ORBITAL AND SUPERORBITAL PERIODS OF 1E 1740.7–2942 AND GRS 1758–258

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ABSTRACT

Five years of Rossi X-Ray Timing Explorer (RXTE) observations of the Galactic black hole candidates 1E 1740.7–2942 and GRS 1758–258 show a periodic modulation with an amplitude of 3%–4% in each source at 12.73 ± 0.05 and 18.45 ± 0.10 days, respectively. We interpret the modulations as orbital, suggesting that the objects have red giant companions. Combining the RXTE data with earlier data (Zhang, Harmon, & Liang) from the Burst and Transient Source Experiment on the Compton Gamma Ray Observatory, we find a long period or quasi-period of about 600 days in 1E 1740.7–2942 and a suggestion of a similar 600 day period in GRS 1758–258. These timescales are longer than any yet found for either precessing systems like Hercules X-1 and SS 433 or binaries like LMC X-3 and Cygnus X-1 with more irregular long periods.

Subject headings: stars: individual (GRS 1758–258, 1E 1740.7–2942) — X-rays: stars

1. INTRODUCTION

The Galactic bulge X-ray sources 1E 1740.7–2942 and GRS 1758–258 are generally called black hole candidates because of the similarity of their X-ray spectral and timing behavior to that of Cygnus X-1 in its usual hard state. Like Cyg X-1, both sources occasionally enter an intermediate or soft state, but the evolution of their spectral hardness and luminosity is very different (Smith, Heindl, & Swank 2002). Both have prominent, bright radio lobes about an arcminute in size (Mirabel et al. 1992; Rodriguez, Mirabel, & Martí 1992), while Cyg X-1 does not (Martí et al. 1996), showing only a milliarcsecond jet near its core (Stirling et al. 2001).

The counterparts of 1E 1740.7–2942 and GRS 1758–258 are unknown because of high extinction; therefore, there are no orbital solutions or estimated masses. For GRS 1758–258, Heindl & Smith (2002) recently used Chandra data to confirm the association of the X-ray source with the radio core source (“VLA-C”), and Cui et al. (2001) did the same for 1E 1740.7–2942. Martí et al. (1998) identified two candidate counterparts to VLA-C/GRS 1758–258 in I- and K-band images. The brighter and closer candidate was found, through multiband photometry and near-infrared spectroscopy, to be a likely K0 III giant. Revised astrometry (Rothenstein et al. 2002) of infrared observations by Eikenberry et al. (2001b) confirm that this star (“star A”) is consistent with VLA-C at the 3 σ level. Martí et al. (2000) and Eikenberry et al. (2001b) agree on several possible high-mass candidates for the companion of 1E 1740.7–2942 in its more crowded and obscured field, but a low-mass companion would be unobservable at the current K-band sensitivity.

2. OBSERVATIONS

We use a 5 yr (1997–2001) series of observations by the Rossi X-Ray Timing Explorer (RXTE) of 1E 1740.7–2942 and GRS 1758–258 (Main et al. 1999; Smith et al. 2001, 2002). The observations, each of 1000–1500 s, were taken approximately weekly in 1997–2000 and twice weekly since early 2001. Monthly observations in 1996 are too sparse to improve our results and are not included. Data cannot be taken from late November to late January of each year when the Sun is close to the Galactic center.

We use the Proportional Counter Array (PCA), layer 1, in the range of 2.5–25 keV. Instrumental background has been subtracted using the “faint source” model, and Galactic diffuse emission has been subtracted using pointings to nearby fields without bright point sources. To compensate for gain changes, we accumulate counts in bands of constant energy, not channel number. We offset-point by about a half-degree from each source to avoid nearby bright sources. Details of the offsets and background pointings are given in Main et al. (1999).

Since our orbital signals are small, we made two checks for systematic errors. Different observations use different subsets of the five detectors of the PCA. We repeated the entire analysis below using only the third detector, which is always on, and found no change except for the expected statistical degradation. Slight changes in the PCA field of view due to changes in the roll angle of the spacecraft take place over months and so cannot mimic the shorter orbital periods.

3. ANALYSIS AND RESULTS

3.1. Orbital Modulation

During long intervals of relatively stable hard-state emission, these sources show low-amplitude modulations that are most naturally interpreted as orbital. Figures 1a and 2a show the 1997–2001 background-subtracted light curves from 12 to 25 keV. There are gaps due to the annual solar constraint and to transitions to the intermediate and soft states (Smith et al. 2001, 2002). Luminosity variations are so large during the state transitions and soft periods that they decrease the significance of the orbital measurements. The data cut is impartial in that only the spectral power-law photon index is used to determine which parts of the data to remove: it is harder than 2.0 in the surviving data.

We high-pass–filtered the data by subtracting out a smoothed version of the light curve (Figs. 1a and 2a), leaving only high-frequency residuals (Figs. 1b and 2b). To make the smoothed curve, we replaced each data point with a value generated by fitting a polynomial of order \( a \) to all data within \( \pm b \) days of it. Raising \( N \) or lowering \( P \) increases the amount of smoothing. The figure shown is for \( N = 10 \) and \( P = 1 \), but the results are not highly sensitive to these values.

We then took a Lomb-Scargle periodogram of the residuals with the result shown in Figures 1c and 2c: peaks at 12.73 ±
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Fig. 1.—Analysis of the light curve of 1E 1740.7−2942. (a) Count rate greater than 12 keV per detector of the PCA. The error bars are smaller than the plotting symbols. The smoothed curve is described in § 3. (b) Same data high-pass–filtered by subtraction of the smoothed curve. (c) Fine histogram: Lomb-Scargle periodogram of the data in (b). Coarse histogram: Highest values achieved by applying the same analysis to scrambled data (see text). (d) Data from (b) folded on the period of the peak in (c) and normalized to the average count rate. The smooth curve is the best-fit sine function.

Fig. 2.—Same as Fig. 1, but for GRS 1758−258. GRS 1758−258 spent more of its time in the soft state, so more data have been removed.

0.05 days in 1E 1740.7−2942 and 18.45 ± 0.10 days in GRS 1758−258. The errors are the half-width at half-maximum of the peaks. Although these values would be near the Nyquist frequency for weekly sampling, the irregularity in the sampling times extends the useful frequency range many times higher.

Figures 1d and 2d show the residuals folded on the best-fit periods and divided by the average count rate. The phases are referenced to 00:00 UT on 1996 January 1. The best-fit amplitudes are 3.43% ± 0.26% for 1E 1740.7−2942 and 4.42% ± 0.32% for GRS 1758−258.

When the data from each source are divided into three roughly equal intervals, the orbital modulation is seen in all three as the highest periodogram peak in the range of 1–30 days. We also repeated the analysis in 2.5–4.0, 4.0–6.0, 6.0–8.0, 8.0–10.0, and 10.0–12.0 keV bands. The modulations are not as strong, but in every band they are the highest peaks from 1 to 30 days. Neither the amplitude nor the phase varies significantly with energy, although the amplitude may increase slightly with energy in 1E 1740.7−2942 (Fig. 3). The 2.5–4.0 keV band is not used for 1E 1740.7−2942 because of its high absorption column.
We demonstrated by simulations that our process neither creates spurious signals nor destroys real ones. To look for spurious signals, we randomly permuted the values of each triplet of data points in Figures 1a and 2a. This creates data with the same sampling times, average, and long-term evolution as the real set, but with any high-frequency signals destroyed. A thousand differently permuted data sets were analyzed for each source, giving the coarse histograms in Figures 1c and 2c, which show the highest power seen in 1 day wide period bins in any of the 1000 trials. It is clear that peaks of the size of the real signals do not occur.

To test the usefulness of the high-pass filtering, we added to the original data small sinusoidal signals with 3%–20% of the mean flux and 10–20 day periods. We then did the analysis with and without filtering. We found that filtering improves the sensitivity to artificial signals by a factor of 2–4, varying with the period and data set. Artificial signals with the amplitude of the real ones can be seen, but only by filtering first, proving the necessity of the procedure.

3.2. Superorbital Period Modulation

To search for longer periods, we combined data (Zhang, Harmon, & Liang 1997) from the Burst and Transient Source Experiment (BATSE) on the Compton Gamma Ray Observatory with our RXTE/PCA data, extrapolating the PCA data to the BATSE range of 20–100 keV. For most black holes in the hard state, this is not a bad approximation: only beyond 100 keV do the spectra steepen significantly. Figures 4 and 5 show the combined light curves and their periodograms. The major dips in the light curves all correspond to softenings of the spectra.

The periodogram for 1E 1740.7–2942 shows a clear peak around 600 days. Each individual 600 day cycle is visible if the single low point from BATSE in 1993 is included. The data for GRS 1758–258 are less conclusive. The BATSE data are poorer for GRS 1758–258, in part because of its slightly lower luminosity but probably also because of the proximity of the bright Z source GX 5−1.

4. INTERPRETATION

If the 12 and 18 day modulations are orbital, then the companions of 1E 1740.7–2942 and GRS 1758–258 must be giant stars to fill their Roche lobes. For GRS 1758–258, infrared observations rule out a high-mass companion (Martí et al. 1998; Eikenberry et al. 2001b) and therefore make wind accretion less likely. Star A of Martí et al. (1998), a K0 III giant, would almost exactly fill its Roche lobe with a 10 $M_\odot$ companion and an 18 day orbit (Smith, Heindl, & Swank 2000; Rothstein et al. 2002). Perhaps both systems have companions on the first giant branch and are in a long-lived evolutionary phase with accretion driven by the gradual nuclear evolution and expansion of the secondaries, as has been suggested for long-
period neutron star binaries like Cygnus X-2 (Webbink, Rapaport, & Savonije 1983). King et al. (1997), however, found that such systems should have unstable disks and appear as transients if the primary is a black hole.

Low-amplitude (~7%) X-ray modulation with a similar shape was recently discovered in another persistently luminous black hole candidate, LMC X-3, at its previously known orbital period of 1.7 days (Boyd, Smale, & Dolan 2001). Cyg X-1 also shows low-amplitude orbital X-ray modulation, which is not observed in the soft state. Wen et al. (1999) offered two interpretations: partial absorption by the optically thin wind of the secondary (see also Brocksopp et al. 1999) and partial obscuration of an extended emission region (corona) by the accretion stream. The lack of modulation in the soft state was explained in the first picture by increased ionization and decreased mass in the wind, and in the second picture by shrinkage of the corona.

Because their amplitude and phase are independent of energy (Fig. 3), the modulations of 1E 1740.7—2942 and GRS 1758—258 are consistent with an extended emission region and an optically thick absorber such as the companion star. Wind absorption would produce more modulation at lower energy, as is seen in Cyg X-1 (Brocksopp et al. 1999). Assuming the secondary itself is the occultor, then given the size and inclination of the binaries, we could determine the size of the hard-state emission region from the amplitude of the modulation. We are planning infrared observations of star A over the orbit to determine the primary mass, system size, and inclination using radial velocity, velocity broadening, and ellipsoidal modulation measurements.

The prominent radio lobes of 1E 1740.7—2942 and GRS 1758—258, appearing far from the core sources, imply strong collimation of the jets. Spruit, Foglizzo, & Stehle (1997) show that in a jet collimated by the poloidal magnetic field of an accretion disk, collimation is proportional to the ratio of the outer to inner disk radii. The very large disks implied by the long binary periods in these systems may support this model.

The 600 day superorbital periods that we report here are the longest seen in any system so far. Hercules X-1 and LMC X-4 have very regular long X-ray periods, about 35 and 30 days, respectively (Tananbaum et al. 1972; Lang et al. 1981), which are explained by disk precession with periodic partial obscuration of the X-ray–emitting regions (e.g., Wijers & Pringle 1999). Jet precession at a period of about 162 days is observed via Doppler shifts of emission lines in SS 433 (Margon et al. 1979; Eikenberry et al. 2001a) and is presumed to be caused by precession of the disk. Other systems, such as the black hole candidate LMC X-3, show more irregular variations, associated with spectral state changes that are not consistent with disk obscuration (Paul, Kitamoto, & Makino 2000; Wilms et al. 2001). Brocksopp, Groot, & Wilms (2001) review recent models of long-period variability involving changes in accretion rate either due to a limit cycle caused by X-ray evaporation of the outer parts of the accretion disk (Shields et al. 1986) or due to changes in the companion that cause it to fill its Roche lobe only occasionally (Wu et al. 2001). Cyg X-1 in different epochs has been reported to show long periods at 294 and 142 days (Priedhorsky, Terrell, & Holt 1983; Brocksopp et al. 1999).

Ogilvie & Dubus (2001) calculated the susceptibility of disks in X-ray binaries to radiation-driven warping. We find the binary separations of 1E 1740.7—2942 and GRS 1758—258 to be about (2.5±5)×10^{-3} cm for black hole masses of 3–20 M_{\odot}. Using Figure 7 of Ogilvie & Dubus (2001), we find that for a secondary of 1.1 M_{\odot} (i.e., star A), black hole masses greater than 6 M_{\odot} fall in the “indeterminate instability zone,” with possible cyclings between flat and warped disks. Such cyclings might explain the long, semiregular periods with spectral changes, even with constant mass transfer from the companion. For lower masses of the primary, the systems would fall in the regime of persistent warping and stable precession, as in SS 433.

A recent observation of GRS 1758—258, however, suggests that variations in accretion do play a role in its long-term variability. An extreme luminosity drop is visible at about 2001.25 in Figure 5. Smith et al. (2001) found that GRS 1758—258 entered a soft state suddenly and then decayed exponentially with a 1 month timescale. Exponentially decaying emission in the soft state is easily explained by the steady draining of a thin accretion disk with little or no mass input.

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