New estimate of the black hole mass in the binary system MWC 656

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Abstract: This work consists of the study of the MWC 656 binary system. It was the first binary system composed of a Be star and a black hole ever found. Black holes orbiting Be star are of great interest in the study of supernova explosions and formation of a binary system composed of a neutron star and a black hole because their merging in nearby galaxies could be detected via gravitational waves. We analysed the radial velocities from the photo-spheric He I absorption lines generated in the Be star and from the He II emission line generated in the accretion disc of the compact object. Two single-line fits and one double line fit are presented. From the single-line fits we observed that the epoch and the argument of periastron correspond to those of a binary system. However, we found different eccentricities: e=0.41±0.08 from the Be star orbit and e=0.09±0.03 from the black hole orbit. In addition, from the double-line fit, fixing e to 0.2, we estimated the mass range of the compact object to be M_2 =3.0–7.4$M_\odot$ which still implies the presence of a black hole. Furthermore, we calculated that a mass loss of ΔM=(3.6±1.9) $M_\odot$ in a supernova explosion is enough to explain an eccentricity of 0.2±0.1 and the measured space velocity of the binary system.

I. INTRODUCTION

MWC 656 (= HD 215227) turned out to be a system of a black hole (BH) orbiting a Be star, thus it was the first Be-BH binary system ever found (Casares et al. 2014). Compact objects orbiting Be stars had always been found with a neutron star (NS). Therefore, this discovery solved the problem of the missing Be-BH binaries (Belczynski and Ziolkowski 2009). The main feature of Be stars is their outflowing disc (excretion disc) on the equatorial plane around the star, due to its fast rotation.

Williams et al. (2010) presented an optical photometric periodicity of 60.37±0.04 d for MWC 656. Later on, Casares et al. (2014), noticed the presence of a Fe II emission line from the system, which had to be originated in the excretion disc. Moreover, this emission line presented a double peak, that is related to Keplerian motion. Also a He II emission line was observed with a double peak, indicative of keplerian motion as well. The radial velocities from the He II emission line were in anti-phase with the radial velocities from the Fe II emission line. Therefore, the He II emission line had to be originated in the accretion disc around the compact object. Furthermore by fitting a double-line solution to the radial velocity curves of the Fe II and the He II emission lines, they obtained an eccentricity of 0.10±0.04 and a mass ratio of M_2/M_1=0.41±0.07 $M_\odot$. They also located the system at a distance of 2.6±0.6 kpc and classified the spectra of the Be star as B1.5–B2 III, which implies a mass of M_1=13±3 $M_\odot$. Therefore, the mass range of the compact object was estimated to be M_2=3.8–6.9 $M_\odot$, being MWC 656 the first Be-BH binary system ever found.

Be stars with compact objects orbiting them are of great interest in studies of a supernova (SN) because in their evolution one or two supernovas may be produced. The first one, may be created when the progenitor of the compact objects collapses, thus the Be-NS or the Be-BH binary system is born. As Be stars have masses in the 3–18 $M_\odot$ range, a second SN may be produced. Although, this mass range is probably not enough to form a BH, a NS could emerge in this SN. Therefore, Be stars orbiting BH are highly interesting because if the objects remain bound after the SN, a binary system of BH-NS emerges. Furthermore, Grudzinska et al (2015) stated that if these system were close (not wide), their merging in nearby galaxies could be detected by the LIGO observatory via gravitational waves.

In addition, from the velocity distribution of pulsars, Repetto et al. (2017) concluded that NSs had to receive a natal kick at birth. However, in the formation of BHs there is no need of these kicks. Only the mass loss in the supernova explosion is enough to explain their space velocities as it can be seen in Nelemans et al. (1999).

In this work, we present fits to new radial velocity data for the binary system MWC 656. In section II of this document we present the data of the photo-spheric He I absorption lines of the Be star and the He II emission lines of the accretion disc around the compact object. These lines were used to obtain the radial velocities which are analysed in this work. In section III we explain some issues of the code SBOP that was used to fit the radial velocities. In section IV we show the results of the radial velocity fitting using single-line or double-line fitting. In section V we discuss if a symmetric supernova explosion scenario is enough to explain the space velocity of MWC 656. Finally, the conclusions of this study are presented in section VI.

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II. OBSERVATIONAL DATA

The observational data used in this study are the radial velocities of the photo-spheric absorption lines originated in the Be star and the emission lines originated in the accretion disc around the compact object. From the Be star the followings absorption lines of He I were observed: 4388, 4471, 4713 and 5048Å. In the following we will refer to them as He I lines. From the accretion disc the He II 4686Å emission line was observed and we will refer to it has He II line. From 2011 April 24 to 2015 December 12, 193 medium-resolution spectra of MWC 656 were obtained using the 2.0-m Liverpool telescope located at the Observatorio del Roque de Los Muchachos (ORM) located in La Palma, Spain. Moreover, 38 high-resolution spectra were measured with two other telescopes: 13 spectra between the nights of 2013 April 21 and August 17 were collected using the 1.2-m STELLA I telescope at Izaña Observatory at Tenerife, Spain; finally, 25 spectra were observed between 2014 May 24 and 2015 September 23 using the 2.5-m Nordic Optical Telescope (NOT), located at the ORM.

The data analysed in this work are the radial velocities obtained from the spectra. Only the data measured by the NOT were used to compute the radial velocities of the He I absorption lines due to the high-resolution of the telescope. On the other hand, all the spectra were used for the He II emission line.

III. RADIAL VELOCITY FITTING WITH SBOP

The radial velocity fits in the following sections were computed using the code SBOP (Spectroscopic Binary Orbit Program) (P. Etzel 2014). SBOP allows fitting the radial velocity points to an eccentric orbit model for a single-line or a double-line. In particular it allows to fit the following parameters -some as fixed and others as variable-: epoch of periastron (T_0), argument of periastron (ω) eccentricity (e), systemic velocity (γ) and velocity semi-amplitude (K). In addition, the mass ratio ($q{=}M_2/M_1$) and $M\sin^3(i)$ are computed with the double-line solution as well, being i the inclination of the orbit.

The way to proceed with the code SBOP was to run it with different values of the input parameters. If it was possible for the program to make the fit of the radial velocities with the given inputs, it returned the parameters of the fitted solution. In order to avoid falling in local minima these outputs were compared with the ones obtained varying the input parameters. Finally, if they did not differ significantly, they were accepted as good. In some cases a solution with a negative eccentric value was found. Although the absolute value of the eccentricity and other parameters seemed to be coherent, they were not accepted as a valid solution of the fit. In other cases the velocity semi-amplitude was negative which implied a negative inclination of the binary orbit. These solutions were also dismissed.

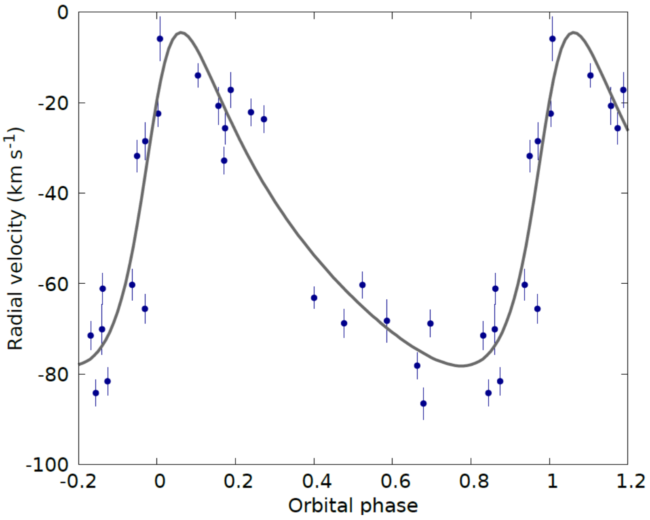

FIG. 1: Radial velocities of the photo-spheric absorption lines of He I from the Be star as a function of the orbital phase (blue points). Error bars represent 1-σ uncertainties. The solid line represents the single-line fit that was computed using the code SBOP with the period fixed to 59.10 d. The parameters of the fit are presented in the second column of TABLE 1. The corresponding orbit is shown in FIG. 2.

IV. RESULTS AND DISCUSSION

A. He I and He II single-line fits

First, a single-line model was fitted to the radial velocities of the He I absorption lines with a period fixed to 59.10 d. An orbital period of 59.10 d was used instead of the photometric period of 60.37 d found by Williams et al. (2010) because the long-term study of the radial velocities reveals that 59.10 d is the real orbital period from the binary system (J. Casares, private communication). The radial velocities of the He I absorption lines are represented in FIG. 1 and their computed radial velocity curve is over-plotted as well. The parameters that best fit the eccentric orbit are presented in the second column of TABLE 1. Furthermore, the orbit of the binary system is drawn in FIG. 2.

Second, we fitted the radial velocities of the He II emission line from the accretion disc with the period fixed to 59.10 d. The radial velocities of the He II emission line are represented in FIG. 3 and their computed radial velocity curve is over-plotted as well. In addition, the parameters of the He II single-line fit are shown in the third column of TABLE 1.

The results of the fit in TABLE 1 correspond to a binary system, as it was expected: the arguments of periastron are in anti-phase, they differ 180°, and the epochs of periastron differ a multiple of the period (within 1-σ

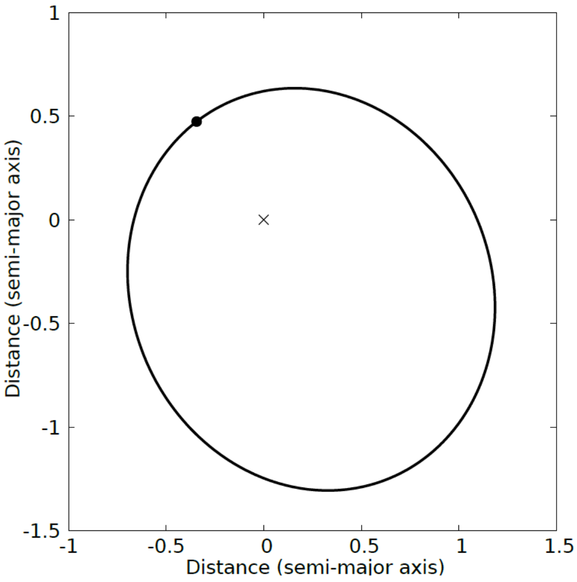

FIG. 2: Orbit of the compact object around the Be star corresponding to the He I single-line fit shown in FIG. 1. The eccentricity is e=0.41 and the argument of periastron ω=306°. The position of the compact object at periastron is represented with a black circle and the Be star position is represented with a cross at (0,0). The observer is at the bottom.

TABLE I: Orbital parameters obtained from the single-line fits of the radial velocity curve of both the Be star and the accretion disc around the compact object. The second column corresponds to the single-line fit of the He I absorption lines and the third one corresponds to the He II emission line. The orbital period P was fixed to 59.10 d, while the other parameters T_0 (where HJD refers to heliocentric Julian date), e, ω, γ and K were computed using the code SBOP.

Parameter	He I absorption lines	He II emission line
P (days)	59.10 (fixed)	59.10 (fixed)
T_0 (HJD−2450000)	6982.7 ± 1.8	7039.7 ± 3.4
e	0.41 ± 0.08	0.09 ± 0.03
ω (°)	306 ± 17	103 ± 21
γ (km s^{-1})	-50 ± 2	-38 ± 2
K (km s^{-1})	37 ± 4	84 ± 3

uncertainties). However, we note that there is a discrepancy in e and γ that will be commented in the following section.

B. He I - He II double-line fit

The double-line fitting made to the He I and He II lines requires to solve two problems. First, there is a long-term variability in the central velocity of the Fe II emission line of the excretion disc of the Be star. Furthermore, this variability has also been observed in the He II emission line of the accretion disc around the compact object, both with a variability of ∼7 years (J. Casares, private communication). However, there are not enough data covering the long-term variability to accurately determine the systemic velocity of the binary system. We tried double-line fits to the radial velocity curves of He I and He II lines applying different offsets to the last ones. An offset of -13 km s^{-1} provided reasonable results after visual inspection (with an uncertainty of ±5 km s^{-1}). This offset was not applied to the He II single-line fit because it would only produce a displacement to the radial velocities without affect the parameters of the fit (other than γ).

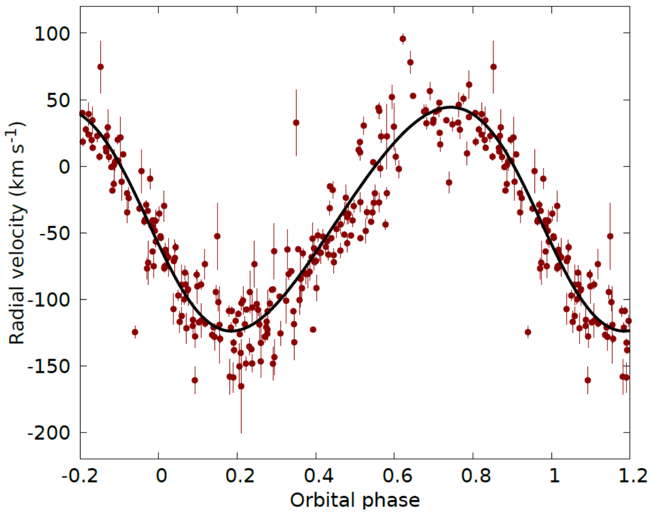

FIG. 3: Radial velocities of the He II emission line as a function of the orbital phase (red points). Error bars represent 1-σ uncertainties. The solid line represents the single-line fit that was computed using the code SBOP with the orbital period fixed to 59.10 d. The parameters of the fit are presented in the third column of TABLE 1.

Second, there is a large difference in the eccentricities found in the single line fits. The eccentricity of the He I single-line fit is probably more accurate than the eccentricity of the He II single-line fit because it is known that the He II emission line is contaminated by an S-wave component which swings between the He II double peak (Casares et al. 2014). The problem is that the double peak and the S-wave can not be disentangled with three Gaussians beacuse the majority of the He II spectra were not measured with enough spectral resolution. Therefore, only a single Gaussian was fitted which took in the double peak and the S-wave and thus the measured He II radial velocities where contaminated by the S-wave. The problem is that in all the double-line fits, with the period fixed, we obtained $e \simeq$0.1, similar to the eccentricity found in the He II single-line fit. That is because there are more data of the He II emission line so it carried more weight in the double-line solution using the code SBOP. For this reason, we decided to fix the eccentricity in the double-line fit. Different fits were computed with the period fixed to 59.10 d and the eccen-

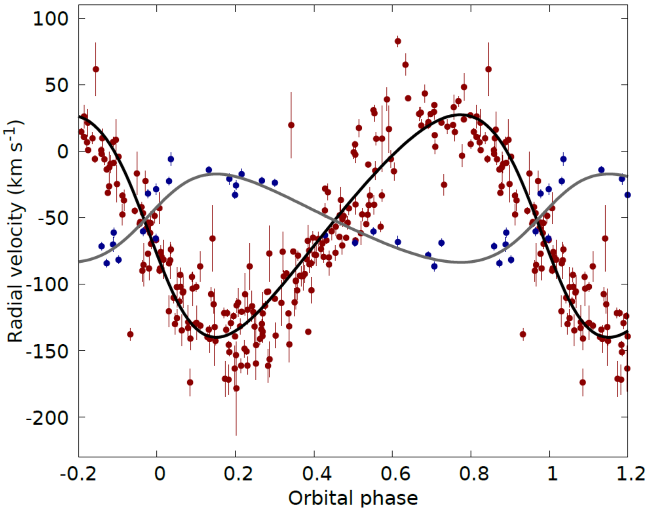

FIG. 4: Radial velocities as a function of the orbital phase of the He I absorption lines generated in the Be star (blue points) and the He II emission line originated in the accretion disc around the compact object (red points) already shown in FIG. 1 and FIG. 2 (with an offset here of -13 km s^{-1}). Error bars represent 1-σ uncertainties. The solid lines (grey line for He I and black line for He II) represent the double line fit which was computed using the code SBOP with P=59.10 d and e=0.2 fixed. The parameters of the fit are presented in TABLE 2. The corresponding orbit is shown in FIG. 5.

TABLE II: Orbital parameters obtained using the code SBOP in the double-line fit of the radial velocity curves of both the He I photo-spheric absorption lines and the He II emission line. The parameters P=59.10 d and e=0.2 were fixed while the computed parameters were: T_0, ω, γ, K, $M\sin^3(i)$ (where M is the mass of the object and i the inclination of the orbit) and the mass ratio q. The subscript 1 and 2 refer to the Be star and the compact object, respectively.

Parameter	Value
P (days)	59.10 (fixed)
T_0 (HJD$-$2450000)	7040.2 ± 1.5
e	0.2 (fixed)
ω (°)	285 ± 10
γ (km s^{-1})	-52 ± 2
K_1 (km s^{-1})	33 ± 12
K_2 (km s^{-1})	84 ± 3
$M_1\sin^3(i)$ ($M_\odot$)	6.6 ± 1.4
$M_2\sin^3(i)$ ($M_\odot$)	2.6 ± 1.1
q=M_2/M_1	0.40 ± 0.14

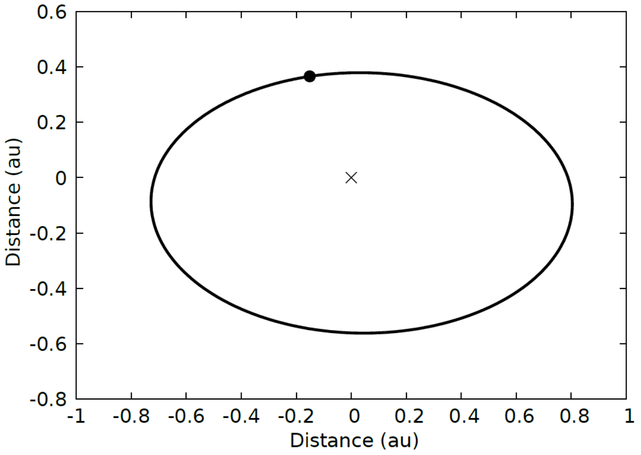

FIG. 5: Orbit of the compact object around the Be star seen with an inclination of i=52.9°, e=0.2 and ω=284°. These parameters are the same than those of the fit shown in FIG. 4. The semi-major axis was computed with the third Kepler's law and is expressed in astronomical units. The position of the compact object at periastron is represented with a black circle and the Be star position is represented with a cross at (0,0).

tricity fixed between the values found in the single-line fits. The result that fits better the radial velocity curves in the double-line fit was with e=0.2. The double-line solution with P=59.10 d and e=0.2 fixed is plotted with the representation of the radial velocities in FIG. 4 and the parameters are listed in TABLE 2.

Since the mass of the Be star obtained by Casares et al. (2014) is M_1=13±3$M_\odot$ and our mass ratio is q=0.40±0.14, the mass of the companion is:

$$M_2 = 5.2 \pm 2.2 M_\odot$$

The presence of the He II emission line in the accretion disc around the companion of the Be star implies that it has to be a compact object. Moreover, it can not be a white dwarf because the mass range M_2 = 3.0–7.4$M_\odot$ of the compact object highly exceeds the Chandrasekhar mass limit. Moreover, Chamel et al. (2013) presented a maximum mass of neutron stars in the range M=2–3$M_\odot$. Therefore, the companion can not be a NS either and it strongly points towards a BH. In addition this value includes the mass range (M_2=3.8–6.9$M\odot$) found by Casares et al. (2014). Once the value of both masses is known, the semi-major axis (a) can be computed with the third Kepler's law, and the orbit inclination (i) from the fit. The results are: a=0.8±0.2 au and i=52.9±0.2°. With these parameters the orbit of the binary system was plotted in FIGURE 5.

We note that the BH mass range could be improved in two ways. First, by using more data from the He I absorption line in order to avoid to overrate the He II emission line in the double-line fit. Second, by using higher resolution spectra to measure the He II line, in order to disentangle the double peak and the S-wave with 3 Gaussians and get rid of the S-wave. This would also allow us to make this fit without fixing the eccentricity of the binary system.

V. MASS LOSS IN SN EXPLOSION

A supernova explosion (SNe) can accelerate a binary system by two ways. The first one, is caused in a symmetric SNe by the ejection of mass, which modifies the binary system orbital parameters and its space velocity. The second one, is caused by asymmetries in the SNe which produce a substantial kick velocity to the compact object. The kick further modifies the orbital parameters, particularly the eccentricity, and slightly increases the space velocity of the binary system. In some systems there is no need of additional kick velocities to explain their eccentricity ant space velocity (Nelemans et al. 1999). Therefore we will study the space velocity of MWC 656 in the case of a symmetric SNe.

Using the parameters in section IV we computed the mass loss in a symmetric SNe which is given by Nelemans et al. (1999):

$$\Delta M = e_{\mathrm{postSN}}(M_1 + M_2) = (3.6 \pm 1.9) M\odot \qquad (1)$$

where e_{postSN} is the eccentricity after the SN occurs, which we consider the current one, here taken as 0.2±0.1. M_1 and M_2 refer to the Be star mass and the BH mass, respectively.

Considering the post supernova period as the current one (59.10±0.05 d) and using the equation 5 from Nelemans et al. (1999) to compute the re-circularized period, we obtain:

$$P_{\mathrm{re-circ}} = P_{\mathrm{postSN}}(1 - {e_{\mathrm{postSN}}}^2)^{3/2} = (56 \pm 3)\ \mathrm{d} \qquad (2)$$

With these parameters the theoretical space velocity can be computed as follows (Nelemans et al. 1999):

$$\left(\frac{v_{\mathrm{sys}}}{\mathrm{km\,s^{-1}}}\right) = \\ = 213 \left(\frac{\Delta M}{M\odot}\right) \left(\frac{M_1}{M\odot}\right) \left(\frac{P_{\mathrm{re-circ}}}{\mathrm{days}}\right)^{-\frac{1}{3}} \left(\frac{M_1 + M_2}{M\odot}\right)^{-\frac{5}{3}} \qquad (3)$$

obtaining a theoretical space velocity for the binary system MWC 656 of:

$$v_{\mathrm{sys}} = (21 \pm 11) \mathrm{km\,s^{-1}}$$

This value is compatible within uncertainties with the computed space velocity of (20±17)km s^{-1} (M. Ribó, private communication). This space velocity was computed with the distance, the position and the galactic rotation model from Reid et al. (2014) and with the proper motion of Gaia (Gaia Collaboration et al. 2016). Hence, a symmetric SN explosion with a mass loss of (3.6±0.9) $M_\odot$ is enough to explain both the eccentricity and the space velocity and there is not need of any additional kick.

VI. CONCLUSIONS

In this work we have presented a study of the MWC 656 binary system. We analysed with the code SBOP the radial velocities from photo-spheric the He I absorption lines generated in the Be star and from the He II emission line generated in the accretion disc around the compact object. SBOP allowed us to fit the radial velocity points to an eccentric orbit model for a single-line or a double-line. First, we presented two single-line fits with the period fixed (P=59.10 d) which reveal that the epoch and the argument of periastron corresponds to a binary system. Moreover, we obtained an eccentric orbit with e=0.41 and e=0.09 for the Be star and the compact object, respectively. Second, a double-line fit was made with the period fixed to 59.10 d and the eccentricity fixed to 0.2. From this fit we obtained a mass ratio of 0.40±0.14, which allowed us to estimate the mass of the compact object to 3.0–7.4$M_\odot$. Therefore, this high mass still implies the presence of a black hole. In addition, we estimate that a mass loss of ΔM=(3.6±1.9)$M_\odot$ in a symmetric supernova explosion scenario is enough to explain both the eccentricity and the space velocity of the MWC 656 binary system.

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