The first black hole orbiting a Be star

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Abstract: Stellar-mass black holes have been discovered in binary systems. The study of radial velocities of the companion stars allows us to restrict the masses of the compact objects. The Be/Compact Object binary system MWC 656 (also known as HD 215227) shows Fe II 4583Å and He II 4686Å emission lines (both double-peaked) on its spectrum. These lines indicate the existence of disks surrounding the binary components. Through the analysis of the radial velocities of He II (formed in the surrounding gas of the compact object) and Fe II (formed in the circumstellar disk around the Be star) emission lines using the SBOP program, the existence of a compact object with a mass in the range of 3.7 to 6.9 solar masses (within errors) is proved. As the lower value of the mass of the compact object is above the Tolman-Oppenheimer-Volkoff limit (3 solar masses), the Be star companion is classified as a black hole. Around 80 Be X-ray binaries have been found up to now. All but MWC 656 are supposed to be Be/Neutron star systems. For this reason, MWC 656 has been considered the first binary system consisting of a Be star and a black hole. Finally, the difficulty of detecting these Be/Black hole binaries through X-ray surveys is explained thanks to the study of black holes states.

I. INTRODUCTION

A black hole (BH) is a space-time region where the gravitational field is so strong that no object carrying information can get out of it [1]. The black holes discovered up to now appear to be clustered in 3 ranges of masses. Stellar-mass black holes display a mass is in the range of 3 to ~20 solar masses. Intermediate-mass black holes span a range in mass from 100 to 1000 solar masses. Finally, super-massive black holes have masses in the range of 10^5 to 10^9 solar masses [2].

About half of the stars form binary systems. One of the binary components can be a compact object, either a neutron star (NS) or a black hole (BH) [3]. If the binary components are close enough, mass transfer towards the compact object can take place. Some of these binaries emit X-rays and are classified as X-ray binaries. There are two types of X-ray binaries: low mass X-ray binaries, where the mass of the stellar companion is below 1 solar mass, and high mass X-ray binaries, where the companion mass is ≥ 8 solar masses. The X-ray emission arises from the accretion of gas that occurs when the donor star supplies matter to the compact object: if the companion is a low-mass star through Roche lobe overflow, if the companion is a massive star through stellar winds [4]. Stellar-mass black holes have all been discovered through their X-ray emission [5].

When the companion star in an X-ray binary is a Be star, which is a fast rotating star that shows characteristic spectral emission lines of hydrogen and has a circumstellar disk surrounding it, the system is called a Be X-ray binary [5]. Binary evolution models predict the existence of BH accreting mass from the disk of Be star companions [6].

From a theoretical point of view, black holes from Be/BH binaries are supposed to be in long quiescent states, i.e. they have a low X-ray luminosity. For this reason, these binary systems are supposed to be difficult to detect through their X-ray emission. Probably, this is the cause of the absence of Be/BH binaries [7].

There are approximately 80 Be X-ray binaries known. All of them are thought to be Be/NS systems: 50 of them are known to be NS because X-ray pulses are detected, and the others are supposed to be NS from their X-ray spectrum [5]. However, Casares *et al.* (2012) suggested that the binary system MWC 656 (also known as HD 215227) could host a BH as compact object [8]. The aim of this dissertation is to show this BH solution for the binary system MWC 656, reproducing the recent work done by [5].

In this work, we clarify why the stellar-mass black holes have a lower limit (Section II). In section III we explain how to derive the compact object mass thanks to the radial velocities of the binary system. In section IV we show the radial velocity curves of the components of the binary system MWC 656 and their subsequent analysis using the Spectroscopic Binary Orbit Program (SBOP) [9]. Also, in section IV we derive the BH mass. Finally, in section V we discuss why it is difficult to detect Be/BH through their X-ray emission.

II. TOV LIMIT

When the life of stars comes to the end, the pressure (generated by nuclear fusion) can no longer compensate the gravity. At this moment, the gravitational collapse begins, leading to a white dwarf, a neutron star or a black hole [10].

In white dwarfs, the degeneracy pressure of the electrons, which are fermions and obey the Pauli exclusion principle, balances the gravitational force. A maximum mass limit of M~1.44 solar masses exists for white dwarfs (known as Chandrasekhar limit) [11]. If the mass is above this limit, the electron degeneracy pressure cannot support the object against collapse. Therefore, the star continues collapsing. The temperature and the density increase greatly, so that the electronic capture ($p^+ + e^- \rightarrow n + \nu$) can take place. The amount of neutrons increases enormously and the neutron degeneracy pressure (neutrons are fermions too) acts, counteracting the gravity and leading to a neutron star. As in white dwarfs, there is an upper limit to the mass of a neutron-degenerate celestial body, the Tolman-Oppenheimer-Volkoff limit or TOV limit. Beyond this limit, the neutron degeneracy pressure is not able to support the gravitational force and a black hole is formed [2].

In order to get the value of the TOV limit, the equation of state (EOS) of nuclear matter must be solved. For that very reason, the outcome depends on the EOS used. Also, the result depends on the spinning velocity of the neutron star. In the event of a static NS, the TOV limit is around 2.1 solar masses [12]. However, if this star is rotating quickly, this

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limit rises up to 2.9 solar masses [13]. Therefore, when the mass of a compact object is above 3 solar masses, we consider that the compact object is a black hole.

III. RADIAL VELOCITIES IN BINARY SYSTEMS

The radial velocity analysis of the spectral lines of a star allows us to determine the possible existence of a black hole orbiting it.

To keep things simple, we start by analyzing a binary system in which $m_1 >> m_2$. We will generalize this to $m_1 > m_2$.

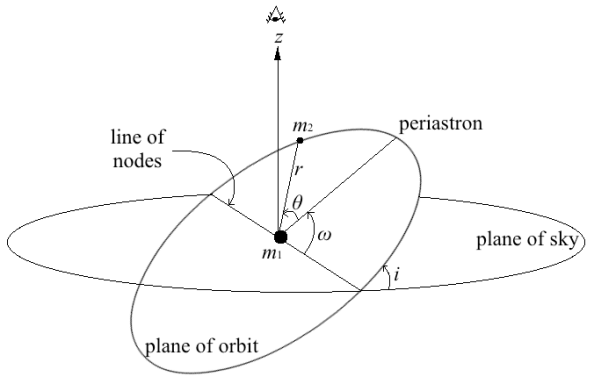

FIG. 1: In this binary system a body of mass m_2 is orbiting another astronomical object of mass m_1 on the plane of orbit, considering the observer and the plane of sky too. Furthermore, this figure shows the periastron and the orbital parameters of the binary system.

We show in Fig.(1) the plane of the orbit and the plane of sky of a binary system. The z-axis is aligned with the line of sight, which joins the observer with the centre of masses of the system (CM). Considering that $z = 0$ is the CM of the orbit, it is easy to see that m_2 is at

$$z = r\sin(\theta + \omega)\sin i \tag{1}$$

where r is the distance between m_1 and m_2, θ is the angle between the periastron and the position of m_2, ω is the angle between the line of nodes and periastron and i is the orbital inclination. If we take the derivative of z with respect to time, we will obtain how the distance m_2-CM projected on the CM-observer line changes, i.e. the radial velocity v_r. Therefore,

$$v_r = \dot{z} = \left[\dot{r}\sin(\theta + \omega) + r\dot{\theta}\cos(\theta + \omega)\right]\sin i \tag{2}$$

Experimentally, we can measure the radial velocity through optical spectroscopy: the difference between the wavelength λ_{obs} observed from a moving source and the wavelength λ_{rest} measured in the laboratory for a reference source at rest is related to the radial velocity v_r of the source,

$$\frac{v_r}{c} = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}} \tag{3}$$

where c is the speed of light. For this reason, if we know λ_{obs} and λ_{rest} we will be able to derive v_r [2].

Carrying on with the theoretical explanation, we must know $\dot{r}$ and $r\dot{\theta}$ to find v_r. The orbits are elliptical, so we can use the general equation of an ellipse

$$r = \frac{a(1-e^2)}{1 + e\cos\theta} \quad , \tag{4}$$

where a is the semi-major axis and e is the eccentricity. Taking the derivative of r with respect to time

$$\dot{r} = \frac{er\dot{\theta}\sin\theta}{1 + e\cos\theta} \tag{5}$$

In order to get $r\dot{\theta}$ we use the second Kepler's law integrated during a full period, P:

$$\frac{A}{P} = \frac{1}{2}r^2\dot{\theta} \tag{6}$$

where $A = \pi a^2\sqrt{1-e^2}$ for an ellipse. Rewriting this law as $r\dot{\theta} = 2A/rP$ and replacing the known values of r and A, we get

$$r\dot{\theta} = \frac{2\pi a(1 + e\cos\theta)}{P\sqrt{1-e^2}} \tag{7}$$

This leads to the following result:

$$\dot{r} = \frac{2\pi ae\sin\theta}{P\sqrt{1-e^2}} \tag{8}$$

Finally, replacing $\dot{r}$ and $r\dot{\theta}$ into v_r and using a couple of trigonometric identities, we find:

$$v_r = K\left[\cos(\theta + \omega) + e\cos\omega\right] \tag{9}$$

$$K = \frac{2\pi a\sin i}{P\sqrt{1-e^2}} \tag{10}$$

where K is the radial velocity semi-amplitude of m_2 [14].

Now, we generalize this to $m_1 > m_2$. For this reason, m_1 is not in the CM. Therefore, m_1 and m_2 are orbiting around the CM, so we can write their radial velocities

$$\begin{aligned} v_r(1) &= K_1\left[\cos(\theta_1 + \omega_1) + e_1\cos\omega_1\right] \\ v_r(2) &= K_2\left[\cos(\theta_2 + \omega_2) + e_2\cos\omega_2\right] \end{aligned} \tag{11}$$

where $K_i = K_i(a_i)$ following equation (10), $\theta_2 = \theta_1 + 180^\circ$, $\omega_2 = \omega_1 + 180^\circ$ and $e_1 = e_2$. Let us remove the dependence on a_i in the quantity K_i. With this purpose, we use the third law of Kepler (with $a = a_1 + a_2$)

$$P^2 = \frac{4\pi^2 a^3}{G(m_1 + m_2)} \tag{12}$$

and the following CM property: $m_1 a_1 = m_2 a_2$. Using all this information, we get

$$K_1 = \left(\frac{2\pi G}{P}\right)^{1/3} m_2 (m_1 + m_2)^{-2/3} \frac{\sin i}{\sqrt{1-e^2}}$$
$$K_2 = \left(\frac{2\pi G}{P}\right)^{1/3} m_1 (m_1 + m_2)^{-2/3} \frac{\sin i}{\sqrt{1-e^2}} \quad (13)$$

Dividing both equations,

$$\frac{K_1}{K_2} = \frac{m_2}{m_1} \quad (14)$$

Therefore, if the value of m_1 and the values of the radial velocity semi-amplitudes of the binary system are known, we can then estimate the value of m_2.

In a high mass X-ray binary, m_2 is the mass of the compact object and m_1 the mass of the more massive companion star. If m_2 is beyond 3 solar masses, then the compact object will be a BH (see Section II for further information).

In addition, we define the mass function of m_2 [15] as

$$f(m_2) = \frac{4\pi^2}{G} \frac{(a_1 \sin i)^3}{P^2} = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2} \quad (15)$$

This is an important equation because the value of $f(m_2)$ is the minimum mass of the compact object. We are able to prove this by rewriting equation (15):

$$f(m_2) = \frac{m_2 \sin^3 i}{\left(1 + \frac{m_1}{m_2}\right)^2} \quad (16)$$

In this equation, $\sin^3 i \leq 1$ and the denominator is always larger than 1, so $f(m_2) < m_2$. Therefore, we have already shown that $f(m_2)$ is the minimum mass of the compact object. We can get the equation for $f(m_1)$ exchanging the subscripts 1 and 2 one another in (15).

IV. MWC 656 AND ITS BH

A. Observations

MWC 656 was observerd in 2011-2012 with the Mercator and Liverpool Telescopes, located in the Observatorio del Roque De Los Muchachos, on La Palma (Spain), to obtain optical spectra to derive radial velocities. We show in Fig.(2) a spectrum from Mercator, which reveals a double-peaked Fe II 4583Å emission line originated in the Be circumstellar disk (double-peaked profiles are the signature of gas orbiting in Keplerian geometry around its host). The Fe II profile centroid is modulated with the 60.37-day orbital period (inferred from photometric variability [16]) as it is shown in Fig.(3) using 34 data points from the Liverpool Telescope (LT). The Mercator spectrum from Fig.(2) also shows a He II 4686Å emission line, which requires temperatures hotter than can be achieved in disks around Be stars. Furthermore, the He II profile is double-peaked too, indicative of a disk in Keplerian motion, and its centroid is modulated with the 60.37-day orbital period as we can see in Fig.(3) using the data from the LT. In this figure, we can also observe that this is in antiphase with the radial velocity curve of the Be star, an indication that the He II emission line comes from the accretion disk surrounding the companion instead of from the star [5].

The periodic variation of both emission lines confirms us that MWC 656 is a binary system. Thanks to the He II emission line, we have an indication that there is accretion of gas towards the compact object orbiting the Be star. Now we are going to analyse the data from both emission lines to determine the orbital parameters.

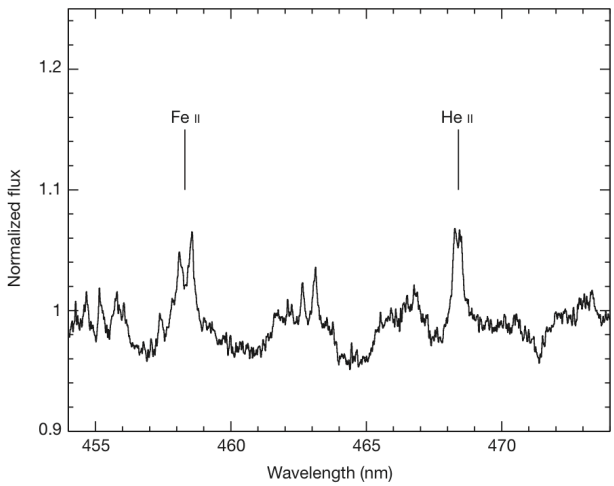

FIG. 2: Optical spectrum of MWC 656 obtained with the Mercator telescope. The emission lines Fe II 4.583Å and He II 4.686Å are indicated. From Casares *et al.* (2014).

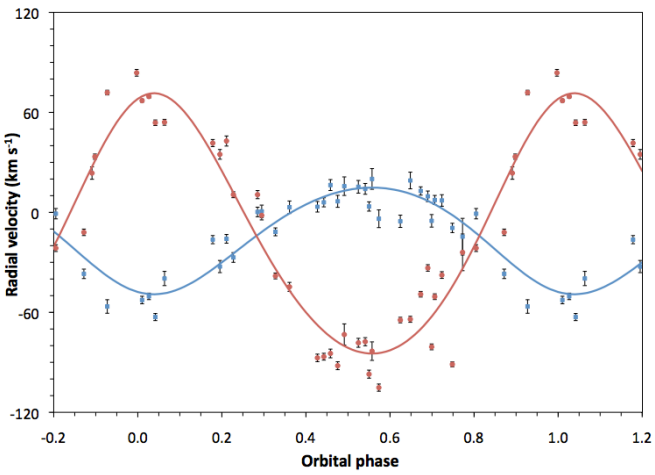

FIG. 3: Radial velocity curves of MWC 656 and its companion obtained from Liverpool Telescope Data. The orbital phase has been computed using P = 60.37d and T_0 = 2453243.7HJD. The blue squares represent the data obtained from the Fe II 4583Å line, while the red circles represent the data obtained from the He II 4686Å line. A combined orbital fit (obtained using SBOP) is overplotted. The He II data were shifted +30km s^{-1} (see Section IV.B for details).

B. Analysis of radial velocities

Radial velocities were analyzed using the Spectroscopic Binary Orbit Program (SBOP) [9], which allowed us to get the orbital elements for He II and Fe II emission lines, separately. The results are shown in Table I.

Parameter	Fe II λ4583	He II λ4686
P (days)	60.37 (Fixed)	60.37 (Fixed)
T_0 (HJD-2450000)	3243.1±4.2	3245.3±6.1
e	0.24±0.06	0.08±0.05
ω (º)	164.4±26.3	351.7±32.7
γ (km s^{-1})	-13.5±2.3	-44.5±2.8
K (km s^{-1})	31.0±3.7	78.8±3.6
a sin$i$ ($R_\odot$)	35.9±4.3	93.7±4.3
$f(M)$ ($M_\odot$)	0.17±0.07	3.03±0.42

TABLE I: Orbital parameters derived from the radial velocities of the Fe II and He II emission lines using SBOP, where P is the orbital period (fixed to the photometric value [16]), T_0 is the epoch of periastron (units of Heliocentric Julian Date), e is the orbit eccentricity, ω the longitude of periastron, γ the systemic velocity, K the velocity semi-amplitude, a the semi-major axis, i the binary inclination and $f(M)$ the mass function of the stellar mass M.

We can see in Table I that the epochs of periastron are compatible within errors and that a 180º phase displacement is present in ω (within the errors), as expected if the lines are formed in two different objects orbiting a common CM [5].

Furthermore, the systemic velocity γ is shown for both lines in Table I. Both values of γ must be the same in order to be a binary system. However, γ values are not compatible. There is a difference of +30km s^{-1} caused by an S-wave component seen in the core of the He II profile, typically associated with the presence of a bright spot in the outer accretion disk [17], so that the real systemic velocity is ~15km s^{-1}.

For these reasons, after correcting the data of the He II emission line with this +30km s^{-1} shift, we can get a solution for both lines jointly, instead of separately. The best-fitting curves to the data are plotted in Fig.(3) and the best-fitting parameters are shown in Table II.

Parameter	Value
P (days)	60.37 (Fixed)
T_0 (HJD-2450000)	3243.70±7.86
e	0.10±0.05
ω (º)	163.0±20.8
γ (km s^{-1})	-14.1±2.4
K_1 (km s^{-1})	32.0±5.7
K_2 (km s^{-1})	78.1±6.1
a_1 sin$i$ ($R_\odot$)	38.0±8.0
a_2 sin$i$ ($R_\odot$)	92.8±7.2
M_1 sin^3i ($M_\odot$)	5.83±1.00
M_2 sin^3i ($M_\odot$)	2.39±0.62
M_2/M_1	0.41±0.08

TABLE II: Orbital parameters for MWC 656 derived from a joint fit to both He II and Fe II radial velocities using SBOP. Orbital parameters are the same as in Table I and the subscript denotes the object considered in each case.

C. The mass of the compact object

The solution shown in Table II yields a mass ratio $q = M_2 / M_1 = 0.41 \pm 0.08$. Now, we want to know the mass of the compact object, M_2. First we need to know the Be star mass, as we have already said (Section III). For this reason, a precise spectral classification of the star is needed [5]. Williams (2010) [16] suggested that MWC 656 was a B3 IV. However, Casares *et al.* (2014) [5] performed a spectral classification study and concluded that the star is B1.5 III and has a mass between 10 and 16 solar masses.

These values place the companion star in the range of 3.7 to 6.9 solar masses, considering the uncertainty of the mass ratio. As the TOV limit is in 3 solar masses (Section II), the compact object is a black hole.

The Be star mass could be underestimated due to the high spinning velocity of the star, so that the mass of the BH could be even higher [5].

Our result is compatible with the previous result from [5] within errors. The difference between both lower limits of the mass of the compact object is owing to the errors of the orbital parameters obtained with SBOP, which lead to a different value for δq.

V. THE STATE OF THE BH IN MWC 656

Black holes show different X-ray spectral states, usually following a cycle of variability [18]. Before the description of the spectral states, a brief explanation of the components of a BH X-ray emission should be done. The emission can be separated in two components: a thermal component, which obeys a black body radiation law, and a non-thermal component, associated to a power law like

$$F = N_0 E^{-\Gamma} \quad , \qquad (17)$$

where F is the flux, N_0 the photon number, E the energy and Γ the photon index. Any obtained flux of a BH is typically a combination of both components and the percentage of the components varies depending on its spectral state [18].

There are 4 different states:

- High/soft state (also known as thermal state): The black hole X-ray flux is dominated by the blackbody component (the heat radiation arisen from its inner accretion disk), contributing above the 75% of the total flux emitted, so that the non-thermal component (photon comptonitzation caused by accelerated electrons that transfer energy to the photons) is less than 25%. No detection through radio waves can be done because there are no relativistic jets in this state. In this state the accretion disk is known to extend quite close to the BH.

- Low/hard state: The BH has a hard power law component ($\Gamma \sim 1.7$) that contributes ≥85% of the total flux emitted, so that the contribution of the non-thermal component is very high. The flux of the accretion disk is weak in this state and its temperature is colder than in the thermal state. The hard state is associated with the presence of quasi-steady relativistic radio jets.

- Steep power law state or very high state: The BH has a strong power law component too ($\Gamma \sim 2.5$). This state can be considered as an intermediate state between the thermal state

and the hard state. It is characterized by a sizable thermal component below 50-80%. The very high state differs from the thermal state because the power low is higher in the first one.

- Quiescent state: This state is characterised for BH luminosities four or more orders of magnitude below the luminosity of the high/soft state, i.e. $< 10^{-5} L_{\mathrm{Edd}}$ (the Eddington luminosity, L_{Edd}, is the maximum luminosity a body achieve when the radiation balances the gravity) [19 and references therein]. Black holes tend to be the biggest part of their life in this state, characterised by a non-thermal component of $\Gamma \sim 1.5 - 2.1$.

Casares *et al.* (2014) [5] suggested that Be/BH binary systems are difficult to detect through X-ray surveys owing to black holes are in a very long quiescent state on these systems [7]. Munar-Adrover *et al.* (2014) [19] have detected MWC in X-rays with a luminosity of $\sim 10^{-7} L_{\mathrm{Edd}}$, showing that its BH is, indeed, in quiescence.

VI. CONCLUSIONS

Despite the difficulty of detecting black holes in binary systems orbiting Be-type stars through X-ray surveys because they remain quiescent during a long period of time, a black hole has been suggested in MWC 656. In this work we explained the mass limit (TOV) to consider a source to be a BH, how to obtain the orbital parameters from radial velocity data and we have analyzed the Fe II and He II emission lines from MWC 656 using SBOP to derive the mass of its compact object. We reproduced within errors the results published in Casares *et al.* (2014). After all of this, the existence of the Be/BH binary systems is confirmed. This is an important fact for understanding the evolution of the massive binaries.

Acknowledgments

I thank Marc Ribó for giving me a hand when it was needed. I thank Jorge Casares for sending us the radial velocity data of the He II and Fe II emission lines. Also, I thank Ignasi Ribas for his help with SBOP. Finally, I thank my family for encouraging me at the stressful moments.

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