Periods of two enigmatic black hole candidates
GRS 1915+105 and IGR J17091-3624

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Abstract

Galactic black hole candidates GRS 1915+105 and IGR J17091-3624 have many similarities in their light curves and spectral properties. However, very little is known about the orbital elements of their companions. In case the orbits are eccentric, tidal forces by the black hole on the companion can cause modulations of accretion rates in orbital time scale. We look for these modulations in the light curves of these two objects and find that their periodicities are around 28.3 d (29.0 d) and 32.2 d respectively. Eccentricities are at the most 0.071 and 0.46 respectively. We conclude that both these objects have long orbital periods and are eccentric. This could be a reason why light curves have several similar variability class transitions as reported in the literature.

Keywords: Black Holes - Accretion disks - X-rays

1 Introduction

The stellar mass black hole binary GRS 1915+105 (Harlaftis & Greiner, 2004) was first discovered in 1992 by the WATCH detectors (Castro-Tirado et al. 1992) as a transient source with a significant variability in X-rays (Castro-Tirado et al. 1994) GRS 1915+105 was monitored more than thousands of times by RXTE and it was found that nature of the light curve was highly unpredictable with variability in timescales ranging from seconds to days (Greiner et al. 1996; Morgan et al. 1997). Several observers have reported that this object exhibited many types of variability classes which are named as: $\alpha$, $\beta$, $\gamma$, $\delta$, $\phi$, $\chi_1$, $\chi_2$, $\chi_3$, $\chi_4$, $\mu$, $\nu$, $\lambda$, $\kappa$, $\rho$, $\theta$ (Yadav et al. 1999, Rao et al. 2000, Belloni et al. 2000, Chakrabarti et al. 2000, Naik et al. 2002). Pal, Chakrabarti & Nandi (2013) showed that these variability class transitions are results of variation of geometry of the Compton cloud, apart from the usual variation in accretion rates of Keplerian and low-angular momentum, sub-Keplerian disks. Mass of the compact object, companion and orbital periodicity of GRS 1915+105 system are $\sim 14.4 \pm 4.4 \, M_\odot$, $0.81 \pm 0.53 \, M_\odot$ and $33.5 \pm 1.5 \, d$ respectively (Greiner et al., 2001b, Harlaftis & Greiner, 2004:).

It has been reported that another black hole candidate IGR J17091-3624 also exhibits several types of light curves similar to those of GRS 1915+105 (Altamirano et al., 2011;
Recently, Ghosh & Chakrabarti (2014) pointed out that it may be unlikely that binary orbits in compact systems are exactly circular. In other words, they should have some eccentricity, however small. In that case, tidal forces $F_{t,a}$ and $F_{t,p}$ exerted by the black hole on the companion at perinigrumcavum (periasteron for a black hole) and aponigrumcavum (apoastron for a black hole) would be given by (e.g., Zeilik & Gregory, 1997),

$$F_{t,a} \propto \frac{1}{a(1+e)^3},$$

and

$$F_{t,p} \propto \frac{1}{a(1-e)^3},$$

where, $a$ and $e$ are semi-major axis and eccentricity respectively. While absolute values of forces depend on several parameters, such as mass and radius of the companion, ratio of tidal forces, namely,

$$\frac{F_{t,a}}{F_{t,p}} = \frac{(1-e)^3}{(1+e)^3},$$

depends only on eccentricity. In case of two component flows around a black hole (Chakrabarti & Titarchuk, 1995), Keplerian rate and the sub-Keplerian rate which are proportional to these forces, would be modulated periodically. In case of modulation of Keplerian rates, emitted flux of seed photons, and therefore, emitted Comptonized X-rays would be modulated, i.e.,

$$\frac{\dot{M}_a}{\dot{M}_p} = \frac{(1-e)^3}{(1+e)^3} = \frac{\mathcal{F}_a}{\mathcal{F}_p},$$

where, $\mathcal{F}$ represents photon fluxes due to these rates. When low-angular momentum flow is modulated it increased hardness of emitted spectrum. Whereas the density wave formed due to modulation of the Keplerian rate propagate in viscous time scale towards the black hole, modulated low-angular momentum rates move faster, almost in a free fall time scale. Evidences of these two rates have been found in many binary systems (Smith et al., 2001, 2002, 2007; Soria et al., 2011). If the viscosity changes in orbital time scale, modulations may be irregular and light curve of X-rays may not give a well defined peak at orbital period. We call it quasi-orbital periodicity (QOP) and we find evidence of such peaks in several systems of interest, such as Cyg X-1, Cyg X-3, H 1705-25, XTE J1650-500, GRS 1009-45, GRS 1758-258 and 1E 1704.7-2942 (Ghosh & Chakrabarti, 2014). Eccentricities are also obtained from $rms$ value of power density spectra (PDS) and values obtained agree with observational results, wherever available.

In the present paper, we wish to seek similar evidences of periodicities of two most enigmatic black hole candidates, namely, GRS 1915+105 and IGR J17091-3624 which show similar variability class transitions. Most interestingly, IGR J17091-3624 started exhibiting such properties only after an outburst, which leads us to believe that both objects are somehow in spectrally soft-intermediate state of a normal outburst (Pal & Chakrabarti, 2014). In any case, since accretion rates of Keplerian and sub-Keplerian components are high, it is likely that we should observe modulations of soft and hard photon fluxes in orbital periods, provided orbits have some eccentricity.

In the next Section, we present out data analysis procedure. In §3, results of data analysis of both objects are given. We present light curves and power density spectra. Finally, in §4, we present discussions and concluding remarks.
2 Data Analysis

We use ASCII version of public/archival RXTE/ASM dwell by dwell light curve data (MJD 50500 - MJD 55498) for X-ray binary source GRS 1915+105 and Swift/BAT orbital light curve data (up to MJD 56782) for both the X-ray binary sources GRS 1915+105 and IGR J17091-3624. RXTE/ASM has a collecting area of 90 $cm^2$ and operates over 1.5 – 12 keV range. Swift/BAT has an all-sky hard X-ray surveyor. It is operating over 15 – 150 keV with a detecting area of 5200 $cm^2$. We used data in 15 – 50 keV range. In order to observe long-time behaviour of both the sources, Swift/BAT data for about 9 years are analyzed. Besides, we used RXTE/ASM data for over 13 years for GRS 1915+105. As duration of available RXTE/ASM data of IGR J17091-3624 is too small, only of about a hundred days, as well as irregular, we did not use it. Obtained data was not continuous because there are ‘gaps’ in the data, especially, due to annual solar constraint. In order to overcome these shortcomings, especially due to unevenness of data interval, we wrote a fortran code to interpolate data at equal time intervals. This was required to obtain power density spectrum. Using Perl script ascii2flc, the fits files for the light curves suitable for running xronos are created. These are used to produce power density spectra (PDS) using powspec task of xronos package. A normalization factor of $-2$ was used. We extracted expected white-noise-subtracted power density spectra for time bins of 0.05 d and 0.25 d. Since observed peaks are expected to be Lorentzian type, we fit PDS peaks with Lorentzian profiles in order to determine centroids of quasi-orbital periods (QOPs). All periods are obtained with 90% confidence level (1.64$\sigma$). We also plot light curves with data in modified Julian day (MJD). For convenience, we choose units of frequencies as $d^{-1}$ instead of Hz. Photon counts are expressed in $cm^{-2}s^{-1}$ as usual.

3 Results

In Fig. 1(a-d), we present results of GRS 1915+105. Fig. 1a contains entire RXTE/ASM data (1.5 – 12keV) of about 5000 days. Power Density Spectrum (PDS) of this data is shown in Fig.1b. It does not show any conspicuous peak. However, when we take one year of ASM data (MJD 52740 - MJD 53105) when the object was in a specific variability class ($\chi$) as shown in Fig. 1c and take PDS, we obtain a peak at 29.0d (Fig. 1d).

In Fig. 2, we compare results of our analysis of SWIFT/BAT all sky survey data of IGR J17091-3624 and GRS 1915+105. Available data of 3366 days were used. PDSs show a hump in IGR J17091-3624 source at $T = 32.2$ days. Several shallow peaks were seen in PDS result of GRS 1915+105. In view of our result from RXTE/ASM data, relevant peak in this case appears to be located at $T = 28.3$ days. Both the Lorentzian fits were made with 90% confidence level (1.64$\sigma$).

In Table 1, we compare orbital elements of the two objects under consideration. Our results indicate that periods in both the systems are close to each other at about 30 d. The rms values obtained from the Lorentzian fits of QOPs vary, however. For IGR J17091-3624 this is 2006.5%. For GRS, we obtained high rms value for RXTE/ASM data (Fig. 1), while a lower rms value for the Swift data (Fig. 2). From Eq.(2), we get an estimate of rms value as,

$$\frac{\Delta N}{N} = \frac{3e + e^3}{1 + 3e^2},$$

where, $N$ is photon number and $\Delta N$ is the difference in photon numbers obtained due to modulations of the accretion rates while the companion was at perinigruncavum and aponigruncavum respectively. Putting the rms values of 10.97% and 21.25% respectively
for GRS 1915+105, we obtain estimates of eccentricity to be 0.037 and 0.071 respectively.
It is possible that in χ state, since the Keplarian rate is smaller, modulations of the rate at
the outer edge would cause larger fractional change, and hence larger rms value. In case
of IGR J17091-3624, rms exceeds 100% and Eq.(3) cannot be directly used. We assume
that this high value reflects directly quantity $N_p/N_a$, i.e., ratio of modulated photons.
This gives an estimate of eccentricity to be 0.46 which we have put in Table 1.

| X-Ray Binary (BH/BHC) | $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | Period T(d) | T(d) (PDS) (Swift) | T(d) (PDS) (RXTE) | $rms$ % | $e$ |
|----------------------|-----------------|-----------------|--------------|------------------|-----------------|----------|-----|
| IGR J17091-3624      | $\sim 15^a$     | -               | O(10)$^b$    | 32.2$^{+12.3}_{-6.7}$ | -               | 2006.6   | 0.46|
| GRS 1915+105         | 14 $\pm$ 4$^c$  | 1.2 $\pm$ 0.2$^d$ | 33.5 $\pm$ 1.5$^e$ | 28.3$^{+4.6}_{-3.5}$ | 29.0$^{+2.5}_{-2.1}$ | 10.97     | 21.25| 0.037
|                      |                 |                 |              |                  |                 |           |     |

$^a$Altamirano & Belloni (2012), $^b$Wijnands et al.(2012), $^c$Greiner (2001), $^{a,c}$Greiner et al. (2001a,b)

### 4 Discussion and Conclusions

GRS 1915+105 and IGR J17091-3624 are two enigmatic sources which have shown similarities in light curves (Altamirano et al. 2011, Rodriguez et al. 2011, Capitanio et al. 2012 and references therein). However, the orbital elements of these objects are largely unknown. From basic theory of tidal forces, it is well known (Zeilik & Gregory, 1997) that the tidal force exerted by the compact primary is inversely proportional to the cube of
the distance. This, along with a premise that the orbits need not be strictly circular, we came to a conclusion that there should be a modulation of tidal force (and thus accretion rates) over an orbital period. Degree of modulation would depend on eccentricity (see, Eq.1-3) provided tidal force is the sole reason for mass transfer. Of course, if over the course of time there are wild variation of viscosity, modulation would propagate through the accretion disk with a wide range of viscous time lag, and the effects we seek could be wiped out.

We show in this paper, that if we take power density spectra over the entire raw data of RXTE/ASM, GRS 1915+105 does not give any periodicity. There could be several reasons: (a) the orbit may be strictly circular, (b) there may be wild variation of viscosity over the years, or, (c) the mass transfer is not primarily due to tidal force. We rule out both (a) and (c) because using one year data when the object was in the so-called $\chi$-class (where viscosity could be almost constant, e.g., Pal, Chakrabarti & Nandi, 2013), we see a distinct periodicity at 29.0 d. We then proceeded to analyze the data from Swift/BAT and found that PDS of light curve (15 – 50 keV) GRS 1915+105 continues to show a peak at 28.3 d. Within error bars (Table 1) these two estimates match. From the rms values of the Lorentzian fits at 1.64$\sigma$ we find the eccentricity could be at the most 0.071.

IGR J17091-3624 data in RXTE/ASM was very irregular and for a few days only. We could analyze Swift/BAT data of about 3366 days. The PDS showed prominent peak at 32.2 d. The broadening of the peak at the quasi orbital period could have been caused by variations of viscosity. However, the rms value was unusually big. If one assumes that the rms is a representation of $N_p/N_a$, the eccentricity becomes 0.46.

According to Chakrabarti & Titarchuk (1995), an accretion flow consists of two components, one being Keplerian and the other is of lower angular momentum, mainly coming from winds of the companion or return flow from inner edge. While modulation due to tidal force in Keplerian component will propagate in viscous time scale, it will maintain a constant phase lag in orbit after orbit from the time the perturbation of density is
launched, provided viscosity remains constant. In Table 1, we provide error bars over the periods. These error bars may be mainly because of variation in viscosity. Enhancement of the Keplerian rate would enhance the injected photon flux and would cause the modulation that we observe in this paper. Low angular momentum flow rate may not strongly depend on the orbital phase. If the rate is at all enhanced, it would harden the spectrum. In future, we shall carry out deeper analysis using the modulations in different spectral states.

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