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X-RAY TIMING IN 1E 1740.7−2942 AND GRS 1758−258

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ABSTRACT

We report on deep observations of the Galactic bulge sources 1E 1740.7−2942 and GRS 1758−258 with the *Rossi X-Ray Timing Explorer*. These objects form a class of two, showing radio jets, very hard spectra, and persistent emission. Here we show that their power spectra are also similar: flat-topped noise, breaking to a power law, with a pair of weak, harmonically spaced quasi-periodic oscillations above the break and an integrated rms variability of ∼20%. We discuss to what extent these results can be considered support for the identification of both as black hole candidates.

Subject headings: accretion, accretion disks — black hole physics — X-rays: stars

1. INTRODUCTION

1E 1740.7−2942 and GRS 1758−258 are by far the brightest persistent sources in the Galactic bulge above ∼50 keV (Sunyaev et al. 1991). Although variable over times of days to years, they spend approximately half their time near their brightest observed level. Their spectra are typical of a black hole low (hard) state (Heindl et al. 1993; Sunyaev et al. 1991). Both have a core-and-jet structure in the radio (Heindl, Prince, & Grunsfeld 1994; Mirabel et al. 1992; Rodriguez, Mirabel, & Martí 1992) and have therefore been described as microquasars. These characteristics make this pair of objects a subclass among the black hole candidates.

This subclass shares features with other black hole candidates. Radio jets also appear in the much brighter, more spectacularly variable objects more usually called microquasars: GRS 1915+105 and GRO J1655−40 (Greiner, Morgan, & Remillard 1996; Zhang et al. 1997b), whose jets, too, are brighter and more variable. Maximum luminosities around 3×10^{37} ergs s^{-1} are shared with Cyg X-1 and the recently discovered transient GRS 1737−31 (Cui et al. 1997b). The property of being near maximum luminosity half the time or more is shared with Cyg X-1. The property of having been observed only in the hard state is shared with GRS 1737−31, GS 2023+338, GRO J0422+32, and GRO J1719−24, although the total amount of time devoted to these objects varies widely (Zhang, Cui, & Chen 1997a; Tanaka & Lewin 1995).

Despite the hard spectra of the two objects, there has been some evidence of state changes: the detection of a soft component from GRS 1758−258 on one occasion by *ROSAT* (Mereghetti, Belloni, & Goldwurm 1994) and changes in the spectral shape of 1E 1740.7−2942 above 20 keV with intensity, from BATSE data (Zhang et al. 1997c). If confirmed, these strengthen the similarities to Cyg X-1.

1E 1740.7−2942 has been suggested as a source of the Galactic center positron-annihilation line at 511 keV. Transient emission lines consistent with broadened, redshifted annihilation have been observed from it by SIGMA (Gilfanov et al. 1994), although one was contradicted by OSSE and BATSE (Jung et al. 1995; Smith et al. 1996a). Other searches for these transients have given negative results, both for 1E 1740.7−2942 and for the whole sky (Harris, Share, & Leising 1994; Smith et al. 1996b).

1E 1740.7−2942 and GRS 1758−258 have high Galactic extinction in the optical, and counterparts have not been identified; only O stars and red supergiants have been ruled out as companions (Chen, Gehrels, & Leventhal 1994). There have therefore been no mass determinations; it has even been suggested (Bally & Leventhal 1991) that 1E 1740.7−2942 does not need a companion and could be accreting directly from a nearby molecular cloud.

Both sources were observed by SIGMA and ART-P to vary between observations separated by 6 months from a hard X-ray flux of about 130 mcrab (40 mcrab in the 8–20 keV ART-P band) to a level less than 10 mcrab and consistent with zero (Churazov et al. 1994; Pavlinsky, Grebenev, & Sunyaev 1994). Day-to-day variability is also seen in these data, including a 1 day jump in ART-P flux from 1E 1740.7−2942 from ∼3 to ∼18 mcrab.

2. OBSERVATIONS

Our observing program with the *Rossi X-Ray Timing Explorer* (*RXTE*) consists of ongoing monitoring observations and one deep observation of each source. In this Letter we present the timing analysis of Proportional Counter Array (PCA) data from the deep observations. The PCA (Jahoda et al. 1996) is a set of five Xenon proportional counters of ∼1300 cm^2 that are sensitive from 2 to 60 keV and share a 1° FWHM passively collimated field of view.

When short *RXTE* pointings showed that 1E 1740.7−2942 and GRS 1758−258 were near their historically brightest states, the deep observations were taken (see Table 1). The 1E 1740.7−2942 observations were made in seven pointings over 5 days, and the GRS 1758−258 observations comprised three pointings in 3 days. Because of transient high-voltage breakdown problems, only three of the five detectors in the PCA were used during the later pointings at 1E 1740.7−2942.

The pointing directions were offset to avoid other nearby X-ray sources: A1742−294 and other Galactic center sources near 1E 1740.7−2942 and GX 5-1 near GRS 1758−258. The map of the Galactic center region by ART-P on *Granat* (Grebenev et al. 1997) shows these regions. The instrumental effective

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TABLE 1
RXTE OBSERVATIONS OF 1E 1740.7−2942 AND GRS 1758−258

Source	Dates (UT)	Pointing Direction α(J2000)	Pointing Direction δ(J2000)	Offset[a] (deg)	Time (ks)
1E 1740.7−2942	1996 Mar 16–19	17 42 36	−30 11 35	0.53	33.5[b]
GRS 1758−258	1996 Aug 3–5	18 01 15	−26 14 43	0.50	54.0
1E background	1996 Feb 2–4	17 49 20	−27 46 43	...	24.0
GRS background 1	1996 Feb 2–5	17 59 59	−26 44 48	...	13.0
GRS background 2	1996 Feb 11–12	18 05 26	−24 34 19	...	10.6

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Source positions from Heindl et al. 1994 and Rodriguez et al. 1992.

[b] 20.6 ks with five proportional counter units (PCUs) on and 12.9 ks with three PCUs on.

areas resulting from the offsets were 43% and 46% of nominal values for 1E 1740.7−2942 and GRS 1758−258, respectively.

Since both sources lie in the Galactic plane, background observations were made to determine the Galactic diffuse emission. For 1E 1740.7−2942, the background field is opposite in Galactic longitude and equal in Galactic latitude to the source field. For GRS 1758−258, the background fields are at the same Galactic latitude as the source field and on either side in Galactic longitude. Typical raw PCA rates from the source and background fields were 365 and 210 counts s^{-1} for 1E 1740.7−2942 and 280 and 150 counts s^{-1} for GRS 1758−258, respectively, of which roughly 100 counts s^{-1} is instrumental background.

Using PCA data alone, both spectra are fitted reasonably well by a power law of index −1.6 and an absorption column consistent with previous measurements, i.e., a spectrum typical of the low (hard) state of black hole accretion. Detailed fitting of the energy spectra (including data from the High Energy X-Ray Timing Experiment [HEXTE]) will be the subject of another paper.

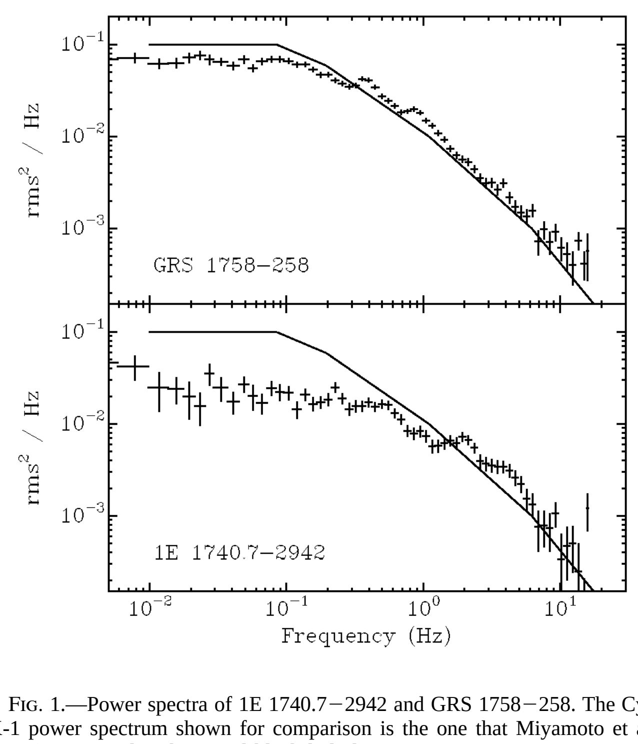

FIG. 1.—Power spectra of 1E 1740.7−2942 and GRS 1758−258. The Cyg X-1 power spectrum shown for comparison is the one that Miyamoto et al. (1992) compared with several black hole low-state power spectra.

3. TIMING RESULTS AND DISCUSSION

The counts were summed into 31.25 ms bins for the timing analysis. Figure 1 shows the power spectra with the Poisson level from counting statistics subtracted. They represent averages of 210 and 130 intervals (for GRS 1758−258 and 1E 1740.7−2942, respectively) of 256 s each. The full energy range of the PCA (2–60 keV) was used for each plot, but the contribution above 20 keV is small.

Both power spectra show flat (white) noise at low frequencies, breaking to a power law. Each plot shows a typical power spectrum from Cyg X-1 for comparison (Miyamoto et al. 1992). Belloni & Hasinger (1990) showed that the low-state power spectra from Cyg X-1 always had the same normalization above the break frequency, which varied. Miyamoto et al. (1992) noted that this held true from one black hole candidate to another, and Figure 1 indicates that it holds true here. Cui et al. (1997a) explain flat-topped power spectra as white noise from the inner edge of the disk, with a Comptonizing corona acting as a low-pass filter to produce the break and the break frequency related to corona size.

The integrated fractional rms variability (0.002–16.0 Hz) is 20% for 1E 1740.7−2942 and 24% for GRS 1758−258. This is nearly independent of energy, being 22%, 19%, and 22% for energy bands 2–6, 6–13, and 13–28 keV in 1E 1740.7−2942 and 26%, 27%, and 25% for the same energy bands in GRS 1758−258. If there are time lags between different energy bands, the rms over the full energy range can be less than the rms in any of the individual bands.

We fit the power spectra with a broken power law (index 0 below the break and free above it) and with a pair of zero-centered Lorentzians, which correspond to an exponential shot model with shots of two distinct time constants (Grove et al. 1994). For 1E 1740.7−2942 the second Lorentzian does not improve the fit significantly, and we leave it out. We also add a pair of Lorentzian quasi-periodic oscillations (QPOs), with the frequency of the higher twice that of the lower. Freeing the frequency ratio never significantly improved the fit, and both sources require both QPOs. The least significant QPO (the higher harmonic in 1E 1740.7−2942) is required at the 99.9% level by an *F*-test.

The broken power-law model $P(\nu)$ is defined with amplitude n [(fractional rms)^2/Hz], index k, and break frequency ν_0 (see Table 2):

$$P(\nu) = n \quad (\nu \le \nu_0), \qquad P(\nu) = n\left(\frac{\nu}{\nu_0}\right)^k \quad (\nu > \nu_0). \qquad (1)$$

The zero-centered Lorentzians (Table 3) have area a and half-

TABLE 2
BROKEN POWER-LAW FITS TO POWER SPECTRA

Parameter	1E 1740.7−2942	GRS 1758−258
$n \times 100$ (rms^2 Hz^{-1})	1.786 ± 0.067	6.09 ± 0.15
ν_0 (Hz)	0.429 ± 0.024	0.1254 ± 0.0051
k	−1.19 ± 0.10	−1.009 ± 0.016
$A_1 \times 1000$ (rms^2)	4.8 ± 1.2	3.48 ± 0.44
B_1 (Hz)	0.40 ± 0.12	0.0651 ± 0.0099
C_1 (Hz)	2.005 ± 0.068	0.3937 ± 0.0063
$A_2 \times 100$ (rms^2)	0.80 ± 0.32	1.63 ± 0.15
B_2 (Hz)	1.32 ± 0.50	0.558 ± 0.046
χ^2_r (degrees of freedom)	1.118 (55)	1.166 (55)

TABLE 3
LORENTZIAN FITS TO POWER SPECTRA

Parameter	1E 1740.7−2942	GRS 1758−258
$a_1 \times 100$ (rms^2)	4.27 ± 0.24	4.53 ± 0.27
b_1 (Hz)	0.675 ± 0.049	0.228 ± 0.016
$a_2 \times 100$ (rms^2)	…	4.64 ± 0.32
b_2 (Hz)	…	4.84 ± 0.75
$A_1 \times 1000$ (rms^2)	4.8 ± 1.2	3.20 ± 0.67
B_1 (Hz)	0.40 ± 0.11	0.063 ± 0.013
C_1 (Hz)	1.993 ± 0.066	0.3998 ± 0.0074
$A_2 \times 100$ (rms^2)	1.66 ± 0.26	1.88 ± 0.26
B_2 (Hz)	2.14 ± 0.37	0.539 ± 0.056
χ^2_r (degrees of freedom)	1.077 (56)	1.351 (54)

width at half-maximum (HWHM) b, and the QPO Lorentzians (in both models) have area A, HWHM B, and center frequency C:

$$P(\nu) = \frac{ab/\pi}{\nu^2 + b^2}, \quad P(\nu) = \frac{AB/\pi}{(\nu - C)^2 + B^2}. \tag{2}$$

There is no C_2 in either table because it is fixed at $2C_1$.

We also tried fitting with the model of Viklinin, Churazov, & Gilfanov (1994), in which QPOs appear under the shot noise model by suppressing further shots for a time after each shot. The relative frequencies and amplitudes of the predicted QPOs did not match our data. This does not mean that suppression of subsequent shots is the wrong way to think about the power spectrum, just that the suppression after a shot is more complicated than the simple step function that Viklinin et al. (1994) solved analytically. Such suppression is also part of the model of the accretion disk as a self-organized critical state (Mineshige, Takeuchi, & Nishimori 1994) and has been observed directly in Cyg X-1 (Negoro, Miyamoto, & Kitamoto 1994).

QPOs from 0.04 to ∼10 Hz have been seen in the low-, high-, and very high accretion states of black hole candidates (van der Klis 1995). The ones that look most similar to Figure 1 are from the low state of GX 339−4 (Motch et al. 1983), from the very high state of Nova Muscae (GS 1124−68) (although the overall normalization is much lower) (Miyamoto et al. 1994), and from the low state of the X-ray burster and atoll source X1608−522 (Yoshida et al. 1993). Therefore, although most black hole QPOs are at lower frequencies than most QPOs in neutron star binaries, this is not always the case, and low-frequency QPOs cannot be considered a certain black hole signature. Indeed, frequencies below 10 Hz are too low to be related to dynamic timescales in the inner parts of the accretion disk, where black hole and neutron star systems have the greatest chance of differing.

Since autocorrelation functions contain the same information as power spectra, they are not shown here. We have, however, fitted decaying exponentials to them at the shortest times (using only as many data points as can be fit well by this function). The $1/e$ decay constants were 0.08 s for 1E 1740.7−2942 and 0.25 s for GRS 1758−258.

Miyamoto et al. (1988) showed that in Cyg X-1, hard (15.8–24.4 keV) photons lagged behind the soft (1.2–5.7 keV). This phase lag decreased only slightly, from ∼0.1 to ∼0.04 rad, as the period increased from 0.1 to 10 s. Miyamoto et al. (1992) showed that this behavior is characteristic of black hole low-state accretion in general. In Cyg X-1, the coherence below 1 Hz between variations in two energy bands was observed to be about 0.95 by *Ginga* (Vaughan & Nowak 1997).

Figure 2 shows the phase lag and coherence for GRS 1758−258 using energy bands 2–6 keV and 6–28 keV. While the lag is not well enough determined for a detailed comparison, below 1 Hz it resembles the "canonical" behavior described by Miyamoto et al. (1992). The coherence, averaged up to 0.4 Hz, is 0.953 ± 0.017, a 2.8 σ deviation from unity and consistent with the Cyg X-1 result. The statistics for 1E 1740.7−2942 were inadequate for this analysis.

Miyamoto et al. (1988) pointed out that for inverse Compton scattering in a uniform cloud, the time lag rather than the phase lag is expected to be nearly constant. Hua, Kazanas, & Titarchuk (1997) have shown that varying the radial mass distribution of the cloud can reproduce the observed lags within the inverse Compton model. Vaughan & Nowak (1997) and Hua et al. (1997) found in theoretical studies that many time evolution effects could destroy high coherences and that these high values therefore put important constraints on models of the sources.

In summary, we find that the timing properties of 1E 1740.7−2942 and GRS 1758−258, like the energy spectra, appear to be those of a black hole in a low (hard) state, although similar power spectra (Yoshida et al. 1993) and energy spectra (Zhang et al. 1996) can be seen in atoll sources. Both objects show a pair of harmonically spaced QPOs; although this is not obviously a signature of either a black hole or of low-state accretion, it now appears to be a common phenomenon.

We have been accumulating a series of short monitoring observations of these objects since the launch of *RXTE* and in a later paper will present longer term correlations among the spectral and temporal properties. The persistence of hard spectra and the accompanying high variability over long periods may prove a better black hole signature than the appearance of these characteristics on a single occasion. None of the neu-

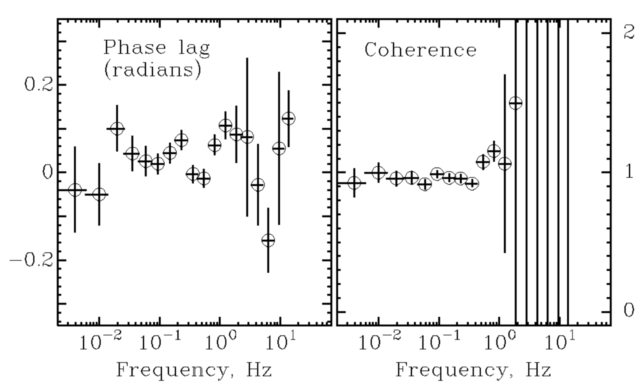

FIG. 2.—Phase lags and coherence for GRS 1758−258 for the energy bands 2–6 and 6–28 keV. A positive lag indicates that the harder photons are delayed.

tron star binaries show hard emission most of the time, although the hard state of X1608−522 lasted for about 160 days (Zhang et al. 1996).

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