

# Mass of the compact object in the Be/ $\gamma$ -ray binaries LSI+61°303 and MWC 148

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(Submitted on 4.04.2017. Accepted on 18.05.2017)

**Abstract.** We estimate the mass of the compact object in the  $\gamma$ -ray binaries LSI+61°303 and MWC 148, using the latest data for the inclination, orbital motion and assuming that the orbital plane coincides with the equatorial plane of the Be star. For LSI+61°303 we find the mass of the compact object to be most likely in the range  $1.3 M_{\odot} < M_2 < 2.0 M_{\odot}$ , which means that it is probably a neutron star. For MWC 148, we find the mass of the compact object in a higher range,  $2.1 M_{\odot} < M_2 < 7.3 M_{\odot}$ , which increases the chances for this system to host a black hole companion.

**Key words:** Stars: emission-line, Be – binaries: spectroscopic – Gamma rays: stars – Stars: individual: LSI+61303, MWC 148

## 1 Introduction

The  $\gamma$ -ray binaries are high-mass stellar systems whose spectral energy distribution contains a significant and persistent non-thermal component, at energies above 1 MeV and up to the TeV domain. Only a handful of these objects are currently known (Dubus 2013; Paredes et al. 2013). Among this scarce group, one finds a dominant presence of luminous, emission line optical stars with Oe or Be spectral type. Their unseen compact companion can be either a neutron star or a black hole. Here, we will broadly refer to these systems as Be/ $\gamma$ -ray binaries. They can also be considered as a subclass of the more numerous normal Be/X-ray binaries, which contain more than 90 confirmed and suspected objects (Reig 2011), but detected only up to keV energies.

At present there are three confirmed Be/ $\gamma$ -ray binaries so far – LS 2883 = PSR B1259–63 (Aharonian et al. 2005), LSI+61°303 = 2CG 135+01 (Albert et al. 2009), and MWC 148 = HESS J0632+057 (Aharonian et al. 2007). Some other binaries may be related to this group, such as the system MWC 656 = AGL J2241+4454 with GeV transient  $\gamma$ -ray emission (Lucarelli et al. 2010; Casares et al. 2012).

The nature of the compact object is certainly known in PSR B1259–63 (e.g. Chernyakova et al. 2015 and references therein). It is a neutron star acting as radio pulsar with a period of 47.76 ms (Shannon et al. 2014). The neutron star has a mass  $\sim 1.4 M_{\odot}$  and is orbiting a O9.5Ve star with mass  $M_1 \approx 30 M_{\odot}$  (Negueruela et al. 2011). For MWC 656, Casares et al. (2014) have analyzed the radial velocities variability and found convincing evidences for a black hole of 3.8 to 6.9  $M_{\odot}$  orbiting an B1.5-B2 IIIe primary with  $M_1 \approx 10 - 16 M_{\odot}$ . More information on the compact object masses is needed to better discriminate among different possible theoretical scenarios for high energy emission. These mainly include the magnetospheric pulsar model and the microquasar jet model where a black hole could be expected

(see e.g. Paredes et al. 2013). Other alternative scenarios could also play a role here, such as the propeller regime in neutron stars proposed more than three decades ago as a possible mechanism for TeV  $\gamma$ -ray emission (Wang & Robertson 1985)

In this work, we estimate the range of masses for the compact objects in two Be/ $\gamma$ -ray binaries – the systems LSI+61°303 and MWC 148.

## 2 Mass of the compact object

In the following, we will assume that the inclination of the orbit  $i_{orb}$  is approximately equal to the inclination of the Be star equatorial plane with respect to the line of sight within a few degrees. The question is whether it is a plausible assumption is shortly addressed in Sect.3. In particular, we apply Kepler’s third law:

$$P_{orb}^2 = \frac{4\pi^2(a_1 + a_2)^3}{G(M_1 + M_2)} \quad (1)$$

where  $G$  is the gravitational constant,  $P_{orb}$  is the orbital period of the binary,  $a_1$  is the semi-major axis of the orbit of the primary,  $a_2$  is the semi-major axis of the orbit of the secondary,  $M_1$  is mass of the primary, and  $M_2$  is the mass of the compact object.

For the primary star mass, we use the best information available. In the LSI+61°303 case, an appropriate range of values was derived from its spectral type and the latest calibrations by Hohle et al. (2010) based on revised Hipparcos data. In the MWC 148 case, the most accurate primary mass values come from the comparison of its average optical spectrum with several grids of stellar models (Aragona et al. 2010).

Given a pair  $(M_1, M_2)$  and the system orbital period, we compute the relative semi-major axis  $a = a_1 + a_2$  using Eq. 1. From published Doppler radial velocity observations, we also have an estimate of the projected semi-major axis  $a_1 \sin i_{orb}$  of the optically visible primary star. This parameter can be de-projected using the assumed value of the orbital inclination. Then, we can obtain the secondary semi-major axis as  $a_2 = a - a_1$ , and get an estimate of the secondary star mass as  $M_2 = M_1(a_1/a_2)$ . While keeping  $M_1$  fixed, the procedure is iterated until the secondary mass converges within a dozen iterations. The calculation is consequently repeated across the whole range of allowed primary mass values.

A consistency check of the procedure is that the resulting  $M_2$  estimate has to be above the strict lower limit to the compact object mass provided by the well known concept of mass function. This is given observationally by the following combination of projected semi-major axis and orbital inclination:

$$f(M_2) = \frac{4\pi^2(a_1 \sin i_{orb})^3}{GP_{orb}^2} \quad (2)$$

## 2.1 LSI+61°303

From a radio survey of the galactic plane, LSI+61°303 (V615 Cas) was first proposed by Gregory & Taylor (1978) as a  $\gamma$ -ray source in the *COS B* satellite catalogue (Swanenburg et al. 1981). It became a confirmed TeV source many years later (Albert et al. 2006). A Bayesian analysis of radio observations gives the orbital period of the binary as  $P_{orb} = 26.4960 \pm 0.0028$  d (Gregory 2002). The orbital eccentricity is  $e \simeq 0.537$ , obtained on the basis of the radial velocity measurements of the primary (Casares et al. 2005; Aragona et al. 2009). The inclination of the primary star Be disc in LSI+61°303 to the line of sight is probably  $i_{Be} \sim 70^\circ$  according to Zamanov et al. (2013). Aragona et al. (2009) give  $a_1 \sin i_{orb} = 8.64 \pm 0.52 R_\odot$ . For the primary, Grundstrom et al. (2007) suggested a B0V star. A B0V star is expected to have on average  $M_1 \approx 15.0 \pm 2.83 M_\odot$  (Hohle et al. 2010). We calculated  $M_2$  as described above for a few sets of parameters  $a_1 \sin i_{orb} = 8.12, 8.64, 9.16 R_\odot$  and  $i_{orb} = 65^\circ, 70^\circ, 75^\circ$ . The specified lines are plotted in Fig. 1. The red (dotted) lines are for  $a_1 \sin i_{orb} = 8.12 M_\odot, i = 65^\circ$  and  $a_1 \sin i_{orb} = 9.16 M_\odot, i = 65^\circ$ . The blue (dashed) lines are for  $i = 75^\circ$ . The black (solid) line represents  $a_1 \sin i_{orb} = 8.64 R_\odot, i_{orb} = 70^\circ$ , corresponding to the average values of separation and inclination.

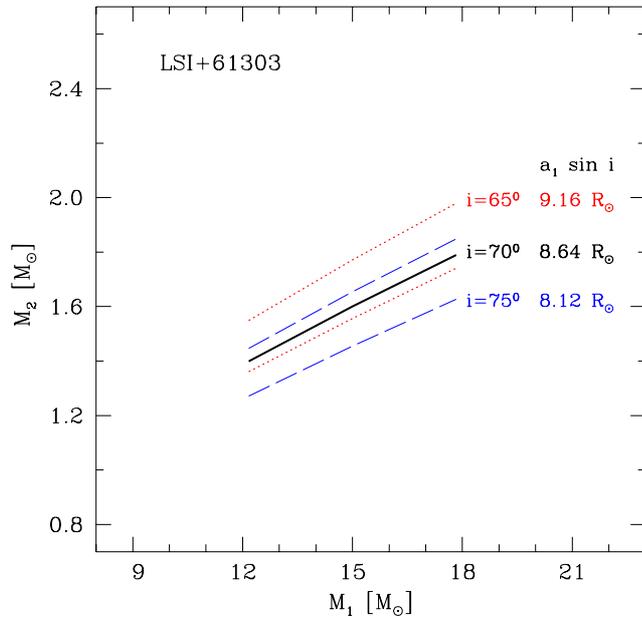
Assuming a B0V star with mass in the range  $12.17 M_\odot < M_1 < 17.83 M_\odot$ , we estimate the mass of the compact object in the range  $1.27 < M_2 < 1.98 M_\odot$ , with most likely value  $M_2 \approx 1.6 M_\odot$ .

## 2.2 MWC 148

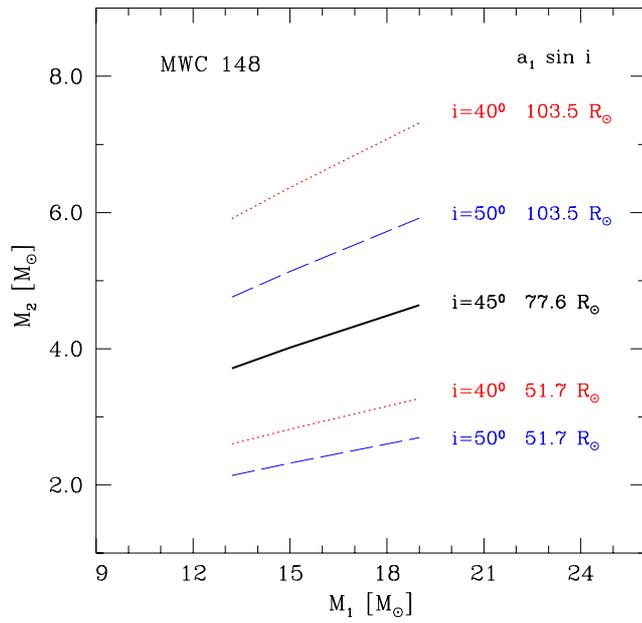
MWC 148 (HD 259440) was identified as the counterpart of the variable TeV source HESS J0632+057 (Aharonian et al. 2007, Maier & for the VERITAS Collaboration 2015). We adopt  $P_{orb} = 315_{-4}^{+6}$  d derived from the X-ray data (Aliu et al. 2014), which is consistent with the previous result of  $321 \pm 5$  days (Bongiorno et al. 2011). For this object, Aragona et al. (2010) derived  $M_1 = 13.2 - 19.0 M_\odot$  from their spectral model fits. From radial velocity measurements, Casares et al. (2012) also estimated  $a_1 \sin i_{orb} = 77.6 \pm 25.9 R_\odot$  with an eccentricity of  $e = 0.83$ .

The optical emission lines of MWC 148 are very similar to those of the well-known bright Be star  $\gamma$  Cas (Zamanov et al. 2016). All detected lines in the optical spectral range 4100 - 7500 Å (Balmer lines, HeI lines and FeII lines) have similar intensities, profiles, equivalent widths, and even a remarkable "wine-bottle" structure is apparent in the  $H\alpha$  line profile.

The models of Hummel (1994) demonstrate that the profiles of emission lines formed in Be discs are the most sensitive to the footpoint density and inclination angle and that the wine bottle structure in  $H\alpha$  is visible for specific inclinations  $i = 15^\circ - 45^\circ$ . Hanuschik (1989) demonstrated that there is a strong correlation between FWHM of  $H\alpha$  and  $v \sin i$ . Because both stars have similar mass and they are Be stars and rotatates at almost critical velocity, the similarity between the FWHM of the emission lines indicates similar  $\sin i$ .



**Fig. 1.** Mass of the compact object versus the mass of the primary for the  $\gamma$ -ray binary LSI+61 $^\circ$ 303.



**Fig. 2.** Mass of the compact object versus the mass of the primary for the  $\gamma$ -ray binary MWC 148.

Based on such a strong resemblance, we consider that the Be star geometry in MWC 148 should be similar to that of  $\gamma$  Cas, for which the inclination is  $43^\circ \pm 3^\circ$  (Pöeckert & Marlborough 1978; Clarke 1990). Therefore, we will proceed with our estimates of the compact object mass in MWC 148 by adopting different inclinations in the vicinity of this value.

We calculate  $M_2$  for different sets of parameters  $a_1 \sin i_{orb} = 51.7, 77.6, 103.5 R_\odot$  and  $i_{orb} = 40^\circ, 45^\circ, 50^\circ$ . The lines corresponding to these values are plotted in Fig. 2. The red (dotted) lines are for  $i = 40^\circ$ . The blue (dashed) lines are for  $i = 50^\circ$ . The black solid line represent  $a_1 \sin i_{orb} = 77.6 R_\odot, i_{orb} = 45^\circ$ , corresponding to the average values of separation and inclination.

Assuming a mass of primary star in the range  $13.2 \leq M_1 \leq 19.0 M_\odot$ , we estimate mass of the compact object in the range  $2.1 M_\odot < M_2 < 7.3 M_\odot$ , with most likely value  $M_2 \approx 4.0 M_\odot$ .

### 3 Discussion

The two  $\gamma$ -ray binaries discussed here have non-zero eccentricities and misalignment between the spin axis of the primary component and the spin axis of the binary orbit could be theoretically possible (Brandt & Podsiadlowski 1995; Okazaki & Hayasaki 2007; Martin et al. 2014). However, if a significant misalignment existed, then we would expect to see considerable variability in the  $H\alpha$  emission line at the time when the compact object crosses the circumstellar disc – twice in each orbital period. No such variability is detected in the observations of  $H\alpha$  emission, which means that any misalignment is less than the opening half-angle of the circumstellar disc. The opening half-angle of the Be stars circumstellar disc are  $\approx 10^\circ$  (Tycner et al. 2006; Cyr et al. 2015), and in Sect. 2, we have supposed that the orbital plane coincides with the equatorial plane of the Be star within a few degrees. Therefore, our main assumption in this work appears to be justified at least for the two systems being considered. Our derived mass ranges are also dependent on additional assumptions on the physical properties of non-degenerate stars, specially the mass, according to the most recent data available.

Strict lower limits to the mass of the compact objects are set from the mass functions of the different spectroscopic orbital solutions. For LSI+61°303 the mass function is  $f(M_2) = 0.0124 \pm 0.0022 M_\odot$  (Aragona et al. 2009), for MWC 148 it is  $f(M_2) = 0.06^{+0.15}_{-0.05} M_\odot$  (Casares et al. 2012). The resulting mass ranges for both objects are, of course, safely above these values and therefore consistent with what is known from radial velocity observations.

The masses of neutron stars ( $M_{NS}$ ) measured in binary stars are in the range  $0.9 M_\odot < M_{NS} < 2.7 M_\odot$  (Özel et al. 2012). The compact stars with a mass between  $1.4 M_\odot$  (Chandrasekhar limit) and  $2.8 M_\odot$  should be neutron stars (e.g. Chamel et al. 2013). The mass ranges calculated in Sect. 2 point to the compact object in LSI+61°303 being most probably a neutron star with a mass  $\approx 1.6 M_\odot$ . The spin period of the neutron star is expected to be  $P_{spin} \approx 0.05 - 0.15$  s (Maraschi & Treves 1981; Zamanov 1995), although the observational search for pulsations have not confirmed

it yet (Coe et al. 1982; Peracaula et al. 1997; McSwain et al. 2011; Cañellas et al. 2012).

There is a maximum mass a neutron star may have (e.g. Bombaci 1996). Antoniadis et al. (2016) considering the mass function of neutron stars and mass measurements in binary millisecond pulsar establish that this maximum mass is of about  $2.15 M_{\odot}$ . The compact stars with a mass above the Tolman-Oppenheimer-Volkoff limit should be black holes. The measured masses of Galactic black holes are in the range  $2.5\text{--}15 M_{\odot}$  (Özel et al. 2010). Our estimate of the mass of the compact object in MWC 148 (Sect. 2.2) points to that it is likely to be a black hole with mass  $\sim 4.0 M_{\odot}$ . The calculated mass range for LSI+61°303 is narrower than that of MWC 148, mainly because the projected semimajor axis  $a_1 \sin i_{orb}$  is known with a considerably better accuracy, 6% and 33% for LSI+61°303 and MWC 148, respectively.

In most systems with an early-type optical companion,  $\gamma$ -rays are usually believed to arise from the interaction between the stellar wind of the primary and a pulsar magnetosphere instead of a black hole. However, an active debate is still open with both pulsar and microquasar models in dispute (see e.g. Dubus 2013; Massi & Torricelli-Giamponi 2016). Both interpretations are competing to explain not only the  $\gamma$ -ray emission, but also the changing milli-arcsecond radio structures observed with interferometric techniques. If future multiwavelength observations confirm the black hole nature of the companion star in MWC148 proposed here, this would have important consequences on our general understanding of  $\gamma$ -ray binaries. The  $\gamma$ -ray binary class could be then a multiface phenomenon with very different physical scenarios coexisting in different systems.

**Conclusions:** From the above considerations, it appears that: (i) the compact object in LSI+61°303 is most probably a neutron star with mass  $\sim 1.6 M_{\odot}$ , (ii) the compact object in MWC 148 is likely to be a black hole with a mass  $\sim 4.0 M_{\odot}$ .

The proposed non-uniform natures of the compact object in these two system suggests that different physical scenarios, accounting for very high energy emission in binary systems, can actually take place in real systems.

**Acknowledgements:** This work was partly supported by grant AYA2016-76012-C3-3-P from the Spanish Ministerio de Economía y Competitividad (MINECO).

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