PROCEEDINGS OF SCIENCE

The First Be/BH System

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A significant fraction of high-mass X-ray binary systems are composed of Be stars orbited by neutron stars (NSs). However, binary population synthesis models predicted the existence of Be stars orbited by black holes (BHs) as well, although their detection had been elusive until recently. After a possible gamma-ray flare detected by the *AGILE* satellite, the Be star MWC 656 was discovered to be a member of a binary system. Subsequent radial velocity studies revealed that the orbiting compact object is in fact a BH. X-ray observations revealed the binary system to be in quiescence, allowing thus studies of quiescent BH in high-mass X-ray binaries (HMXBs) for the first time. These studies are particularly interesting in the context of the known radio/X-ray correlation of stellar-mass black holes. We note that this is the first stellar-mass BH that has not been discovered by its prominent X-ray emission. Finally, studies of the formation and evolution of Be/BH systems have been conducted, revealing that evolved descendents of these systems in nearby galaxies can lead to detectable gravitational waves from NS-BH mergers. Here I review all these discoveries related to the first Be/BH system MWC 656 and provide an outlook of the current observational efforts aimed at better understanding Be/BH systems.

XI Multifrequency Behaviour of High Energy Cosmic Sources Workshop
25-30 May 2015
Palermo, Italy

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PoS(MULTIF15)036

1. Introduction

MWC 656 has been found to be a binary system composed of a Be star orbited by a black hole (BH), thus being the first Be/BH system to be discovered (Casares et al., 2014). This discovery has lead to significant advances in different branches of the study of binary systems, in particular opening the discovery space of quiescent stellar-mass black holes, partially solving the problem of the absence of Be/BH systems, helping to improve binary population synthesis models and providing some initial estimates of NS-BH mergers that could lead to the detection of gravitational waves (GWs) in nearby galaxies.

Here I review the most important discoveries related to the Be/BH system MWC 656 and comment on the future prospects related to this and other potential Be/BH systems.

2. The gamma-ray signal

On 2010 July Lucarelli et al. (2010) reported the detection of a new unidentified gamma-ray source with the *AGILE* satellite, namely AGL J2241+4454. The source had galactic coordinates $(l, b) = (100.0^\circ, -12.2^\circ) \pm 0.6^\circ \pm 0.1^\circ$ (statistic and systematic uncertainties, respectively), and a flux above 100 MeV of 1.5×10^{-6} ph cm^{-2} s^{-1}. However, *Fermi*/LAT did not detect the source, and yielded a flux upper limit around one order of magnitude smaller than the *AGILE* flux[1].

Although this discrepancy has remained controversial for a long time, in a recent work Alexander & McSwain (2015) analyzed the *AGILE* and the *Fermi*/LAT data paying special attention to the different observational time windows of the source around the time of detection. These authors found that the *Fermi*/LAT data show an enhancement of emission during the *AGILE* detection, nearly reaching a 3σ deviation with respect to the median. This gives more credit to the existence of AGL J2241+4454.

3. The Be star MWC 656 and its photometric periodicity

Even if AGL J2241+4454 is outside the Galactic Plane, the large position uncertainty prevents a direct identification of counterparts at other wavelengths. However, Williams et al. (2010) studied the position error circle and suggested two possible counterparts: the probable quasar RX J2243.1+4441 and the Be star HD 215227 ($V = 8.8$ mag), also known as MWC 656. These authors suggested a spectral classification of B3 I Vne+sh for MWC 656 and derived a distance of 2.6 ± 1.0 kpc. They also compiled optical photometry from different archives and discovered a periodicity of 60.37 ± 0.04 d in MWC 656, suggesting binarity.

New optical photometric observations of MWC 656 conducted with the Telescope Fabra-ROA Montsec (TFRM) spanning from 2012 May to 2012 September already confirmed the photometric periodicity (Paredes-Fortuny et al., 2012). An improved TFRM lightcurve, with 181 measurements spanning from 2012 July to 2016 January folded using a period of 60.37 d and $JD_0 = 2453243.3$, is shown in Fig. 1-left (Paredes-Fortuny, 2016). The photometric periodicity is very clear.

[1]http://fermisky.blogspot.com.es/2010/07/

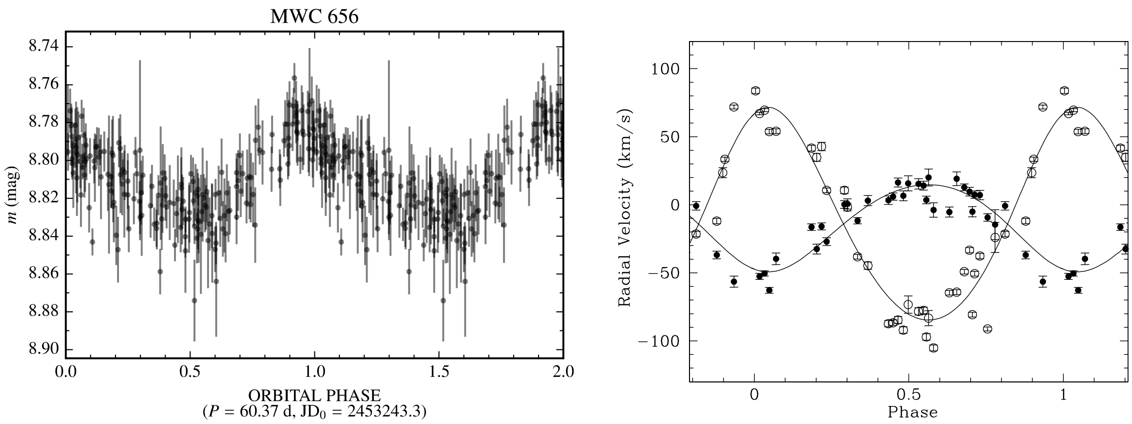

Figure 1: Left: TFRM photometry of MWC 656 as a function of the orbital phase, which confirms the periodicity reported earlier. From Paredes-Fortuny (2016). Right: Radial velocity values of MWC 656 obtained from Fe II emission lines from the Be disk (solid circles) and He II emission lines from the compact object accretion disk (open circles) measured in Liverpool Telescope spectra. The double-line best-fit solution is superimposed. From Casares et al. (2014).

4. Radial velocity studies and discovery of the first Be/BH system

Despite the clear periodicity found in the optical photometry of MWC 656, binarity can only be assessed with radial velocity measurements. In a first study based on Liverpool Telescope (LT) data, Casares et al. (2012) found that the main parameters of the Hα emission line (equivalent width, full width at half-maximum and centroid velocity) were modulated on the proposed orbital period of 60.37 d. These authors also presented the first radial velocity curve, which was based on three photospheric absorption He I lines lines that were not overlapping with emission lines from the Be disk: 4471, 4713 and 5048 Å. Modelling with the Spectroscopic Binary Orbit Program (SBOP), with the orbital period fixed at 60.37 d and the eccentricity fixed at 0.4, provided a reasonably good fit that yielded compact object mass estimates compatible either with a NS or a BH.

In a second study, Casares et al. (2014) realized about the presence of a He II emission line at 4686 Å in a high-resolution spectrum obtained with the Mercator telescope. This line is remarkable because it requires temperatures hotter than the ones that can be achieved in disks around B stars. Furthermore, the He II profile was double-peaked, which is the signature of gas orbiting in a Keplerian geometry. This, together with a radial velocity variability from LT data that was in anti-phase compared to the Be star one, suggested that this emission line could be originated in a disk orbiting the compact object, namely an accretion disk. On the other hand, to better trace the motion of the Be star, Casares et al. (2014) decided to use the double-peaked Fe II emission line at 4583 Å originated in the inner part of the Be star decretion disk, because it was less noisy than photospheric lines. A model with a double-line eccentric binary orbit in SBOP fixing the orbital period at 60.37 d (see Fig. 1-right) provided the orbital elements, most notably a mass ratio between both objects of 0.41 ± 0.07. Casares et al. (2014) refined the spectral classifcation of the Be star to B1.5-B2 III, implying a mass in the range of 10–16 $M_{\odot}$ and leading to a compact object with a

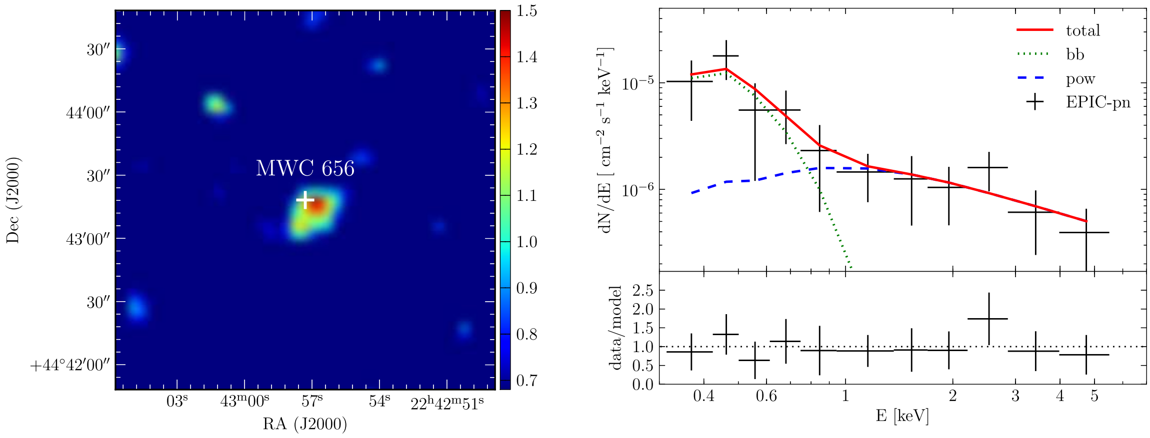

Figure 2: Left: *XMM-Newton* color image in the 0.3–5.5 keV energy range in the field of of MWC 656, indicated by the white cross. From Munar-Adrover et al. (2014). Right: *XMM-Newton* spectrum of MWC 656 including a combination of a blackbody plus a power law. From Munar-Adrover et al. (2014).

mass in the range 3.8–6.9 $M_\odot$, thus being a BH. The distance was refined to be 2.6 ± 0.6 kpc.

5. The X-ray binary nature of MWC 656 and its multi-wavelength behavior

Archival *ROSAT* data provided an upper limit to the X-ray flux, leading to $L_X < 1.0 \times 10^{32}$ erg s^{-1} (or $< 1.6 \times 10^{-7} L_{Edd}$). Therefore, accretion seemed to be highly inefficient in MWC 656, akin to accretion onto BH in quiescent low-mass X-ray binaries (Casares et al., 2014).

Munar-Adrover et al. (2014) conducted a 14-ks *XMM-Newton* observation on 2013 June 4, which revealed the detection of a faint source at 4.4σ level and coincident with the *Hipparcos* position of MWC 656 at 2.4σ level (see Fig. 2-left). This revealed that MWC 656 was a new high-mass X-ray binary (HMXB). The source was only detected in the low-energy range of the EPIC-pn detector, between 0.3 and 5.5 keV (see Fig. 2-right). The spectrum analysis required a model fit with two components, a blackbody plus a power law, the later dominating above $\simeq$0.8 keV. The thermal emission could be produced in the wind of the Be star, while the non-thermal emission could originate in the vecinity of the BH. The observed non-thermal luminosity was $L_X = (1.6^{+1.0}_{-0.9}) \times 10^{31}$ erg s^{-1}, or $(3.1 \pm 2.3) \times 10^{-8} L_{Edd}$ considering all possible uncertainties, indicating in any case a BH in deep quiescence (see Plotkin et al. 2013 for reference).

Other published multi-wavelength data include radio and TeV observations. In the radio domain the source has been observed with the EVN, the WSRT and the VLA at different frequencies and epochs, leading in all cases to upper limits (Moldón, 2012; Marcote, 2015). The most constraining 3σ upper limit is of 30 μJy, obtained with the EVN on 2011 February 28 by Moldón (2012). It must be noted that Dzib et al. (2015) have claimed a detection with the VLA, although at low significance, thus being still a controversial result. Finally, MWC 656 has also been observed at TeV energies with the MAGIC telescopes, leading to differential upper limits at the level of 5% of the Crab Nebula flux (Aleksić et al., 2015).

It is well known that stellar-mass black holes show a radio/X-ray correlation during the low/hard and quiescent states that traces the accretion/ejection coupling (see e.g. Corbel et al. 2013). Using

PoS(MULTIF15)036

the non-simultaneous EVN radio flux density upper limit and the non-thermal X-ray luminosity, MWC 656 is located in the lower-left side of the luminosity diagram, in a region where it may be consistent with and just above the correlation from Corbel et al. (2013). Consequently, the radio/X-ray correlation might also be valid for BH HMXBs, being Cygnus X-1 in the higher luminosity end and MWC 656 in the lower luminosity end. In this context, MWC 656 should allow us to study accretion processes and the accretion/ejection coupling at very low luminosities for BH HMXBs.

6. Formation and evolution of Be/BH systems and production of gravitational waves

Around 80 HMXB in the Galaxy contain Be stars, $\sim$50 of which have a confirmed NS as compact object (while the non-confirmed ones display properties similar to those of Be/NS systems). The lack of Be/BH systems until the discovery of MWC 656 was understood in two possible ways: 1) Be/BH systems are difficult to find because of efficient disk truncation, leading to very long quiescent states or 2) their absence could be driven by binary evolution, with Be/BH binaries having a lower probability of being formed and surviving a common envelope (CE) phase (see Belczynski & Ziolkowski 2009 and references therein). However, MWC 656 was discovered through a claimed gamma-ray flare and subsequent optical study, and not by its X-ray activity. This is a clear bias, suggesting that there might be lots of hidden (non-active) Be/BH systems waiting to be discovered. In the context of binary population synthesis models, this indicates that CE mergers would be less frequent than commonly assumed and/or that NS kicks would be best described by the radio pulsar birth velocity distribution (Casares et al., 2014).

New simulations using the StarTrack binary population synthesis models have been conducted to understand the formation channel of MWC 656, constrain the population of Be/BH systems and study the fate of MWC 656 as a possible NS-BH merger (Grudzinska et al., 2015). In particular, it has been assumed that all donors beyond main sequence are allowed to survive the CE phase. Considering 10 Gyr of evolution of the Galactic disk, 8700 B/BH systems were formed (around 1/3 of which would be Be/BH systems). However, only 13 of them had periods, eccentricities and masses similar to MWC 656. In addition, the simulated number of B/BH systems at present is 39, but only 0.007 with properties similar to MWC 656 (probability below 1%). The future evolution of MWC 656 will lead to the formation of a NS that can form a close or a wide NS-BH system or that can disrupt the binary. In case of close NS-BH systems the simulations indicate that the compact objects would merge on timescales of a few Gyr, producing GWs. Considering the detection rates by advanced LIGO/Virgo and making a few assumption, Grudzinska et al. (2015) estimate that GWs from NS-BH mergers descendent from Be/BH systems in nearby galaxies could be detected at a rate of 0.1 ± 0.1 yr^{-1}.

7. Conclusions and outlook

The study of the first Be/BH system MWC 656 has had important implications in different branches of the study of binary systems. On one hand, this has been the first stellar-mass black hole to be discovered only with optical observations, which clearly points to the existence of observational biases in the discovery of stellar-mass black holes in general, and in combination with Be stars in particular. On the other hand, this is the first BH in HMXB system that shows a quiescent

PoS(MULTIF15)036

X-ray flux, allowing thus studies of quiescent BH in HMXBs for the first time, particulary in the context of radio/X-ray correlations and the accretion/ejection coupling in stellar-mass black holes. Finally, Be/BH systems could lead to the formation of close NS-BH systems that could merge on Gyr timescales, which could lead to the detection of GWs from such systems in nearby galaxies.

Ongoing studies on MWC 656 include the analysis of a long joint *Chandra*/VLA observation conducted in 2015 July, as well as improved orbital parameters from a long-term spectroscopic campaign. In addition, the team involved in the discovery of MWC 656 is now pursuing the discovery of more Be/BH systems that could lead to enlarge the very scarce population of such systems.

Acknowledgments

M.R. acknowledges partial support by the Spanish Ministerio de Economía y Competitividad (MINECO) under grants FPA2013-48381-C6-6-P, FPA2014-55819-C4-4-P and FPA2015-69210-C6-2-R (MINECO/FEDER, UE), MDM-2014-0369 of ICCUB (Unidad de Excelencia 'María de Maeztu'), and the Catalan DEC grant 2014 SGR 86.

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