Investigating the orbital parameters of the gamma-ray binary HESS J0632+057

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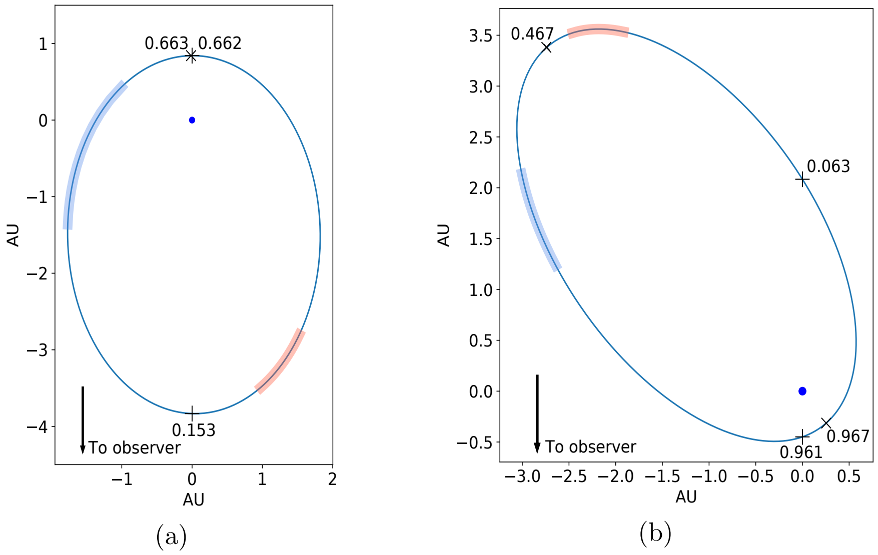
Abstract. Gamma-ray binaries are a small (<10) subclass of high mass binary systems that display non-thermal emission peaking in the gamma-ray regime ($\geq$ 1 MeV). All known systems contain an O/Oe or B/Be star and a compact object in the mass range of a black hole or neutron star. In order to interpret how the non-thermal emission is produced, the orbital parameters need to be determined. HESS J0632+057 is a gamma-ray binary comprising of a Be star and an unknown compact object with an orbital period of ~317 days. Two previous studies by Casares et al. 2012 and Moritani et al. 2018 obtained two different and incompatible orbital solutions. We are undertaking a long-term observational campaign with the High Resolution Spectrograph on the Southern African Large Telescope to establish the radial velocities in order to differentiate between the two proposed orbital solutions. The initial results, from the first observing semester, of Voigt profile fitting to the H α, H β and H γ Balmer emission lines show changes over the observation period, indicating variation within the circumstellar disc, while the radial velocities display a general trend of decreasing with time that is consistent with the Moritani et al. solution.

1. Introduction

Gamma-ray binaries are a rare subclass of high mass binaries displaying multiwavelength non-thermal emission that peaks at energies greater than 1 MeV in a νF_ν representation. Currently less than 10 systems have been identified. All comprise of a compact object, in the mass range of a black hole or neutron star, orbiting an O/Oe or B/Be companion star (see e.g. [1] or [2] and reference therein). The nature of the compact object remains unconfirmed for all but two of the systems, where a young pulsar is observed in both PSR B1259-63/LS 2883 [3] and PSR J2032+4127/MT91 213 [4]. Two scenarios have been proposed to explain the source of the gamma-ray emission, namely the pulsar-wind scenario and the microquasar scenario. In the pulsar-wind scenario, the compact object is a rotationally powered young pulsar. The interaction between the stellar and pulsar wind produces a termination shock wherein particle acceleration will take place. It has been suggested that this scenario would occur during a brief period in the binary evolution of High Mass X-ray Binaries (HMXBs), before the neutron star has spun down enough to allow accretion to occur. Alternatively, in the case of a black hole compact object, the microquasar scenario would occur. Energy from an accretion disc around the compact object powers a relativistic jet, wherein particle acceleration will take place. In both scenarios the non-thermal emission arises from synchrotron and inverse Compton emission of the accelerated



(a) (b)

Figure 1: The binary geometry as determined by the Moritani et al. (a) and Casares et al. solution (b) for orbital periods of 313 and 321 days, respectively. Superior conjunction and inferior conjunction, as well as apastron and periastron are indicated on the orbital paths. The phases for the maxima in the X-ray and TeV light curves are indicated by the broad red (phases 0.3-0.4) and blue (phases 0.7-0.8) lines. The observer views both systems from the bottom of the page as indicated by the arrow.

electrons. A key aspect in modelling and interpreting the observed emission from these systems, is knowing the orbital parameters of the system.

The gamma-ray binary HESS J0632+057 is composed of the Be type star MWC 148 and an unknown compact object, in a ∼317 day orbit (see recent studies by Malyshev et al. 2019 [5] and Adams et al. 2021 [6]). The Be star is surrounded by a circumstellar disc, as evident by the emission lines in the optical spectrum. The observed X-ray and TeV emission displays two maxima in their light curves, at orbital phase 0.3-0.4 and 0.7-0.8 [7]. Two previous studies, by Casares et al. 2012 [8] and Moritani et al. 2018 [9], have previously undertaken radial velocity measurements to determine the orbital parameters of HESS J0632+057. However, they obtained two incompatible solutions. Casares et al. determined the orbital parameters from radial velocity measurements obtained from the faint He I 4471 Å, 4731 Å and 5048 Å photospheric absorption lines, whereas Moritani et al. measured the radial velocity from the wings of the Hα emission line. The orbital geometry for the two solutions is shown in Figure 1. Moritani et al. proposed that the maxima in the X-ray and TeV light curves could be attributed to the compact object passing through the Be star's circumstellar disc, tilted with respect to the orbital plane of the system. The inclined disc model has also been discussed by Malyshev et al. 2019 [5], where they used this interpretation to constrain parameters for the position of periastron and the eccentricity which are compatible with the Moritani et al. solution. They also obtained an orbital period of $316.8^{+1.2_{stat}+1.4_{syst}}_{-0.4_{stat}-1.0_{syst}}$ days from analysis of the Swift-XRT data. Spectral energy distribution modelling of the X-ray and TeV observations by Archer et al. 2020 [10] favour a pulsar-wind scenario; this is consistent with the Moritani et al. solution. An analysis of long-term X-ray and gamma-ray observations reported by Adams et al. 2021 [6] found orbital periods of $317.3 \pm 0.7_{stat} \pm 1.5_{sys}$ days (X-ray) and $316.7 \pm 4.4_{stat} \pm 2.5_{sys}$ days (gamma-ray). In addition, an independent solution for the binary parameters (which are within range of the proposed solution by Moritani et al.) has been proposed by Tokayer et al. 2021 [11], based on modelling the Swift-XRT light curve.

Although there appears to be some consistency in the various different studies with the Moritani et al. solution, optical radial velocity measurements provide a model-independent method to determine the binary parameters. While the method used in Moritani et al. has previously been applied to other binary systems containing Be stars (see [12], and reference therein), it would be preferable to obtain consistent radial velocities from both the emission and absorption lines.

Here we discuss the initial results from a long-term observation campaign to observe HESS J0632+057 using the High Resolution Spectrograph [13] on the Southern African Large Telescope [14], presenting the radial velocity measurements obtained from the Balmer emission lines.

2. Observations, data reduction and analysis

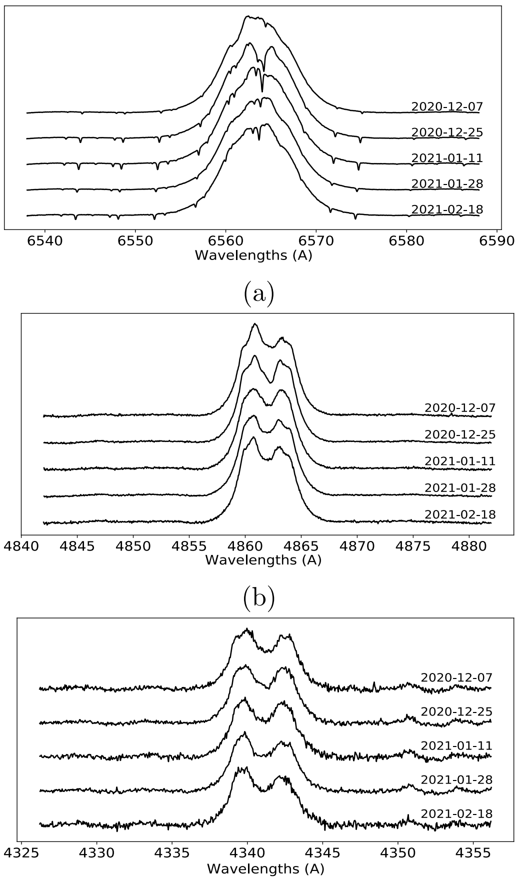
Five spectroscopic observations were obtained with the HRS in High Resolution mode (R∼ 65000-74000) on SALT between December 2020 and February 2021. Each observation consisted of three 600 s exposures. The CCD reduction, spectral extraction, wavelength calibration and flat fielding was performed using the HRS pipeline described in Kniazev et al. 2016 [15]. The merging of the different orders was performed in PYTHON. The three observations taken for each night were averaged together, continuum corrected and adjusted to the barycenter. The change in the Balmer emission lines over the observations is shown in Figure 2.

As a first step, we have measured the radial velocity from the Balmer emission lines, $\mathrm{H}\,\alpha$, $\mathrm{H}\,\beta$ and $\mathrm{H}\,\gamma$, similar to Moritani et al. For each line we fit a Voigt profile to the wings of the emission feature, which was taken as where the emission decreased below half of the peak intensity. An example of the profile fits are shown in Figure 3. The difference between the centre of the fitted lines and the rest wavelength was used to calculate the radial velocity.

3. Results and discussion

Over the observation period, the emission lines show a clear variation. The $\mathrm{H}\,\alpha$ does not show a clear double peak structure, but the line does shift from single peaked, to an indication of a double peak on 2020 December 25, to be single peaked again. The $\mathrm{H}\,\beta$ and $\mathrm{H}\,\gamma$ lines are double peaked in all observations. The $\mathrm{H}\,\beta$ line shows a stronger component in the blue, which shifts through the observations, while similarly, the $\mathrm{H}\,\gamma$ lines show small shift in the V/R variation. This variation indicates changes in the circumstellar disc, including any change to the symmetry of the disc or regions of higher density (see e.g. [16]).

In order to minimize the influence of the changing shape of the emission lines, when measuring the radial velocity, the Voigt profiles were fit to the wings of the lines, as stated above. Since the circumstellar discs of Be stars are Keplerian (see e.g. [17]) the region of the disc closest to the star will have the highest rotation velocity, contributing more light to the wings of the emission lines. The radial velocity measurements for these observations are compared to the orbital solutions presented by Casares et al. and Moritani et al. is shown in Figure 4. For consistency, we have used the orbital periods of 321 and 313 days, given by Casares et al. and Moritani et al. respectively, to phase fold the radial velocities obtained in this work. The difference between these orbital periods and the recent orbital period estimate of ∼317 days, should not significantly impact our analysis. The radial velocities show a general trend of decreasing with orbital phase, and are more consistent with the Moritani et al. solution. There is a systematic difference between the different radial velocities measured for the different lines, but this is on the order of a few$\times$km s^{-1} and the errors shown are statistical, derived from the goodness of fit of the Voigt profile.

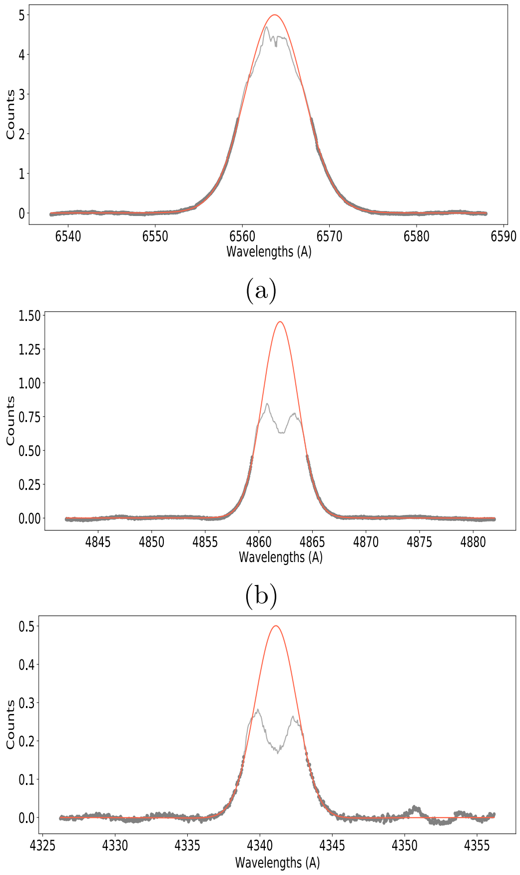


(a)

(b)

(c)

Figure 2: The variation of the H α (a), H β (b) and H γ (c) Balmer emission lines over the observation period. Spectra are normalized and offset for clarity.



(a)

(b)

(c)

Figure 3: Examples of the Voigt profile (red line) fit to the wings of the Balmer lines (thick dotted region). The average of the H α (a), H β (b) and H γ (c) Balmer lines (thin gray line) is shown for illustration.

4. Conclusions

Initial results from spectroscopic observations obtained from SALT showed the emission line profiles changed over the observation period (Figure 2), indicating variations within the circumstellar disc, while the radial velocities display a general trend of decreasing radial velocity with time for all the Hydrogen emission line fits (Figure 4). These results are more consistent with the Moritani et al. solution. In future work the analysis will be performed for the weaker absorption lines originating from the Be star's photosphere. Further observations are proposed to increase the signal-to-noise and obtain full orbital phase coverage to accurately determine the orbital parameters of the binary.

Acknowledgments

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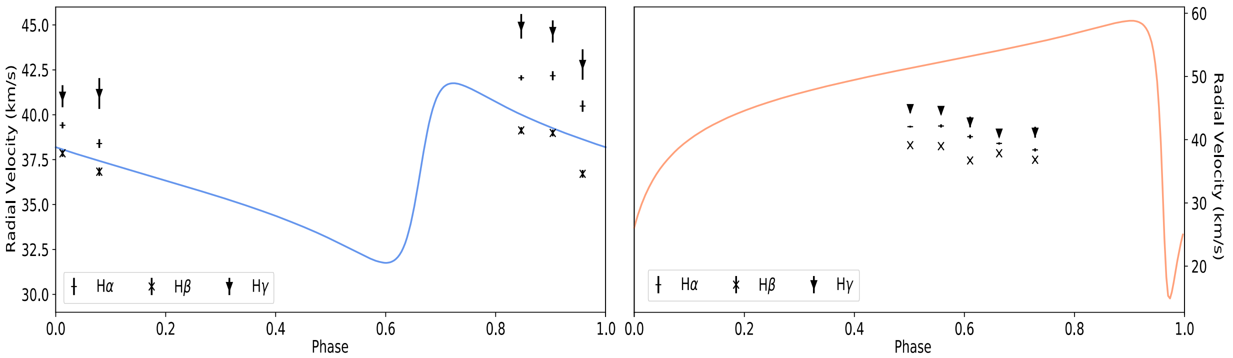

(a) (b)

Figure 4: The radial veolcity measurements of the Balmer emission lines obtained in this work (black data points), plotted against the phase relative to the Moritani et al. (a) and Casares et al. (b) models of their orbital solutions. The error shown in the radial velocities are purely statistical, derived from the goodness of fit from the Voigt profile fits to the wings of the H α, H β and H γ Balmer emission lines.

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