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A BLACK HOLE IN THE X-RAY TRANSIENT XTE J1859+226: THE FIRST CONFIRMED WITH GTC

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RESUMEN

Presentamos los resultados del análisis del primer agujero negro confirmado con GTC en la binaria de rayos X XTE J1859+226. Combinando fotometría visible tomada con el INT, WHT y NOT con espectroscopía de rendija larga tomada con OSIRIS+GTC, hemos obtenido un periodo orbital de 6.58 ± 0.05 h, una amplitud de la velocidad radial de la estrella compañera de $K_2 = 541 \pm 70$ km s^{-1} y un límite superior de la inclinación de 70°, lo que implica un agujero negro de al menos 5.4 $M_\odot$

ABSTRACT

We present the results of the analysis of the first black hole confirmed with GTC in the X-ray binary system XTE J1859+226. By combining optical photometry taken with the INT, WHT and NOT with long-slit spectroscopy with OSIRIS+GTC, we have obtained an orbital period of 6.58 h, a secondary star radial velocity amplitude of $K_2 = 541 \pm 70$ km s^{-1} and an upper limit to the inclination of 70°, implying a black hole mass of at least 5.4 $M_\odot$.

Key Words: accretion, accretion disks — binaries: close — stars: Individual: XTE J1859+226 (=V406 Vul) — X-rays: binaries

1. INTRODUCTION

An X-ray binary (XRB) is a system formed by a “normal” star and a compact object, either a neutron star or a black hole. The transients are a class of XRBs which show sporadic outbursts produced by instabilities in the accretion disc surrounding the compact object. After an outburst, the system brightness begins its decay (which typically lasts for months) to its quiescent state to stay there from years to even centuries until the next outburst. In ∼40 years of X-ray astronomy, only 17 black hole transients have been dynamically confirmed out of an estimated population of 3000–5000 XRBs in our Galaxy (Casares 2010).

The dynamical confirmation of the nature of the compact object requires to obtain the mass function $f(M_x) = K_2^3\ P/2\pi\ \mathrm{G} = M_x\ \sin^3\ i/(1 + M_x/M_2)^2$. From the left side of the equation, we see that this only depends on two observational parameters: (i) the secondary star's radial velocity amplitude K_2, to be obtained through spectroscopy and (ii) the orbital period P of the system obtained through photometry. The mass of the compact object M_x requires to constrain the inclination i (by modelling the light curve of the tidally distorted companion) and the binary mass ratio M_x/M_2, being M_2 the mass of the companion star. As the equation of states establishes the critical mass between a neutron star and a black hole in 3 $M_\odot$, if $f(M_x)$ is greater than that, the compact object has to be a black hole.

2. THE XRB SYSTEM XTE J1859+226

XTE J1859+226 was discovered by the RXTE satellite during its 1999 outburst (Wood et al. 1999). From its X-ray properties it was considered a strong candidate to contain a black hole. After almost a year in outburst, the system decayed to quiescence. Several values of the orbital period were published between 6.72 and 18.72 h (see Uemura et al. 1999; Garnavich, Stanek, & Berlind 1999; McClintock et al. 2000). Zurita et al. (2002), based on observations taken in 2000 with the Isaac Newton Telescope (INT) and the William Herschel Telescope (WHT), at the Observatorio del Roque de Los Muchachos on La Palma (Spain), reported orbital periods between 6.72 and 11.04 h with the same confidence level (68%). Filippenko & Chornock (2001) reported a 9.1 h modulation with 10 spectra taken in 2 nights with the Keck telescopes, obtaining a mass function of 7.4 $M_\odot$, one of the largest ever recorded, but their data were never published in a paper.

3. THE DATA

In 2008 we used the 2.5 m Nordic Optical Telescope (NOT) on La Palma to obtain and model the

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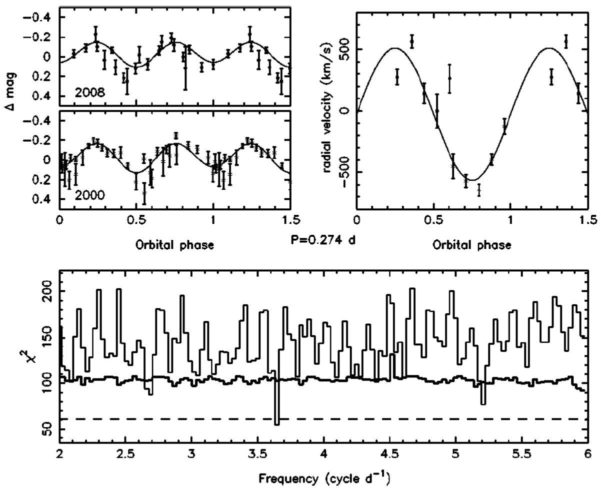

Fig. 1. Top left and right: Optical photometric light curve and radial velocity curve phase folded on the 6.58 h orbital period, respectively. 1.5 cycles are shown for clarity. Bottom panel: χ^2 periodogram. Solid line represents the 99% white noise significance level while the dashed line shows the 99% confidence level above the minimum χ^2 at 3.65 cycles d^{-1} (=6.58 h).

ellipsoidal modulation of the companion star. Despite the dusty weather conditions (calima) producing 1 mag extinction, we found a clear ellipsoidal modulation typical of this type of transient. With the data taken also in quiescence in 2000 (Zurita et al. 2002), we were able to constrain the orbital period between 6.6 and 7.6 h, but periods in this range were equally probable at the same confidence level. Hence, we discarded the 9.1 h period published by Filippenko & Chornock (2001) .

More photometric data were taken in 2010 with the NOT but we found the object in an unexpected active state, ∼1 mag brighter than the quiescence level. The light curves were dominated by flares and dips with amplitudes up to 0.4 mag and typical time-scales of minutes (Corral-Santana, Casares, & Rodríguez-Gil 2010).

The faintness of the object (R∼22.4 in quiescence) required the use of the 10.4 m Gran Telescopio Canarias to take spectra. Two of the 3 observing blocks assigned were carried out using OSIRIS + R1000B and a 0.6 ″ slit obtaining 5 spectra in each one (July and August 2010). The spectra showed clear double peak profiles in the Hα and Hβ emission lines produced in the accretion disc around the compact object. The FWHM measured was of ∼2300 km s^{-1} which was consistent with other systems with accreting black holes.

4. ANALYSIS AND RESULTS

To obtain the orbital period, we computed a simultaneous fit of the 10 radial velocity points taken with GTC and the 32 photometric data taken in 2000 and 2008 with the NOT. The results are shown in Figure 1 which shows a χ^2 periodogram of the data (bottom panel) with the 99% white noise significance level through Monte Carlo simulations (solid line). Three minima above the noise level are clearly seen at 6.58 h, 4.60 h and 8.92 h respectively with increasing χ^2 value. However, the minimum at ∼6.6 h is the only one with a significance above the 99% level at the minimum χ^2. The next minimum at 4.6 h has a significance of only 3×10^{-4}.

The derived K_2 obtained for the adopted orbital period of 6.58±0.05 h is 541±70 km s^{-1}. Combining both parameters in the equation above we obtain a $f(M_x) = 4.5 \pm 0.6\ M_\odot$ and hence the confirmation of a black hole in the binary system. Furthermore, by modelling the light curves we were able to constrain the inclination between 40° and 70°. Even with all of the limitations in the K_2 of our spectroscopy and i, we have obtained that the mass of the black hole is at least 5.42 $M_\odot$. An in depth description of this work can be found in Corral-Santana et al. (2011).

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