Tandem Swift and INTEGRAL Data to Revisit the Orbital and Superorbital Periods of 1E 1740.7–2942

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Abstract

The black hole candidate 1E 1740.7–2942 is one of the strongest hard X-ray sources in the Galactic Center region. No counterparts in longer wavelengths have been identified for this object yet. The presence of characteristic timing signatures in the flux history of X-ray sources has been shown to be an important diagnostic tool for the properties of these systems. Using simultaneous data from NASA’s Swift and ESA’s INTEGRAL missions, we have found two periodic signatures at 12.61 ± 0.06 days and 171.1 ± 3.0 days in long-term hard X-ray light curves of 1E 1740.7–2942. We interpret those as the orbital and superorbital periods of the object, respectively. The reported orbital period is in good agreement with previous studies of 1E 1740.7–2942 using NASA’s RXTE data. We present here the first firm evidence of a superorbital period for 1E 1740.7–2942, which has important implications for the nature of the binary system.

Key words: stars: individual (1E 1740.7-2942) – X-rays: binaries

Supporting material: data behind figure

1. Introduction

Since the production of the first hard X-ray (i.e., \(E > 20\) keV) image of the Galactic Center (GC) region by the XRT telescope (Skinner et al. 1987), 1E 1740.7–2942, discovered by the Einstein satellite (Hertz & Grindlay 1984), is known to be one of the strongest X-ray emitters around the GC. With the advent of nearly continuous sensitive monitoring of the GC region, first provided by the SIGMA telescope (Sunyaev et al. 1991), 1E 1740.7–2942 was found to have spectral states resembling those of Cyg X-1. Then, by analogy, the source has been ever since considered to be a black hole candidate (BHC). Its probable black hole nature was further supported with the observations of radio jets (Mirabel et al. 1992) coming from the central X-ray source.

The nature of 1E 1740.7–2942 system is still a matter of debate in the literature, with the favored hypothesis being that the system is a high-mass X-ray binary (HMXB; Smith et al. 2002). The deepest search in the infrared up to date (Martí et al. 2010) opened a possibility of an extragalactic nature for 1E 1740.7–2942, but this has been recently ruled out by Luque-Escamilla et al. (2015).

From previous studies (e.g., Castro et al. 2014b), 1E 1740.7–2942 is known to spend most of its time in the low/hard state, with most of the flux in hard X-rays. Hence, any attempt in finding a periodic signature in a long-term light curve can be advantageously carried out with a hard X-ray database. In this study, we gather data from the Swift (Gehrels et al. 2004) and INTEGRAL (Winkler et al. 2003) missions to show evidence of two periodic signatures in the flux history of 1E 1740.7–2942, which we interpret as the orbital and superorbital periods of the source.

2. Data Selection and Analysis

The BAT telescope (Barthelmy et al. 2005) at the Swift satellite provides daily measurements of the 15–50 keV flux of 1E 1740.7–2942. These measurements are not adequate for spectral analysis due to the sensitivity constraints of a large field imager in X-rays. However, the ISGRI telescope (Lebrun et al. 2003) on board the INTEGRAL satellite can be used to trace the spectral evolution of 1E 1740.7–2942, as well as to provide the source’s flux. This is where we tandem the strength of both missions to obtain long-period light curves of 1E 1740.7–2942 in its canonical low/hard state (see, e.g., del Santo et al. 2005). In such a way any possible signature in the light curves due to intrinsic spectral variability can be disentangled from other effects. As both BAT and ISGRI are coded–mask imaging instruments, any flux contamination due to source confusion is also avoided, and, thanks to the sensitivity of both telescopes, we can perform flux measurements at hard X-rays, where 1E 1740.7–2942 is brighter. To our knowledge, this is the first time that a search for periodic signatures in 1E 1740.7–2942 can be done without source confusion/contamination and at hard X-rays.

For this work, all the public ISGRI database of 1E 1740.7–2942 from 2003 to 2015 was retrieved, encompassing 362 spectra. A previous study of this spectral database by our group was presented by Castro et al. (2014a). The data reduction was performed using the OSA software (see, e.g., Caballero et al. 2013) and a power-law model was found to fit appropriately each of the 20–200 keV ISGRI spectra. Any spectrum with a signal-to-noise ratio less than 5 and with \(\chi^2_{\text{red}}\) (provided by XSPEC) greater than 2 in this energy range was discarded. The median power-law index was \(\Gamma = 1.8 \pm 0.2\). Hence, all observations with \(1.6 \leq \Gamma \leq 2.0\) were selected, as this indicates that the source is at its canonical low/hard state (see, e.g., Remillard & McClintock 2006). Further, we truncated the ISGRI database to make it begin at the same start date as the BAT database. As a result we had a total of 162 spectra, from which the flux in the 20–50 keV range was used to build a ISGRI/1E 1740.7–2942 long-term 2005–2015 light curve.

The BAT daily flux measurements were chosen to match exactly the same dates for which a spectrum could be extracted from ISGRI, obeying the criteria explained above. This guarantees that the source was at its canonical state, thus allowing us to build a BAT/1E 1740.7–2942 long-term light
curve. For every point removed from the BAT light curve—based on the discarded ISGRI points—the immediate neighbor points were also discarded (since INTEGRAL mission’s orbital period is 3 days). Finally, although the daily coverage of BAT extends further in time, the data were selected up to 2015 to match the final date in the ISGRI database. From the 3459 initial measurements, 1599 BAT data points remained and were used in our analysis.

3. Results

The resulting light curves for both INTEGRAL and Swift data, after our selection criteria and data reduction/analysis, are shown in Figure 1.

Data were first explored in the low-frequency domain. Figure 2 shows, for both INTEGRAL (a) and Swift (b), the Lomb–Scargle periodogram from 0.005 to 0.020 days$^{-1}$ (corresponding to 200–50 days), with a grid of 5000 equally spaced frequencies. Low frequencies dominate the periodograms, and a component with a period around 171 days ($\sim 0.00585$ days$^{-1}$) is present in both databases (vertical gray dotted lines) with a high level of significance. A cross-spectral analysis (see, e.g., Scargle 1989), shown in Figure 2(c), identified this period to be $171.1 \pm 3.0$ days, with the quoted conservative uncertainty determined by the HWHM of the cross-spectrum peak. The marked difference between the power spectra at low frequencies for the INTEGRAL and Swift data sets is explained by the better sampling of the latter. This is particularly noticeable in the light curve, for instance, at MJD $\sim 55300$, with a pronounced dip that was sampled only by the BAT instrument. If the sidelobes seen in the cross-spectrum were related to amplitude modulation, the corresponding timescale would be $\sim 1600$ days—which is a very prominent feature in the light curves. We interpret the additional maxima seen in the low-frequency region as due to a process with $P(\nu) \propto 1/\nu$, very common in other X-ray binaries (see, e.g., Corbet et al. 2008 and Wen et al. 2006).

The folded-phase light curve for the times of maximum with the ephemeris MJD 53552 $\pm E \times 171.1$ days, where $E$ is the number of cycles from the origin, presented in Figure 3, for both sets of data. Although another value for the superorbital period in 1E 1740.7–2942 was mentioned before in the literature (Smith et al. 2002), we present the first robust measurement of such modulation, as it is clearly present in the database of two imaging telescopes—thus free of source confusion and flux contamination.

We performed a further analysis in the Swift database, since its 0.5 days$^{-1}$ Nyquist frequency allows us to explore periodic signatures as short as 2 days in period. The first step was to remove the low-frequency modulations and trends from the long-term light curve. This procedure (also known as detrending) is based in the LOcally Weighted Scatterplot Smoothing (LOWESS) polynomial interpolation (Cleveland 1979) and was applied with a span (i.e., smoothing parameter) of 0.05. The result is presented in Figure 4, which shows the Lomb–Scargle periodograms prior to and after the detrend. A clear signal around 0.079 days$^{-1}$ ($\sim 12.61$ days) emerged after the removal of the low-frequency modulations.
In order to better constrain the significance of this apparent periodicity in the Swift data, we applied a scrambling procedure, which is done by preserving the original time tags of the database but interchanging pairs of fluxes. A new scrambled light curve is produced when 95% of the flux values is switched. We generated 1000 new data sets with this procedure and then calculated the Lomb–Scargle periodograms for each. Figure 5 shows the maximum values of the periodogram for the 1000 scrambled data (gray dots), as well as the periodogram for our original Swift database (red lines). It can be seen that neither the false-alarm levels were surpassed nor a concentration of scrambled data maxima occurred nearby the 12.61 day period, thus considerably reducing the chance of the latter existing due to noise or deficient sampling.

For a better visualization, Figure 6 presents the power spectrum with a magnification around the peak’s region and with the horizontal axis expressed as period. The peak value corresponds to $12.61 \pm 0.06$ days. The uncertainty in the peak location was calculated using an expression very similar to that presented by Horne & Baliunas (1986),

$$
\sigma_P = \frac{1}{2\pi} \sqrt{\frac{24}{N} \frac{P^2}{T} \frac{\sigma}{R}}
$$

where $N$ is the number of data points, $T$ is the span of the light curve, $\sigma^2$ is the variance of the noise around the signal, and $R$ is the semi-amplitude of the signal. However, this tends to produce an optimistic estimate of $\sigma_P$ because it does not take into account the specific timing characteristics (e.g., gaps between measurements) of the light curve. A more realistic value is obtained using the number of bins in a phase-folded diagram for $N$, in which case the ratio $P^2/T$ becomes $\sim 1$. By calculating this way, $\sigma_P$ corresponds to $\sim 0.06$ days—value we adopted for the uncertainty in the 12.61 day signal.

An ephemeris for the times of maximum of the 12.61 day signal can be expressed as MJD 53424.85 $\pm E \times 12.61$ days. The folded-phase light curve for this period is shown in Figure 7. Our interpretation is that this modulation is related to the orbital period of the system (see the discussion below). Both the period and the semi-amplitude normalized to the average count rate (3.5%) are consistent with the values previously measured in the RXTE mission (Smith et al. 2002)—12.73 $\pm 0.05$ days and $\sim 3.4\%$, respectively.

### Figure 4
Lomb–Scargle periodograms of our Swift data prior to (left panel) and after (right panel) removal of low-frequency signatures. Horizontal lines in both panels show the false-alarm levels of 1%, 0.1%, and 0.01% (respectively from bottom to top). A prominent feature is seen at $\sim 0.079$ days$^{-1}$ ($\sim 12.61$ days).

### Figure 5
Lomb–Scargle periodogram of the Swift database (in red) together with peak values for the data generated by scrambling (in gray; see the text for details). We also show false-alarm levels. The periodic signature, interpreted as the orbital period of 1E 1740.7–2942, is clearly seen at $\sim 0.079$ days$^{-1}$.

### Figure 6
Lomb–Scargle periodogram for the Swift database around the 12.61 day modulation.

### Figure 7
Folded-phase light curve of 1E 1740.7–2942 for the orbital period (12.61 days). Here, the scatter of the individual points is larger compared to Figure 3 due to the smaller amplitude of this signal.

### 4. Discussion
The modulation at $171.1 \pm 3.0$ days (shown in Figure 2) was never reported before for 1E 1740.7–2942. In X-ray binaries, long-term modulations, i.e., superorbital periods, are
interpreted as a precession of the accretion disk (see, e.g., Roberts 1974 and Merritt & Petterson 1980). If this proves to be the case, it is expected that variations in this superorbital period should occur on timescales of several years (Brockopp et al. 1999). This has been seen, for example, in Cyg X-1, where data available since the Vela and Ariel missions up to the RXTE and Swift monitoring point to an increase from ∼290 to ∼326 days of the superorbital period (Rico 2008). A continued monitoring of 1E 1740.7−2942 would then be interesting to search for similar variations. A previous report of a tentative superorbital period in 1E 1740.7−2942 suggested a value around 600 days (Smith et al. 2002), significantly different from the value reported here. However, our procedure of examining simultaneously two independent data sets greatly improves the reliability of detecting possible periodic signals. We thus propose, by similarity to other systems, that the 171.1 day feature is the superorbital period associated with the precession of the accretion disk in the system.

Because 1E 1740.7−2942 is very likely a binary system, the periodic modulation at 12.61 ± 0.06 days could be due to the companion star causing a partial eclipse of the region where the hard X-rays are produced, which would occur at every orbit. Assuming that the hard X-ray flux in 1E 1740.7−2942 is due to Comptonization of seed (disk) soft X-ray photons by a corona of relativistic electrons, as proposed by some authors (e.g., Castro et al. 2014b), then one natural explanation of the modulation is the occultation of such a corona by the companion.

Within 2σ, this orbital period agrees with the value of 12.73 ± 0.05 days reported by Smith et al. (2002), which made use of PCA/RXTE data. Furthermore, we note that the orbital periods for 4 HMXB with black holes, Cyg X-1, LMC X-1, LMC X-3, and LSI +61, are already established to be between ∼2 and ∼26 days, so our value is in the right order of magnitude for this kind of system.

Data from the BlackCat Catalog (Corral-Santana et al. 2016) show that for 21 LMXB BH/BHCs the orbital periods are firmly measured. A clear outlier in such a database is the source GRS 1915+105 with an orbital period of ∼33.8 days. The values of mean, median, and standard deviation for the remaining 20 sources are 1.1, 0.3, and 1.6 days, respectively. If from this subset we further withdraw V 404 Cyg, with an orbital period of 6.5 days, the numbers become (mean, median, and standard deviation, respectively): 0.8, 0.3, and 0.9 days. Such results, of course, point to a highly skewed distribution for the measured orbital periods of LMXB BH/BHCs in the direction of shorter (typically less than a day) values. It is thus tempting to assume that the 12.61 day orbital period of 1E 1740.7−2942 points to HMXB nature for the binary system. It is also worthwhile recalling that all reported orbital periods for LMXB BH/BHCs were measured for transient sources, whereas the known HMXB BH/BHCs for which orbital periods were measured are persistent sources—which is the case of 1E 1740.7−2942. Therefore, it is our interpretation that 1E 1740.7−2942 is HMXB BHC, as recently suggested by studies in longer wavelengths (e.g., Luque-Escamilla et al. 2015).

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References
Barthelmy, S. D., Barbier, L. M., Cummings, J. R., et al. 2005, SSRv, 120, 143
Brockopp, C., Tarasov, A. E., Lyuty, V. M., & Roche, P. 1999, A&A, 343, 861
Caballero, I., Zarita Heras, J. A., Mattana, F., et al. 2013, arXiv:1304.1349
Castro, M., D’Amico, F., Braga, J., et al. 2014a, A&A, 569, A82
Castro, M., D’Amico, F., Jablonski, F., & Braga, J. 2014b, Proc. Science (Trieste, Italy: SISSA), 88, http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=228
Cleveland, W. S. 1979, J. Am. Stat. Assoc., 74, 368
Corbet, R. H. D., Sokoloski, J. L., Mukai, K., Markwardt, C. B., & Tueller, J. 2008, ApJ, 675, 1424
Corral-Santana, J. M., Casares, J., Muñoz-Darias, T., et al. 2016, A&A, 587, A61
del Santo, M., Bazzano, A., Zdziarski, A. A., et al. 2005, A&A, 433, 613
Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, ApJ, 611, 1005
Hertz, P., & Grindlay, J. E. 1984, ApJ, 278, 137
Horne, J. H., & Baliunas, S. L. 1986, ApJ, 302, 757
Lebrun, F., Leray, J. P., Lavocat, P., et al. 2003, A&A, 411, L141
Luque-Escamilla, P. L., Martí, J., & Martínez-Arozam J. 2015, A&A, 584, A122
Martí, J., Luque-Escamilla, P. L., Sánchez-Sutil, J. R., et al. 2010, ApJL, 721, L126
Merritt, D., & Petterson, J. A. 1980, ApJ, 236, 255
Miralbel, I. F., Rodriguez, L. F., Cordier, B., et al. 1992, Natur, 358, 215
Remillard, R. A., & McClintock, J. E. 2006, ARA&A, 44, 49
Rico, J. 2008, ApJL, 683, L55
Roberts, W. J. 1974, ApJ, 187, 575
Scargle, J. D. 1982, ApJ, 263, 835
Scargle, J. D. 1989, ApJ, 343, 874
Skinner, G. K., Willmore, A. P., Eyles, C. J., et al. 1987, Natur, 330, 544
Smith, D. M., Heindl, W. A., & Swank, J. H. 2002, ApJL, 578, L129
Sunyaev, R., Churazov, E., Gilfanov, M., et al. 1991, ApJL, 383, L49
Van, L., Levine, A. M., Corbet, R. H. D., & Bradt, H. V. 2006, ApJS, 163, 372
Winkler, C., Courvoisier, T. J.-L., Di Cocco, G., et al. 2003, A&A, 411, L1