MNRAS **000**, 1–6 (2016) Preprint 13 September 2016 Compiled using MNRAS LATEX style file v3.0

Extremely fast orbital decay of the black hole X-ray binary Nova Muscae 1991*

J. I. González Hernández[1,2]†, L. Suárez-Andrés[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*

Accepted 2016 September XX. Received 2016 May 31; in original form 2016 April 15

ABSTRACT

We present new medium-resolution spectroscopic observations of the black hole X-ray binary Nova Muscae 1991 taken with X-Shooter spectrograph installed at the 8.2m-VLT telecope. These observations allow us to measure the time of inferior conjunction of the secondary star with the black hole in this system that, together with previous measurements, yield an orbital period decay of $\dot{P} = -20.7 \pm 12.7$ ms yr^{-1} (-24.5 ± 15.1 μs per orbital cycle). This is significantly faster than those previously measured in the other black hole X-ray binaries A0620-00 and XTE J1118+480. No standard black hole X-ray binary evolutionary model is able to explain this extremely fast orbital decay. At this rate, the secondary star would reach the event horizon (as given by the Schwarzschild radius of about 32 km) in roughly 2.7 Myr. This result has dramatic implications on the evolution and lifetime of black hole X-ray binaries.

Key words: black hole physics – gravitation – stars: individual Nova Muscae 1991 – stars: individual GU Mus – stars: magnetic field – X-rays: binaries.

1 INTRODUCTION

According to the standard theory, the evolution of black hole X-ray binaries (BHXBs) is dictated by angular momentum losses (AMLs), driven by magnetic braking (MB; Verbunt & Zwaan 1981), gravitational radiation (GR; Landau & Lifshitz 1962; Taylor & Weisberg 1982) and mass loss (ML; Rappaport et al. 1982). Magnetic braking is assumed to be the main mechanism responsible for AMLs in BHXBs with short orbital periods of several hours (Rappaport et al. 1982), but an adequate expression for MB still remains a matter of debate (Podsiadlowski et al. 2002; Ivanova 2006; Yungelson & Lasota 2008). The measurement of period variations can provide valuable information on the strength of these processes. The BHXB Nova Muscae 1991 (GS Mus/GRS 1124–683) is a very interesting system because it has an orbital period slightly longer, 10.38 hr (Orosz et al. 1996; Casares et al. 1997), than the two other BHXBs XTE J1118+480 and A0620–00, for which an orbital decay measurement has been obtained (González Hernández et al. 2014).

The black hole mass of Nova Muscae 1991 has been recently refined to $M_{\rm BH} = 11.0^{+2.1}_{-1.4}$ M$_\odot$ (Wu et al. 2016) after previous determinations of $M_{\rm BH} = 7.2 \pm 0.7$ M$_\odot$ (Gelino 2004) and $M_{\rm BH} = 5.8^{+4.7}_{-2.0}$ M$_\odot$ (Shahbaz et al. 1997). Therefore, the BH mass is significantly larger (see Table 1) than in XTE J1118+480, $M_{\rm BH} \sim 7.5$ M$_\odot$ (Khargharia et al. 2013), and A0620–00, $M_{\rm BH} \sim 6.6$ M$_\odot$ (Cantrell et al. 2010).

The standard theory of the evolution of LMXBs (e.g. Verbunt 1993; Podsiadlowski et al. 2002; Taylor & Weisberg 1982), predicts an orbital period first derivative from AMLs due to MB and ML in short-period (SP-) BHXBs as small as $\dot{P}_{\rm MB,ML} \sim -0.02$ ms yr^{-1} whereas GR accounts only for $\dot{P}_{\rm GR} \leq -0.01$ ms yr^{-1}, according to the dynamical parameters of SP-BHXBs. Recently, González Hernández et al. (2012, 2014) reported the first detection of orbital period variations in two SP-BHXB and found them to be significantly larger than expected from conventional AML theory. The period derivative measured are $\dot{P} = -1.9 \pm 0.6$ ms yr^{-1} for XTE J1118+480 and $\dot{P} = -0.6 \pm 0.1$ ms yr^{-1} for A0620-00. Extremely high magnetic fields in the secondary star at about 10–30 kG might explain the fast spiral-in of the companion star. Alternatively, unknown processes or non-standard theories of gravity have been suggested (e.g. Yagi 2012). On the other hand, the detection of middle-infrared excesses from *Spitzer* (Muno & Mauerhan 2006) and WISE (Wang & Wang 2014) have been interpreted as evidence for the presence of candidate circumbinary disks,

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* Based on observations taken with the X-Shooter spectrograph installed at the Very Large Telescope (Program ID: 091.D-0921(A)), at Paranal Observatory of the European Southern Observatory, Chile

† E-mail: jonay@iac.es

Table 1. Kinematical and dynamical binary parameters of XTE J1118+480 and A0620–00

Parameter	Nova Muscae 1991	Ref.*	XTEJ1118+480	Ref.*	A0620−00	Ref.*
$v \sin i$ [km s^{-1}]	85.0 ± 2.6	[1]	96^{+3}_{-11}	[5]	82 ± 2	[9]
i [^{o}]	43.2 ± 2.7	[2]	73.5 ± 5.5	[6]	51.0 ± 0.9	[10]
k_2 [km s^{-1}]	406.8 ± 2.7	[1]	708.8 ± 1.4	[7]	435.4 ± 0.5	[9]
$q = M_2/M_{\rm BH}$	0.079 ± 0.007	[1]	0.024 ± 0.009	[8]	0.060 ± 0.004	[9]
$f(M)$ [M$_\odot$]	3.02 ± 0.06	[1]	6.27 ± 0.04	[7]	2.762 ± 0.009	[8]
$M_{\rm BH}$ [M$_\odot$]	$11.0^{+2.1}_{-1.4}$	[2]	$7.46^{+0.34}_{-0.69}$	[8]	$6.61^{+0.23}_{-0.17}$	[8]
M_2 [M$_\odot$]	0.89 ± 0.18	[2]	0.18 ± 0.06	[8]	0.40 ± 0.01	[8]
a_c [R$_\odot$]	5.49 ± 0.32	[2]	2.54 ± 0.06	[8]	3.79 ± 0.04	[8,11]
R_2 [R$_\odot$]	1.06 ± 0.07	[2]	0.34 ± 0.05	[8]	0.67 ± 0.02	[8,11]
$P_{\rm orb,1}$ [d]	0.432606(3)	[3]	0.1699337(2)	[8]	0.323014(4)	[12]
$P_{\rm orb,0}$ [d]	0.432605(1)	[4]	0.16993404(5)	[8]	0.32301415(7)	[8]
T_0 [d]	2448715.5869(27)	[4]	2451868.8921(2)	[8]	2446082.6671(5)	[8]
$\dot{P}_{\rm orb}$ [s s^{-1}]	$-6.56 \pm 4.03 \times 10^{-10}$	[4]	$-6.01 \pm 1.81 \times 10^{-11}$	[8]	$-1.90 \pm 0.26 \times 10^{-11}$	[8]
$\dot{P}_{\rm orb}$ [ms yr^{-1}]	-20.7 ± 12.7	[4]	-1.90 ± 0.57	[8]	-0.60 ± 0.08	[8]
$\dot{P}_{\rm orb}$ [μs cycle^{-1}]	-24.5 ± 15.1	[4]	-0.88 ± 0.27	[8]	-0.53 ± 0.07	[8]
$\dot{P}_{\rm orb,MC,o}$ [ms yr^{-1}]	-21.1 ± 12.7	[4]	-1.98 ± 0.56	[8]	-0.63 ± 0.08	[8]
$\dot{P}_{\rm orb,MC,c}$ [ms yr^{-1}]	-21.0 ± 14.2	[4]	-1.98 ± 0.59	[8]	-0.62 ± 0.12	[8]

* References: [1] Wu et al. (2015); [2] Wu et al. (2016); [3] Orosz et al. (1996); [4] This work; [5] Calvelo et al. (2009); [6] Khargharia et al. (2013); [7] González Hernández et al. (2008); [8] González Hernández et al. (2014); [9] Neilsen et al. (2008); [10] Cantrell et al. (2010); [11] González Hernández et al. (2011); [12] McClintock & Remillard (1986); [13] Morningstar et al. (2014); [14] Gou et al. (2010)

or jets (Gallo et al. 2007), in these two BHXB systems. However, Chen & Li (2015) have presented AML models including circumbinary disks but found that both the required mass transfer rate and circumbinary disk mass are far greater than the values inferred from observations. This makes unlikely that circumbinary disks are the main cause of the rapid orbital decay observed in these two BHXBs.

González Hernández et al. (2014) suggested that the observed fast orbital decays in XTE J1118+480 and A0620-00 could show an evolutionary sequence where the orbital period decay begins to speed up as the orbital period decreases. In this work we present the detection of an extremely fast orbital period decay in the SP-BHXB Nova Muscae 1991, which in fact has a longer orbital period.

2 OBSERVATIONS

We have conducted new spectroscopic observations of Nova Muscae 1991 using the 8.2m VLT telescope equipped with the X-Shooter spectrograph (Vernet et al. 2011) at Paranal Observatory (European Southern Observatory (ESO), Chile). Seventeen medium-resolution spectra ($\lambda/\delta\lambda \sim 8,800$ in the VIS arm) were obtained during four nights on 2013 April 13, 15, and 28 UT, and 2013 May 09 UT. We also observed the K-dwarf template star BD-05 3763. Radial velocity (RV) measurements (see Fig. 1) were extracted from every spectrum as in González Hernández et al. (2012), by cross-correlating the observed spectra of Nova Muscae 1991 ($m_V \sim 20.5$ at quiescence) with the K-dwarf template spectrum properly broadened with $v \sin i = 85$ km s^{-1} (Wu et al. 2015). Two RV points were rejected due to the low quality of the spectra. We try to correct for possible instrumental drifts during the observations using the telluric spectra within the X-Shooter optical spectral range with corrections in the range 0-14 km/s. We depict the RV points together with a keplerian RV curve with an orbital period fixed to the value $P_{\rm orb} = 0.4326058$ d (Orosz et al. 1996). This single fit to the RV points provides a value of the time at inferior conjunction of the secondary star, T_n (see Table 2). In order to evaluate the uncertainties of this T_n value, we have developped a MCMC bayesian analysis (Rubiño-Martin et al. 2003). We run 20 Markov chains of 75,000 iterations each resulting in a final chain of 90,000 sets of global-fit parameters. We first run the MCMC code using a keplerian function with 4 free parameters (including the orbital period). The result of the period free (P-free) simulation is shown in the upper panel of Fig. 2. This orbital period determination, $P_{\rm orb} = 0.43260(9)$ d, is consistent but less accurate than the orbital period derived by Orosz et al. (1996). We then run two additional period-fixed (P-fix) MCMC simulations whose result is depicted in middle and bottom panels of Fig. 2, one with the period fixed to the P-free MCMC result (middle) and the other one with the period fixed to the orbital period derived by Orosz et al. (1996). Clearly, the T_n determination do not depend on the orbital period choice to be fixed within the error bars. The latter becomes our final adopted value and uncertainty of the time at the inferior conjuction of the secondary star.

In Table 1 we list the updated kinematical and dynamical parameters of this and the two previously mentioned BHXBs.

3 ORBITAL PERIOD DECAY

For the determination of the orbital decay we choose the most conservative T_n value extracted from P-fix MCMC simulation adopting the orbital period by Orosz et al. (1996) (see Table 2).

Assuming a constant rate of change of the orbital period, the time of the nth orbital cycle can be expressed as

Table 2. Time at inferior conjunction of the secondary star in Nova Muscae 1991.

N	$T_n - 2440000^a$	δT_n	Refs.^{b}
0	8715.5875	0.0029	[1]
0	8715.5888	0.0012	[2]
2536	9812.6692	0.0010	[3]
14404	14946.7946	0.0004	[4]
17753	16395.5649	0.0010	[5]
17753	16395.5652	0.0025	[6]
17753	16395.5650	0.0025	[7]

[a] Times in HJD of the n^{th} inferior conjunction, T_n, of Nova Muscae 1991, and uncertainties, δT_n.

[b] [1] Remillard et al. (1992); [2] Orosz et al. (1996); [3] Casares et al. (1997); [4] Wu et al. (2015); [5] This work: value extracted from single keplerian fit with the orbital period fixed (P-fix) to the value given in Orosz et al. (1996); [6] This work: value extracted from the P-fix MCMC bayesian analysis by fixing the orbital period to the P-free MCMC result; [7] This work: value extracted from the P-fix MCMC bayesian analysis by fixing the orbital period to the value given in Orosz et al. (1996); The T_n values in Remillard et al. (1992) and Wu et al. (2015) have been corrected from times at maximum velocity to times at orbital phase 0 using the orbital period in these papers.

$T_n = T_0 + P_0 n + \frac{1}{2} P_0 \dot{P} n^2$, 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 to perform a parabolic fit ($\chi^2_\nu \sim 7.2$) and obtain a period derivative of $\dot{P} = -(6.56 \pm 1.49) \times 10^{-10}$ s/s. However, since the χ^2 of the fit is quite large, we decided to multiply the error bars by a factor of 2.7, providing $\chi^2_\nu \sim 1$. A linear function ($\dot{P} = 0$; $\chi^2_\nu \sim 1.5$) gives a worse fit, whereas a third-order polynomial (including $\ddot{P}$; $\chi^2_\nu \sim 0.02$) gives a significantly lower χ^2_ν value, although due to the still low number of points we do not consider this fit reliable.

We perform an F-test to evaluate how well the parabolic fit reproduces this set of data with respect to the linear fit. and obtain significance values of 0.07 for the first-order versus second-order polynomia, indicating that the second-order polynomial provides a better representation of the current set of data.

We may note here that adding our T_n value to literature values increases considerably the significance of the second-order polynomial fit with respect to the linear fit, due to the longer time baseline of the data. Without our measurement, the significance of the linear fit grows up to 0.45 with respect to the second-order polynomial fit that still provides better representation of the data.

In Fig. 3 we have depicted 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.

The result, $\dot{P} = -(6.6 \pm 4.0) \times 10^{-10}$ s/s, which can also be expressed as $\dot{P} = -20.7 \pm 12.7$ ms yr^{-1}, provides a determination at the $\sim 1.6\sigma$ level (i.e. at $\sim 88\%$ confidence).

Following González Hernández et al. (2014), we perform two MonteCarlo (MC) simulations: (i) with the observed T_n points by randomly varying their values with the uncertainties δT_n in a normal distribution; (ii) with the fitted T_n points on the parabolic fit. We fit 10,000 realizations of the simulated T_n points: for case (i) with weights in the fit given as $1/(\delta T_n)^2$; and for case (ii) without weights. The resulting histograms of $\dot{P}$ are shown in two small panels within Fig. 3.

These MC simulations give $\dot{P}_{\rm MC} \sim -21$ ms yr^{-1} (with an uncertainty of 12.7 – 14.2 ms yr^{-1}) and confirms the

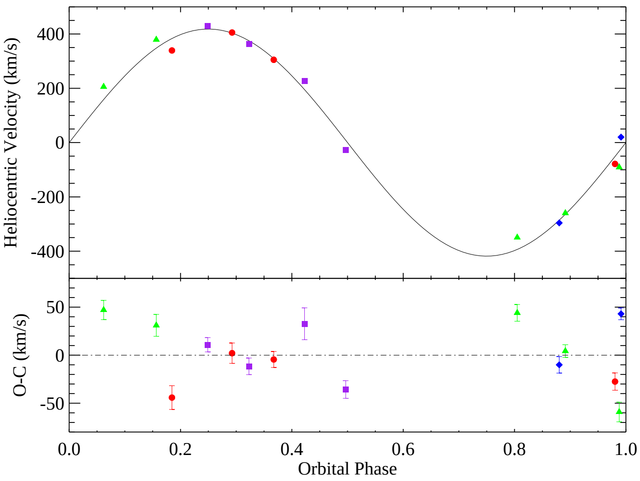

Figure 1. *Top panel*: radial velocities of the secondary star in Nova Muscae 1991 obtained from the VLT/X-Shooter spectroscopic data taken on the four nights of April 13 (red filled circles), April 15 (blue filled diamods), and April 28 (green filled triangles), and May 09 (violet filled squares) in 2013, folded on the best-fitting orbital solution. *Bottom panel*: residuals of the fit, with a rms of ~ 30km s^{-1}.

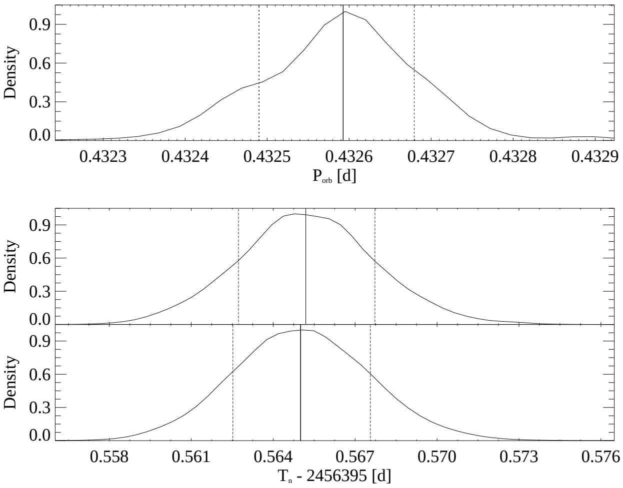

Figure 2. *Top panel*: Posterior distribution of the orbital period, $P_{\rm orb}$, extracted from the MCMC Bayesian analysis of the new X-Shooter RV points of the secondary star in Nova Muscae 1991. *Middle and bottom panel*: Posterior distributions of the time at the inferior conjunction of the secondary star, T_n, by fixing $P_{\rm orb}$ to the MCMC result (middle) and by fixing $P_{\rm orb}$ to the value (bottom) derived by Orosz et al. (1996).

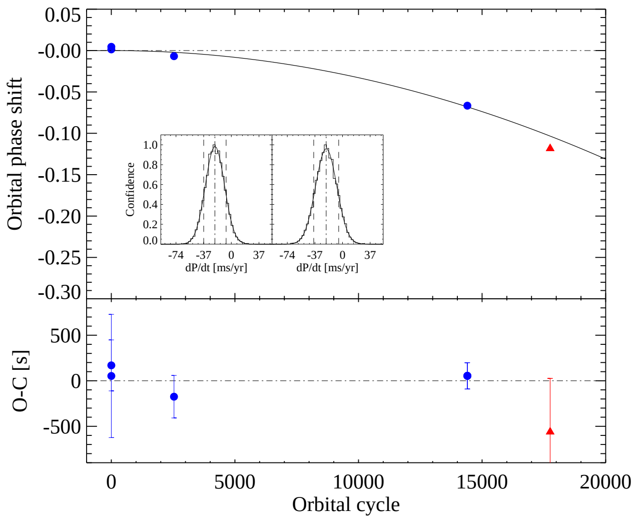

Figure 3. *Top panel*: orbital phase shift at the time of the inferior conjunction (orbital phase 0), T_n, of the secondary star in the BHXB Nova Muscae 1991 versus the orbital cycle number, n, folded on the best-fit parabolic fit. The error bars give the uncertainties δT_n (see text and Table 2). Blue filled circles are previous liturature spectroscopic determinations, and the red filled triangle is a photometric measurement is the new VLT/X-Shooter spectroscopic P-fix MCMC determination (see Table 2). The small panels show two MonteCarlo (MC) simulations of 10,000 realizations taking into account the uncertainties of each T_n point: (i) with the observed data set, i.e. using T_n values as a center of the MC distributions (left small panel), and (ii) using the points on the parabolic fit (rigth small panel). *Bottom panel*: residuals of the fit of the T_n values versus the cycle number n.

extremely fast orbital shrinkage in Nova Muscae 1991 (see Table 1).

4 DISCUSSION AND CONCLUSIONS

Short period BHXBs exhibit negative orbital period derivative but at different rate, with Nova Muscae 1991 ($P_{\rm orb} \sim$ 10.4 hr) showing the fastest orbital decay. Conventional models of AMLs due to GR, MB and ML are far from being able to reproduce this behaviour. González Hernández et al. (2014) suggested an evolutionary sequence in which the orbital decays observed in short-period BHXBs would be faster as the companion star approaches the black hole. However, the case of Nova Muscae 1991 rules out this hypothesis.

González Hernández et al. (2012, 2014) estimated the orbital period derivative, $\dot{P}_{\rm MB,ML}$, when considering only AMLs due to MB and ML. They demonstrated that $\dot{P}_{\rm MB,ML}$ cannot account for the fast orbital decay observed in XTE J1118+480. Standard prescriptions of MB, assuming $\gamma = 2.5$ (Verbunt 1993) and adopting arbitrarily $\beta = -\dot{M}_{\rm BH}/\dot{M}_2 = 0.5$ (Podsiadlowski et al. 2002), and the specific angular momentum, $j_w = 1$, carried away by the mass lost from the system, provide values of $\dot{P}_{\rm MB,ML} \sim -0.028$ ms yr^{-1} for Nova Muscae 1991. In the extreme and unrealistic case, $\gamma = 0$, i.e the strongest possible MB effect, and $\beta = 0$, i.e all the mass transferred by the secondary star is lost from the system, we only get $\dot{P}_{\rm MB,ML} \sim -0.11$ ms yr^{-1}, which is 300 times smaller than the observed orbital period decay. At orbital periods shorter than 3 hr, standard theory predicts that gravitational radiation begins to dominate, but its contribution is totally negligible for Nova Muscae 1991, $\dot{P}_{\rm GR} \sim -0.011$ ms yr^{-1}.

González Hernández et al. (2012, 2014) suggested that extremely high magnetic fields at the surface of the secondary star, in the range $B_S \sim$ 0.4-30 kG, could help to explain the fast orbital decay in XTE J1118+480 and A0620-00. The mass transfer rates (King et al. 1996) of these two systems and Nova Muscae 1991 are estimated to be $\dot{M}_2 \sim 0.10, 0.46, 1.67 \times 10^{-9}$ M$_\odot$ yr^{-1}, respectively. Assuming conservative mass transfer (i.e. no mass lost from the system, $\dot{M}_{\rm BH} = -\dot{M}_2$) and negleting AML due to gravitational radiation, we can make a rough estimate of the magnetic field, B_S, at the surface of the secondary required to accomodate the period decays observed in these three BHXBs (see Justham et al. 2006, for further details). We find $B_S \sim$ [0.7, 2.3, 7.4], [16, 50, 160], [12, 38, 120] kG, respectively, for three values of the wind-driving energy efficiency factor, $f_\epsilon = [10^{-1}, 10^{-2}, 10^{-3}]$ (Tavani & London 1993). The extremely high B_S values estimated at low $f_\epsilon \sim 10^{-3}$, could be compensated with higher mass tranfer rates. However, for $f_\epsilon = 0.1$, the magnitudes of the surface magnetic fields are still consistent with those in peculiar Ap stars (Justham et al. 2006). As discussed in González Hernández et al. (2014) the secondary might have been able to retain the high magnetic field during the binary evolution.

Althought speculative, these high magnetic fields might be connected with the (rotation induced) chromospheric activity on the companion star, as proposed for A0620–00 (González Hernández & Casares 2010) to explain the observed Hα emission feature of the secondary star. Hα emission from the companion has been also detected in XTE J1118+480 (Zurita et al. 2016) and Nova Muscae 1991 (Casares et al. 1997) and (González Hernández et al. 2016, in preparation).

An alternative scenario is that we may be measuring orbital period modulations similar to what has been observed before in other type of binaries such as Algol objects, e.g. V471 Tau (Skillman & Patterson 1988), or cataclysmic variables (CVs Pringle 1975; Warner 1988). In these systems, orbital period modulations of the order of $\Delta P/P \sim 10^{-5} - 10^{-6}$ with different signs have been observed. Theoretical models invoking a variable gravitational quadrupole moment, due to internal deformations, produced by magnetic activity in the outer convection zone have been suggested as the mechanism responsible for those period changes (Applegate & Patterson 1987; Applegate 1992). This mechanism would also imply extremely high magnetic fields (González Hernández et al. 2014), but it appears quite unlikely that the large orbital period decays seen in these BHXBs (all with negative sign) are the result of orbital period modulations.

On the other hand, Schreiber et al. (2016) have recently speculated that nova eruptions may produce frictional AML in CVs, as a possible solution of the WD mass problem, the orbital period distribution and the space density of CVs. This consequential AML could also occur in BHXBs during outburst with significant mass ejections, as has been very recently seen in V404 Cygni (Muñoz-Darias et al. 2016).

Recently, Chen & Li (2015) have proposed AML models including circumbinary disks as a possible way to explain the fast orbital period decays in these BHXBs. This work shows the evolution of orbital period and period derivative for XTE J1118+480 during $\sim 0.8 - 1.2$ Gyr (for initial $M_2 \sim 3 - 1.5$ $\mathrm{M}_\odot$) of its binary evolution. The model requires a current mass transfer rate of about 10^{-8} $\mathrm{M}_\odot$ yr^{-1}, which is significantly larger than the current estimated mass transfer rate of 10^{-10} $\mathrm{M}_\odot$ yr^{-1}. It also requires a circumbinary disk with a mass ($M_{\mathrm{CD}} \sim 2 - 3 \times 10^{-4}$ $\mathrm{M}_\odot$) which is significantly larger than the inferred from mid-IR observations, i.e. $\sim 10^{-9}$ $\mathrm{M}_\odot$ (Muno & Mauerhan 2006). In addition, Gallo et al. (2007) has suggested that non-thermal synchrotron emission from a jet could account for a significant fraction (or even all) of the measured excess mid-IR emission.

The orbital decays observed in these BHXBs, if kept constant, predict that the secondary star will reach the event horizon as given by the Schwarzschild radius of ∼22, 19 and 32 km in about 12 Myr for XTE J1118+480, 70 Myr for A0620–00, and only 2.7 Myr for Nova Muscae 1991. This is an extremely short timescale, although the companion's fate is probably not realistic. In a standard evolutionary scenario with AMLs driven by MB and GR, a minimum orbital period is expected (and observed in CVs, see Gänsicke et al. 2009). The minimum period is caused by the response of the companion star to mass loss when it reaches the substellar limit (Paczynski 1981). It is unclear whether this scenario would be valid here but, in any case, the large orbital period decays measured clearly have very important implications on the evolution and lifetime of short-period BHXBs, which, according to the standard models, is typically $\sim 5 \times 10^9$ yr. In addition, the companion stars with spectral types earlier than K5V show high Li abundances (Martín et al. 1996; González Hernández et al. 2004, 2006), similar to those of low mass stars of the young (120 Myr) Pleiades cluster (Garcia Lopez et al. 1994), which are not easily explained unless a Li preservation mechanism is invoked, on the basis of high rotation velocities of the companion stars kept during the evolution of tidally locked BHXBs (Maccarone et al. 2005; Casares et al. 2007). A shorter lifetime, of $\sim 10^7 - 10^8$ yr, would alleviate this high-Li problem in BHXBs as well as the long-standing birthrate problem of millisecond pulsars and low-mass BHXBs (Naylor & Podsiadlowski 1993; Podsiadlowski et al. 2002). Future observations of these BHXBs, in particular, of Nova Muscae 1991 will probably help to undertand these extremely fast orbital period decays.

ACKNOWLEDGMENTS

JIGH acknowledges financial support from the Spanish Ministry of Economy and Competitiveness (MINECO) under the 2013 Ramón y Cajal program MINECO RYC-2013-14875, and JIGH and RRL also acknowledge financial support from the Spanish ministry project MINECO AYA2014-56359-P. JC also aknowledges support from MINECO through the program AYA2013-42627 and from the Leverhulme Trust through the Visiting Professorship Grant VP2-2015-046.

We are grateful to J. A. Rubiño Martín for provinding us with several routines that allow us to implement the MCMC bayesian analysis.

We are grateful to T. Marsh for the use of the MOLLY analysis package. This work has made use of the IRAF facilities.

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