DISCOVERY OF A TRANSITION TO GLOBAL SPIN-UP IN EXO 2030+375

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ABSTRACT

EXO 2030+375, a 42 s transient X-ray pulsar with a Be star companion, has been observed to undergo an outburst at nearly every periastron passage for the last 13.5 years. From 1994 through 2002, the global trend in the pulsar spin frequency was spin-down. Using Rossi X-Ray Timing Explorer (RXTE) data from 2003 September, we have observed a transition to global spin-up in EXO 2030+375. Although the spin-frequency observations are sparse, the relative spin-up between 2002 June and 2003 September observations, along with an overall brightening of the outbursts since mid-2002 observed with the RXTE All-Sky Monitor, accompanied by an increase in density of the Be disk, indicated by infrared magnitudes, suggest that the pattern observed with BATSE of a roughly constant spin frequency, followed by spin-up, followed by spin-down is repeating. If so, this pattern has approximately an 11 yr period, similar to the 15 ± 3 yr period derived by Wilson et al. for the precession period of a one-armed oscillation in the Be disk. If this pattern is indeed repeating, we predict a transition from spin-up to spin-down in 2005.

Subject headings: accretion, accretion disks — pulsars: individual (EXO 2030+375) — X-rays: binaries

1. INTRODUCTION

1.1. Be/X-Ray Binaries

Be/X-ray transients, the most common type of accreting X-ray pulsar system, consist of a pulsar and a Be (or Oe) star, a main-sequence star of spectral type B or O that shows Balmer emission lines (see, e.g., Porter & Rivinus 2003 for a review). The line emission is believed to be associated with circumstellar material shed by the Be star into its equatorial plane by an unknown mass-loss process, thought to be related to the rapid rotation of the Be star, typically near 70% of the critical breakup velocity (Porter 1996). Near the Be star, the equatorial outflow probably forms a quasi-Keplerian disk (Quirrenbach et al. 1997; Hanuschik 1996).

Be/X-ray binaries typically show three types of behavior: (1) giant outbursts (or type II), characterized by high luminosities and high spin-up rates (i.e., a significant increase in pulse frequency), (2) normal outbursts (or type I), characterized by lower luminosities, low spin-up rates (if any), and repeated occurrence at the orbital period, and (3) quiescence, where the accretion is partially or completely halted (Stella et al. 1986; Motch et al. 1991; Bildsten et al. 1997).

For isolated Be stars, variations in the infrared bands are believed to be good indicators of the size of the Be star’s disk. However, when the Be star is in a binary system with a neutron star, the Be disk is truncated at a resonance radius by tidal forces from the orbit of the neutron star (Okazaki & Negueruela 2001). In these systems, as the disk cannot easily change size because of the truncation radius, changes in mass loss from the Be star produce changes in the disk density, which can even become optically thick at infrared wavelengths (see, e.g., Negueruela et al. 2001 and Miroshnichenko et al. 2001).

In most systems there is no clear correlation between X-ray outbursts and optical activity within single outbursts. The X-ray activity, however, follows the long-term optical activity cycle of the Be star, in the sense that no outbursts occur in periods where optical indicators of the Be star disk, such as Hα emission, have disappeared. Periods of X-ray quiescence when the Be disk is present are also observed; these may be due to the truncation of the Be star disk well within the neutron star orbit (Negueruela et al. 2001; Negueruela & Okazaki 2001).

1.2. EXO 2030+375

EXO 2030+375 is a 42 s transient accreting X-ray pulsar with a B0 Ve star companion (Motch & Janot-Pacheco 1987; Janot-Pacheco et al. 1988; Coe et al. 1988) discovered during a giant outburst in 1985 (Parmar et al. 1989). The most extensive observations of EXO 2030+375 were from the nearly continuous monitoring of its pulse frequency and pulsed flux with the Burst and Transient Source Experiment (BATSE) on the Compton Gamma Ray Observatory from 1991 April until 2000 June (Wilson et al. 2002). We (Wilson et al. 2002) found from BATSE and Rossi X-Ray Timing Explorer (RXTE) data that EXO 2030+375 appeared to have undergone an outburst near most likely every periastron passage for the last 13.5 years. Our BATSE observations revealed that EXO 2030+375’s spin frequency remained roughly constant for about a year, followed by 2 years of spin-up and 6.5 years of spin-down.

The long baseline of X-ray measurements allowed us to make detailed comparisons with optical Hα and infrared measurements, which led to the following interpretation (Wilson et al. 2002): Around MJD 49,000, a major reconfiguration occurred in the Be star’s disk, resulting in a much lower density as indicated by the fainter K-band magnitudes. The lower density meant less matter was available to be accreted, and as a consequence, the X-ray flux dropped and the spin-up of the neutron star ended. At the same time or shortly after, a density perturbation developed in the disk and started to precess without interacting with the neutron star’s orbit. Around MJD 50,000, the density perturbation interacted with the neutron star’s orbit
at a phase corresponding to about 2.5 days before periastron, producing X-ray outbursts that peaked at that time. The density perturbation precessed in a prograde direction around the Be disk, changing the orbital phase of the outburst peaks. At about MJD 50,700, the density perturbation lost contact with the neutron star’s orbit in a position symmetrical with respect to periastron, at about 2.5 days after periastron. This ended the fast migration of the outburst peaks. Wilson et al. (2002) interpreted the trend in the orbital phases from MJD 50,000 to 50,600 (1995 October–1997 June) in terms of a beat frequency between the orbital period and a perturbation period, assuming that the perturbation period was longer than the orbital period, as is typical for one-armed oscillations (density perturbations), and obtained a perturbation period of 15 ± 3 yr.

2. OBSERVATIONS AND ANALYSIS

In 2002 June (MJD 52,425–52,446) and 2003 September (MJD 52,894–52,898), we observed two outbursts of EXO 2030+375 with the RXTE Proportional Counter Array (PCA).1 For each observation, we extracted a barycentered light curve using FTOOLS version 5.3.1 for PCA Standard 1 data (0.125 s time resolution, no energy resolution). Arrival times were corrected using the orbital ephemeris of Wilson et al. (2002). These data were then fitted with a model consisting of a constant background plus a sixth-order Fourier expansion in the pulse-phase model, which consisted of a constant barycentric frequency (νb = 23.9852 and 23.9880 mHz for the 2002 and 2003 outbursts, respectively), generating a pulse profile for each observation. Phase offsets to the constant-frequency model were then generated by cross-correlating the 2–60 keV pulse profiles from each observation with the template profile from 1996 July 4 used in Wilson et al. (2002). These pulse-phase measurements were combined with the frequency measurements from EXOSAT and the phase measurements from BATSE and RXTE described in Wilson et al. (2002). As done in Wilson et al. (2002), we fitted all of the data with a global orbit plus a third-order polynomial intrinsic pulse-frequency model for the EXOSAT-observed frequencies and a different quadratic pulse-phase model for each observation with the template profile from 1996 July 4 used in Wilson et al. (2002) by two additional RXTE outbursts and extending the baseline spanned by observations to 18 years. The best-fit orbital parameters, P orb = 46.0202(2) days, T peri = JD 2,451,099.93(2), a sin i = 238(2) Hz, = 0.416(1), = 210°8(4), with χ²/dof = 646.4/373, were consistent with those derived by Wilson et al. (2002). Within the 2003 outburst, our model suggests at a 2 σ level that spin-up is present, with an estimated spin-up rate of (2.4 ± 1.2) × 10⁻¹⁰ Hz s⁻¹. Infrared photometry in the JHK bands was obtained as part of a monitoring program of Be/X-ray binaries at the 1.5 m Carlos Sánchez Telescope, located at the Teide Observatory in Tenerife, Spain. The instruments used were the continuously variable filter (CVF) photometer up to October 1999 and the CAIN-II camera, equipped with a 256 × 256 HgCdTe (NICMOS3) detector, ever since. Instrumental CVF and CAIN-II values were transformed, respectively, to the standard systems defined by Alonso et al. (1998) and Hunt et al. (1998). The accuracies of the standard JHK values are 0.01 mag (CVF) and 0.03 mag (CAIN-II).

3. RESULTS

Figure 1 shows the best-fit EXO 2030+375 spin frequencies extracted for each BATSE and RXTE outburst from our model.

1 See http://heasarc.gsfc.nasa.gov for observation details.

2 See Table 1 in Wilson et al. (2002) for detailed times.

Between the last outburst detected with BATSE in 2000 April and the RXTE PCA–observed outburst in 2002 June, the average global spin-down rate was (−1.9 ± 0.2) × 10⁻¹⁴ Hz s⁻¹. This is less than half the average spin-down rate observed by Wilson et al. (2002) with BATSE, suggesting that the rate of spin-down had slowed by 2002.

From Figure 1, one can clearly see that between 2002 June and 2003 September, the global trend in EXO 2030+375 changed to spin-up with an average rate of (7.1 ± 0.2) × 10⁻¹⁴ Hz s⁻¹. This rate was about 40% of the average global spin-up rate observed from 1992 February to 1993 November with BATSE (Wilson et al. 2002), suggesting that EXO 2030+375 likely spent some of the interval between the two RXTE observations in a roughly constant spin-frequency state similar to that observed with BATSE in 1991 through early 1992. This possibility is intriguing and suggests that EXO 2030+375 may be repeating the pattern of constant spin, followed by spin-up, followed by spin-down observed with BATSE. To further check this, we compared average spin-up rates between BATSE outbursts spaced by about 460 days, the interval between the RXTE observations. The average spin-up rate between the 1992 August and 1991 May outbursts was (6.2 ± 0.2) × 10⁻¹⁴ Hz s⁻¹ and (7.8 ± 0.2) × 10⁻¹⁴ Hz s⁻¹ between the 1992 September–October and 1991 June–July outbursts, respectively, quite similar to what we observed with RXTE. If the pattern is indeed repeating, then it appears to have a period of about 11 years.

As the pulsar spun up in the BATSE era, the peak pulsed flux of the outbursts increased, a trend that appears to be recurring in the RXTE data. Figure 2 shows the peak pulsed flux measured with BATSE and/or the RXTE PCA for each outburst computed as described in Wilson et al. (2002). Comparing the peak 2–60 keV pulsed fluxes measured with the RXTE PCA in Figure 2 (filled squares) indicates that the pulsed flux has clearly increased in the 2003 observation and is the brightest observed with RXTE to date. The BATSE and RXTE pulsed fluxes cannot easily be directly compared since they are from different energy ranges and are computed using different methods. Figure 3 shows a 4 day average 2–10 keV total flux measured with the RXTE All-Sky Monitor (ASM) from 1996 Jan-
January to 2004 December. From 1996 through late 2001, the outbursts were very faint. In early to mid-2002, the outbursts began to brighten and have continued to do so throughout 2004. INTEGRAL also detected the increasing outburst flux (Gotz et al. 2004).

Figure 4 shows the long-term history of infrared $K$ magnitudes. At approximately the same time when the outburst flux dropped dramatically in the BATSE data, the $K$-band infrared flux from the companion also dropped, indicating a decrease in density of the Be star’s disk (Wilson et al. 2002). The last measurements shown in Wilson et al. (2002) indicated that by late 1999, the Be disk had brightened, i.e., increased in density, but not yet to the level observed when EXO 2030+375 was previously spinning up. We had no observations from late 1999 until 2001 July when the $K$-band magnitudes were brighter than when spin-up was observed with BATSE. In 2002 June–July, the Be disk was very bright. By 2002 November, it had returned to the level observed during the bright BATSE outbursts. Brightening of the X-ray outbursts as observed by the RXTE ASM appeared to approximately coincide with the brightening of the Be disk, indicating that the disk density had again increased. Over the long term, the Be disk density appears to be driving the X-ray outburst intensity.

Wilson et al. (2002) observed a sudden shift in the orbital phase of EXO 2030+375’s outbursts from about 6 days after periastron to about 4 days before periastron, followed by a rapid recovery to peaking about 2.5 days after periastron, interpreted by Wilson et al. (2002) as a new stable orbital phase. However, we have continued to monitor the orbital phase of the outbursts using RXTE ASM outbursts and have found that the orbital phase of the outbursts continued to gradually change. As of 2004 November, the orbital phase of the outburst peak has reached about 5 days after periastron. Figure 5 shows the orbital phase of EXO 2030+375’s outburst peaks from 1991 April to 2004 November. The BATSE outburst peaks are taken from data included in Figure 9 in Wilson et al. (2002). For each periastron passage in which RXTE ASM data were available, we fitted a Gaussian to 46.02 days of single-dwell, 2–
10 keV data, centered on the predicted periastron passage time, to determine the peak time of the outburst.

4. CONCLUSIONS

Based on the 2002 and 2003 outbursts we observed with the RXTE PCA, the global trend for EXO 2030+375 has reversed, changing from spin-down to spin-up. As this change was occurring, RXTE ASM data indicated that the outbursts were brightening, and infrared data indicated that the Be disk density had again increased to at or above its density when BATSE observed spin-up and bright outbursts. The combination of these effects and the similar average spin-up rate between early BATSE outbursts spaced by 460 days (the spacing between the RXTE PCA observations) suggests that the pattern of constant spin, followed by spin-up, followed by spin-down, observed with BATSE, is repeating with an approximately 11 yr cycle. If this pattern continues, we predict that EXO 2030+375 will transition to spin-down in 2005.

The pattern we observe appears to be related to the density of the Be disk, but it is unclear if it is related to the density perturbation that caused the shift in outburst phase. Interestingly, the 11 yr period is similar to the 15 ± 3 yr period derived by Wilson et al. (2002) for the propagation period of a density perturbation around the Be disk. However, this density perturbation was used to explain the shift in orbital phase of the outburst peaks, and the peak phase has not yet returned to 6 days after periastron as was observed with BATSE, suggesting that this cycle may not yet be complete. Evidence of quasi periods in the Hα line profiles (the so-called V/R variability) has been seen in many Be/X-ray binaries with periods ranging from a few weeks to years (Negueruela et al. 1998). This V/R variability is believed to be due to density perturbations in the Be disk. Other Be/X-ray binaries (e.g., 4U 0115+634) have undergone giant outbursts with near simultaneous asymmetry in the Hα profile, indicating a perturbation at the distance of the neutron star orbit. However, EXO 2030+375 was the first object found to exhibit a sudden shift in outburst phase of normal outbursts that was likely correlated with a density perturbation in the Be disk (Wilson et al. 2002). To date, the quasi periods shown in Be/X-ray transients are much shorter than those found in isolated Be stars, whose periods range from 2 years to decades. Perhaps EXO 2030+375 is a counterexample, a Be transient with a decade-long quasi period.

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