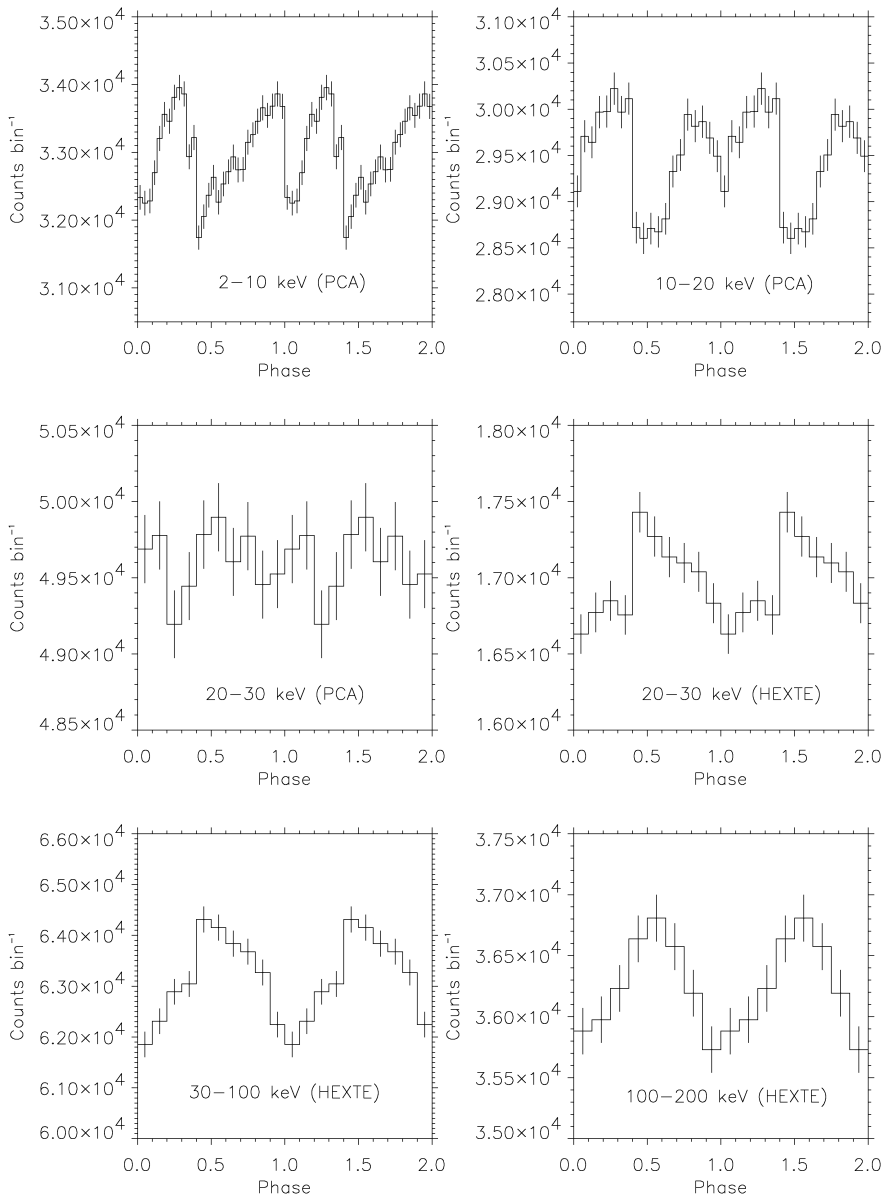

FIG. 2.—Folded light curve of the 89 s pulsations over a range of energies. The two middle panels correspond to the same energy range (see text). The background has not been subtracted.

plasma component), and therefore we do not attempt to constrain the iron line emission from XTE J1906+09.

4. DISCUSSION

Because of the low galactic latitude of the observed field, there is no shortage of possible XTE J1906+09 counterparts.

TABLE 1
PHASE-AVERAGED SPECTRAL FIT RESULTS

Model Parameter	XTE J1906+09	Galactic Ridge
N_H[a]	10.8 ± 4.0	1.8 (fixed)
Photon index	1.9 ± 0.1	1.8 (fixed)
Power-law flux[b]	16.0 ± 2.5	9.0 ± 0.4
Plasma temperature[c]	...	2.9 (fixed)
Plasma flux[b]	...	7.7 ± 0.7

[a] Neutral hydrogen absorption (10^{22} H atoms cm^{-2}).
[b] Unabsorbed 2–10 keV flux (10^{-12} ergs cm^{-2} s^{-1}).
[c] Raymond-Smith plasma temperature (keV).

The *ROSAT* All-Sky Survey (Voges et al. 1996) sources RX J190724+0843.4 and RX J190717+0919.3 (Vasisht et al. 1994) are unlikely counterparts because their count rates are significantly higher (by at least an order of magnitude) than the predicted *ROSAT* PSPC count rate of XTE J1906+09, given the spectral parameters listed in Table 1. The predicted *ROSAT* HRI count rates are 7×10^{-5} and 2.8×10^{-4} counts s^{-1} for the power-law and thermal bremsstrahlung spectral forms, respectively. Supernova remnants such a G42.8+0.6 and other supernova remnants in the field of view (Vasisht et al. 1994) are usually not associated with slow (period greater than 10 s) pulsars because of age constraints.

The pulsation period and inferred luminosity of XTE J1906+09 indicate that the X-ray emission is powered by accretion onto a neutron star. The high absorption column density implied by the spectral fit suggests that the source is located at a distance of at least ~10 kpc, and this yields a lower limit to the X-ray luminosity (2–10 keV) of 2×10^{35} ergs s^{-1}. A

variable pulse shape with energy (Fig. 2) is characteristic of accretion-powered neutron star systems, in which the emergent X-ray emission pattern is determined by the geometry and the distribution of matter in the vicinity. The scattering cross section is also energy dependent, and hence the pulse profile is expected to vary with energy. In addition, at lower energies, more complicated pulsar light curves are expected due to photoelectric absorption by material around the neutron star.

Assuming that XTE J1906+09 is an accretion-powered binary system, we can speculate on the nature of the system. The low luminosity and long spin period of XTE J1906+09 are atypical of low-mass X-ray binary systems but are consistent with a high-mass system in which the accretion takes place via mass ejection from the companion star. Such high-mass X-ray binaries can be divided into two classes: underfilled Roche lobe systems and Be-binary systems. Be-binary systems are transient systems in which the outflow from the Be star companion takes the form of either a stellar wind or an equatorial mass ejection (Rappaport & Van den Heuvel 1982). These sources are transient or highly variable, with X-ray luminosities ranging over ~4 orders of magnitude ($L_X \sim 10^{34}$–10^{38}). If XTE J1906+09 is such a system, it probably has a long orbit ($P_{orb} > 50$ days) due to the observed correlation between orbit and pulsar periods in Be-binaries (Bildsten et al. 1997). One problem with this identification is that the X-ray spectra of these systems are characterized by power laws with photon indices greater than 3 (~20–100 keV; Bildsten et al. 1997). The ~20–250 keV spectrum of XTE J1906+09 (using the HEXTE data only) is fit by a power law of photon index 1.45 ± 0.45, which is significantly harder than this. In addition, there are no known Be stars in the 1° XTE J1906+09 error box (Jaschek & Egret 1982).

XTE J1906+09 could also be an underfilled Roche lobe supergiant system. These systems typically have long orbital periods ($P_{orb} > 2$ days), long spin periods ($P_{spin} > 100$ s), and relatively low X-ray luminosities of 10^{35}–10^{37} ergs s^{-1} (Bildsten et al. 1997). The inferred parameters of XTE J1906+09 are consistent with being a member of this class, but the X-ray spectrum is flatter than that seen from Roche lobe supergiant systems (Bildsten et al. 1997).

The peculiar double M star infrared system discovered by Hartmann et al. (1995) is also in the *RXTE* field of view. The stars in this system are heavily reddened ($A_V \approx 19.2$), which implies a distance of 12–15 kpc, and are thought to be gravitationally bound with an orbit of 2×10^6 yr (Vrba et al. 1996). Using the average extinction curve given in Savage & Mathis (1979) and the relation between N_H and $E(B-V)$ given in Korneef (1982), we derive the relation $A_V \approx 1.6 N_{H22}$ mag, where N_{H22} is N_H in units of 10^{22} cm^{-2}. From the mean XTE J1906+09 N_H value obtained from the power-law and bremsstrahlung fits, we obtain $A_V = 15 \pm 5$ mag, which is consistent with the value seen from these stars.

Given the similarities between the observed properties of XTE J1906+09 and high-mass wind-fed X-ray binary systems, and the similar inferred distances of XTE J1906+09 and the M star supergiant system, we regard the latter as a promising counterpart candidate to XTE J1906+09. The large separation of the M stars would allow one to have a neutron star companion without significant effect on the M star system. Then the M star–neutron star system could be the source of the X-ray flux seen by *RXTE*. Vrba et al. (1996) have suggested that such a combination might be the counterpart of the soft gamma-ray repeater SGR 1900+14. The detection of 89 s pulsations from these IR sources would verify the association of XTE J1906+09 with this system, and XTE J1906+09 would become the first known X-ray triple system.

5. CONCLUSIONS

We have presented the detection of a new 89 s pulsating X-ray source with *RXTE*. The source was detected during observations of a region of Galactic plane containing the SGR 1900+14 error box. Characteristics of the folded light curves and spectrum suggest that the source, XTE J1906+09, is a low-luminosity X-ray binary located beyond the Galactic center. The low luminosity and long pulse period of XTE J1906+09 indicate that this source is probably a high-mass X-ray binary accreting via a stellar wind. We raise the possibility that the new source is associated with the highly absorbed double M supergiant binary system on the edge of the SGR 1900+14 error box. If this identification is correct, XTE J1906+09 is the first known X-ray triple system and a candidate counterpart for SGR 1900+14.

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