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XTE J1118+480: The spiral-in of a star to a black hole

J. I. González Hernández[1,2], R. Rebolo[1,2,3], and J. Casares[1,2]

[1] Instituto de Astrofísica de Canarias (IAC), E-38205 La Laguna, Tenerife, Spain
[2] Depto. Astrofísica, Universidad de La Laguna (ULL), E-38206 La Laguna, Tenerife, Spain
[3] Consejo Superior de Investigaciones Científicas, Spain

Abstract

Using spectroscopic data taken with OSIRIS spectrograph at the 10.4m-GTC telescope, we discover that the orbital period of the secondary star of the black hole binary XTE J1118+480, with an orbital period of $P_{\rm orb} \sim 4.1$ hr, is rapidly decreasing. We have derived an orbital period time derivative of $\dot{P} = -1.83 \pm 0.66$ ms yr^{-1} in this system. Conventional models including magnetic braking and mass loss can marginally explained these observations, but require high magnetic fields in the secondary star and significant mass loss from the system. This result has relevant implications on the strength of magnetic braking in these binary systems and also put tight constraints on the evaporation of black holes in the context of Braneworld gravity theory.

1 Introduction

According to the theory, angular momentum losses (AMLs) in short-period black hole (BH) X-ray binaries (XBs) are driven by magnetic braking [1], gravitational radiation [2], and mass loss [3]. The relative importance of these processes in the evolution of such binaries can be investigated by measuring orbital period changes with time [4].

Magnetic braking is the main mechanism responsible for AML in compact binaries [5], but the current prescription is still a matter of debate and not well established yet [6].

XTE J1118+480 is a galactic BHXB with a short orbital period of 4.1 hours. The black hole in this system was possibly formed in a violent supernova explosion that launched the system via an asymmetric natal kick from its formation region in the Galactic thin disk [7], to its present location in the Galactic halo [8].

This BHXB was discovery on UT 2000 March 29 by the Rossi X-ray Timing Explorer. Since then it has been followed both spectroscopically and photometrically at different epochs which have allowed to derive the times at the inferior conjunction of the ~ 0.2 M$_\odot$ secondary star with respect to the ~ 8 M$_\odot$ black hole [9, 10]. Previous attempts to measure the orbital period time derivative did not succeed due to the small baseline of the observations [11].

2 Observations

A significant effort has been made in the last decade to get high- and medium-resolution spectra of faint low-mass X-ray binaries (see [12] and references therein). Here we have got a total of 97 medium-resolution spectra ($\lambda/\delta\lambda \sim 2,500$) of the short-period BHXB XTE J1118+480 on UT 2011 January 7, February 8, and April 25 –25, 36 and 36 spectra in each night respectively– with the OSIRIS spectrograph [13, 14] at the 10.4m Gran Telescopio Canarias (GTC) telescope installed in the Observatorio del Roque de los Muchachos in La Palma (Canary Islands, Spain) . These spectroscopic data were used to derive radial velocities of the secondary star (see Fig. 1). The complete radial velocity curve is shown in [10]. Each individual OSIRIS spectrum was cross-correlated with the template spectrum of a late-type main-sequence star taken with the same instrument setup and properly broadened with a rotational velocity of $v \sin i = 100$ km s^{-1} [15]. The radial velocity points, which spread over ~ 3 months and a half, provide a new determination of the current orbital period of $P_{\rm orb} = 0.1699338 \pm 0.0000005$ d, which is smaller although still consistent with the orbital period measurement previously determined on UT 2000 December 1 [16].

3 Orbital period decay

We have collected the previous measurements of the times, T_n, at inferior conjunction of the secondary star in XTE J1118+480 at different epochs obtained from both spectroscopic and photometric observations, together with our new three values obtained with GTC/OSIRIS observations in 2011. Assuming a constant rate of change of the orbital period, the time, T_n, of the nth orbital cycle can be expressed as $T_n = T_0 + P_0 n + \frac{1}{2} P_0 \dot{P} n^2$, where P_0 is the orbital period at time T_0 of the reference cycle ($n = 0$), $\dot{P}$ is the orbital period time derivative, and n, the orbital cycle number. We use the IDL routine CURVEFIT and obtain $T_0 = 2451868.8921 \pm 0.0002$ d, $P_0 = 0.16993404 \pm 0.00000005$ d, and a period derivative of $\dot{P} = -(5.8 \pm 2.1) \times 10^{-11}$ s/s with a reduced $\chi^2_\nu = 1.7$ with $\nu = 3$. A linear fit ($\dot{P} = 0$), and a third-order polynomial fit (including $\ddot{P}$), provide worse fits with $\chi^2_\nu = 2.9$ and 2.3, respectively. In Fig. 2 we display the orbital phase shift, defined as $\phi_n = \frac{T_n - T_0}{P_0} - n$, of each of the T_n values as a function of the orbital cycle number n, together with the best-fit second-order solution. This figure shows a clear deviation from the null variation and that $\dot{P}$ is negative. This result, which could be also given as $\dot{P} = -1.83 \pm 0.66$ ms yr^{-1}, is the first measurement of the orbital decay in a low-mass black hole X-ray binary.

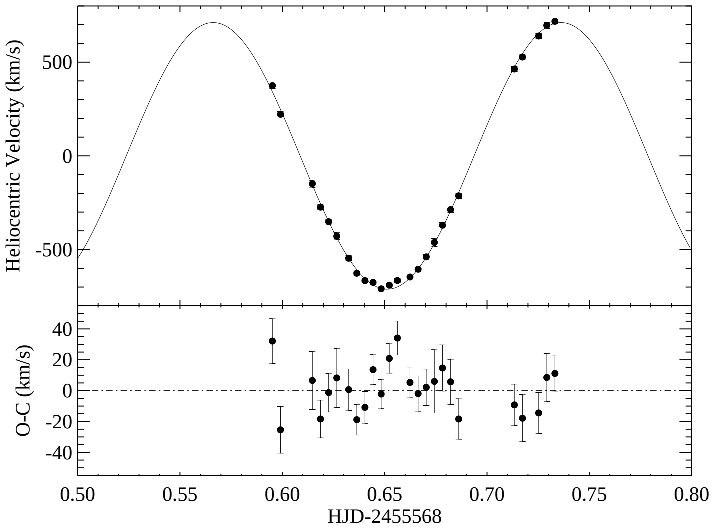

Figure 1: *Top panel*: radial velocities of the secondary star in the black hole X-ray binary XTE J1118+480 obtained from the GTC/OSIRIS spectroscopic data taken the first observing night on UT 2011 January 7 (filled circles), folded on the best-fitting orbital solution. *Bottom panel*: residuals of the fit, with a rms of $\sim$ 15km s^{-1}.

4 Discussion and Conclusions

A measurement of the orbital period decay in short-period BHXBs can provide constraints on the rate at which black holes can evaporate in the Anti-deSitter (AdS) braneworld Randall-Sundrum gravity model via the emission of a large number of conformal field theory modes (for more details see [18]). The orbital period evolution in this system was studied before but with a less number of measurements of T_n spread in a shorter interval of time, thus providing a period derivative consistent with zero at 1σ [11], and an upper-limit of the asymptotic AdS curvature radius $L \leq 97$ μm. In their eq. 2, these authors assumed no angular momentum loss due to mass lost from the system ($j_w = 0$), no accretion onto the black hole ($\beta = 0$), and the parameter γ, which governs the strength of magnetic braking, equal to zero (see Figure 1 in [11]). Adopting the black hole and secondary masses given in [10], our determination of the orbital period time derivative sets an upperbound on the asymptotic AdS curvature radius of braneworld gravity models of $L \leq 35$ μm at 2-σ, which is more stringent than current upper-limits from table-top experiments, which have given an upper-limit of $L \leq 44$ μm [19]. However, we should note that the size of the extra dimensions has been also recently constrained from the age of a black hole in a extragalactic globular cluster, placing an upper-limit as low as $L \leq 3$ μm [20].

Conventional models including magnetic braking and mass loss cannot explained the

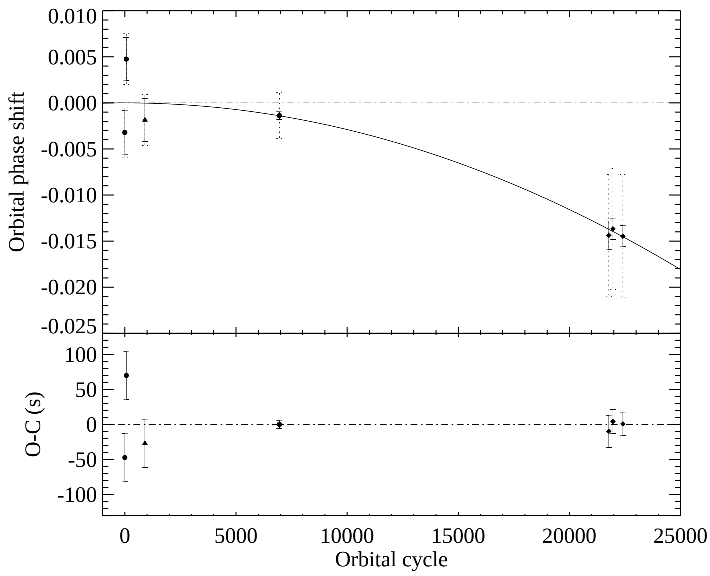

Figure 2: *Top panel*: orbital phase shift at the time of the inferior conjunction (orbital phase 0), T_n, of the secondary star in the low-mass black hole X-ray binary XTE J1118+480 versus the orbital cycle number, n, folded on the best-fit parabolic fit. Filled circles are spectroscopic determinations, the filled triangle is a photometric measurement and filled diamonds are the new GTC/OSIRIS spectroscopic determinations. Solid error bars show the uncertainties associated to the T_n determinations, whereas the dashed error bars also include the uncertainties associated to the T_0 and P_0 determinations. *Bottom panel*: residuals of the fit of the T_n values versus the cycle number n.

current value of the negative orbital-period time-derivative of the secondary star in the short-period BHXB XTE J1118+480. Only a few possibly unrealistic models including that fact that almost all the mass transferred by the secondary star is also lost by the system, may marginally explain this result at $\sim 1.5\ \sigma$. This opens the possibility to search for other explanations as an enhanced magnetic braking due to anomalously high magnetic fields in the secondary star. We have estimated from eq. 5 in [17], and assuming that the mass lost by wind is equal to the mass transfer rate, that a magnetic field at the surface of the companion star of $B_s \geq 10 - 20$ kG would be needed to explain the observed orbital period derivative (see also [10]). This could have strong implications on the evolution of this X-ray binary, in particular if the low-mass secondary star could have been originally a magnetically peculiar Ap/Bp star that has retained most of its primordial magnetic field. This would also connect low-mass XBs with intermediate-mass binaries [17, 21]. Our measurement of the fast orbital period decay in the BHXB XTE J1118+480 is consistent with this scenario although we cannot rule out that another mechanism, not yet identified, is responsible for the loss of angular momentum and hence the evolution of short period black hole X-ray binaries.

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