PROCEEDINGS OF SCIENCE

Constraining the orbital solution of the gamma-ray binary HESS J0632+057

Natalie Matchett,[a,*] **Brian van Soelen**[a] **and Richard O. Gray**[a,b]

[a] *University of the Free State, 205 Nelson Mandela Drive, Bloemfontein, South Africa*

[b] *Department of Physics & Astronomy, Appalachian State University, Boone, NC 26808, USA*

E-mail: natmatch98@gmail.com, vansoelenb@ufs.ac.za

Gamma-ray binaries are a small subclass of high-mass binaries containing an O or B/Be star and a compact object. These systems produce non-thermal emission across all wavelengths but peak at energies greater than 1 MeV. In order to interpret the source of the non-thermal emission in these systems, an orbital solution is required. The gamma-ray binary HESS J0632+057, which consists of a Be star and an unidentified compact object, still lacks a clear orbital solution, complicating the interpretation of the modulated emission, despite previous attempts to constrain the orbital parameters. Two different and incompatible solutions were proposed by Casares et al. 2012 and Moritani et al. 2018 - through radial velocity measurements of the absorption lines and the H α emission line respectively. In order to better constrain the orbital solution, we are undertaking independent radial velocity measurements using the HRS with SALT of both the weak absorption lines and the H α, H β, and H γ emission lines. We present the initial results from our first two semesters of observations.

High Energy Astrophysics in Southern Africa 2022 - HEASA2022
28 September - 1 October 2022
Brandfort, South Africa

*Speaker

https://pos.sissa.it/

PoS(HEASA2022)016

1. Introduction

A small subset of high mass binary systems are known to produce most of their non-thermal emission (in a νF_ν distribution) at energies above 1 MeV, and show orbitally modulated gamma-ray emission (see e.g. [1, 2]). All of these systems consist of a compact object in the mass range of a neutron star or black hole, in orbit around a O or B type star. For three systems, the compact object has been identified as a pulsar [3–5]. It is, therefore, most often assumed that all gamma-ray binaries harbour young, non-accreting pulsars, and that the non-thermal emission is produced at the shock front that forms between the stellar and pulsar winds [6]

The gamma-ray binary system HESS J0632+057 consists of a Be star and an unknown compact object, in a ~320 d orbit [7]. The X-ray and TeV light curves both show two maxima, with the first peak (at phase $\phi \approx 0.3$) being slightly brighter than the second (at $\phi \approx 0.7$) [8].[1] This is similar to another system, PSR B1259-63/LS 2883, where the double peak in the non-thermal light curve is normally interpreted as the pulsar passing through the plane of the Be star's circumstellar disc (see e.g. [9]). The interpretation of the interaction for HESS J0632+057 is complicated as two different and incompatible orbital solutions have been proposed by Casares et al. [10] and Moritani et al. [11] (hereafter C12 and M18 respectively). Both are based on the measurements of the radial velocity of the massive companion, with the former measured from the weak absorption lines, and the latter from the H α emission line. The newer solution presented by M18 suggests the peaks in the light curves occur at points near the circumstellar disc crossing. In addition to the radial velocity solutions by C12 and M18, a number of different solutions have been suggested by modelling the non-thermal emission [12–15].

In order to disentangle the confusion with this source, we are undertaking new high resolution spectroscopic observations of the system to better determine the orbital solution. Since the orbital period is long, observations are required over a few years to sample the full orbit. Here we present the results from the first two seasons of observations.

2. SALT observations

HESS J0632+057 has been observed 5 times between 2020 December and 2021 March (Semester 1), and 3 times between 2021 December and 2022 February (Semester 2) using the High Resolution Spectrograph (HRS; [16]) on the Southern African Large Telescope (SALT; [17]). The HRS is a fibre fed, Èchelle spectrograph that operates with two beams covering the blue (370 – 555 nm) and red (555 – 890 nm) part of the optical spectrum. All observations were taken in High Resolution mode (resolving power of $R = 65000$). The different orders were extracted and wavelength calibrated using the standard HRS pipeline (described in [18]). The orders were then sky subtracted, continuum corrected, combined and corrected to the heliocentre following standard methods using IRAF/PYRAF. The average blue arm spectrum is shown in Fig. 1.

2.1 Radial velocity: absorption lines

Since emission originating from the circumstellar disc dominates the Balmer lines, the velocity was measured for the weaker He I absorption lines, and one C III/O II/ He I composite line, between

[1] Phase $\phi = 0$ is defined at MJD 54 857.0 [7].

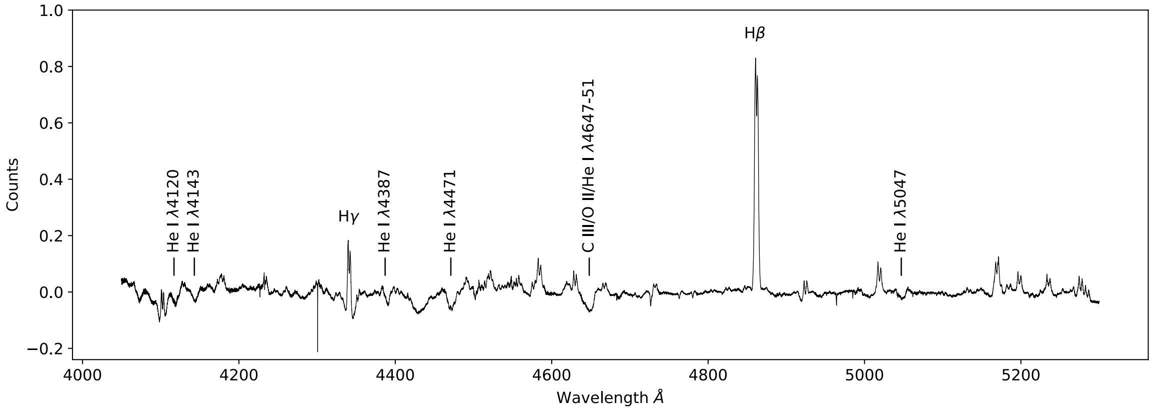

Figure 1: The average blue arm spectrum, with the absorption features used in the cross-correlation as well as the H β and H γ emission features. The H α emission line occurs in the red arm spectrum, not shown here.

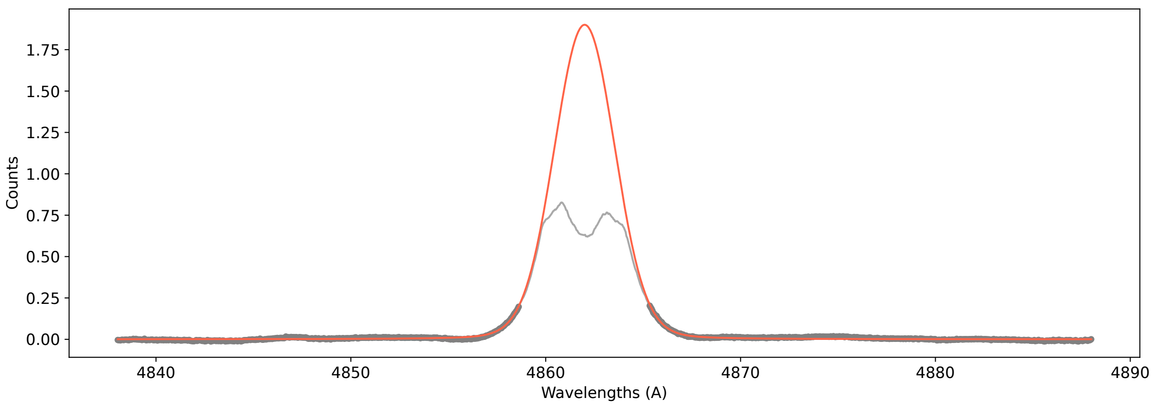

Figure 2: An example of a Voigt profile fit to the wings of the H β emission line. The central wavelength value of the Voigt profile was the used to determine the radial velocity shift.

4000 – 5200 Å. The radial velocity was measured via cross-correlation using the RVSAO package [19], using a template created from the average of all the observations (similar to e.g. [20–22]). The radial velocity of the template was determined from the H β and H γ emission lines. Due to the large number of emission features surrounding the weak absorption lines, a windowed region around each line was selected, the radial velocity was measured for each line individually, and then the average radial velocity of all lines was found.

2.2 Radial velocity: emission lines

The radial velocity of the H α, H β, and H γ emission lines was measured from the Doppler shift of the centre of a Voigt profile which was fit to the wings of the line below 25 per cent of the line peak (an example is shown in Fig. 2). Since the circumstellar discs are believed to be Keplerian, the inner region of the disc closest to the star will have the highest velocity, and produce emission in the wings (see e.g. [23] and references therein). The average radial velocity of the H α, H β, and H γ lines was used for each observation.

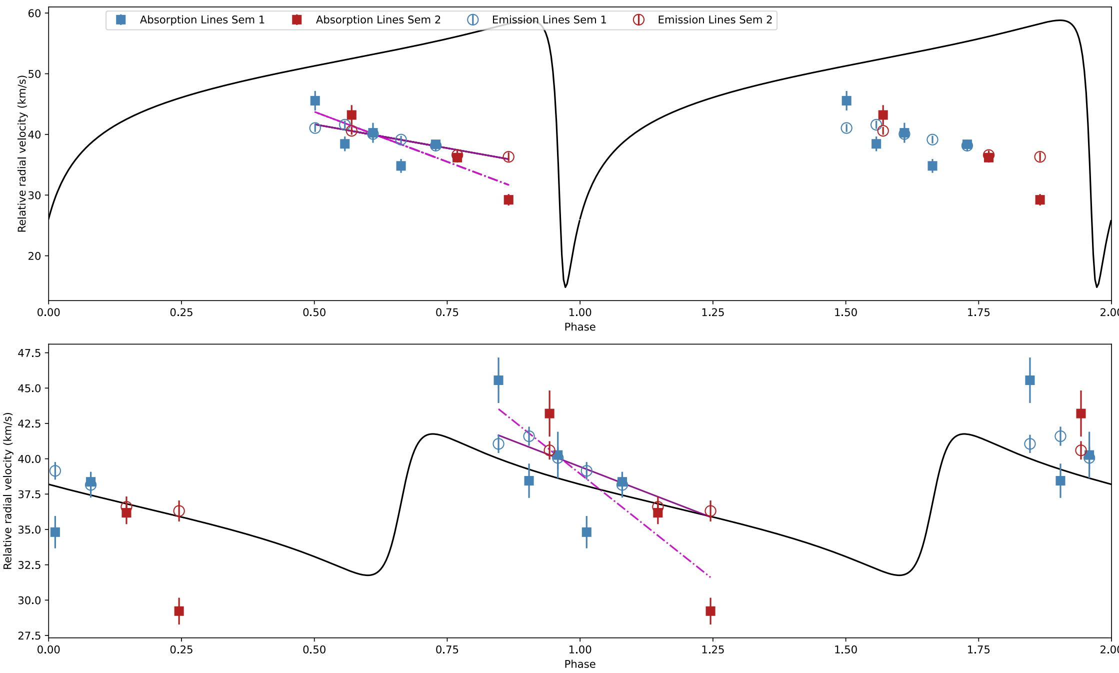

Figure 3: Radial velocity measurements of the massive companion in HESS J0632+057 for Semester 1 (blue points) and Semester 2 (red points) as measured from both the absorption lines (filled squares) and the emission lines (open circles). The radial velocities are compared to the orbital solutions proposed by C12 (top) and M18 (bottom) as indicated by the solid black line. The dashed and solid pink lines show the best linear fit to the radial velocity of the absorption and emission lines, respectively. The results are repeated over two orbits for clarity.

3. Results

The new radial velocities are plotted as a function of orbital phase in Fig. 3, for the both the absorption and emission lines, for Semester 1 and 2. These are compared to the C12 and M18 solutions, using an orbital period of 321 d and 313 d respectively, as was used for those solutions. Both periods are consistent with the most recent reported orbital period of 316.7 ± 4.4 d [8]. There is an $\sim 15\,\mathrm{km\,s^{-1}}$ offset between the velocities and the C12 solution, but they are more in agreement with the M18 solution. Since these new velocities are measured both directly from the emission lines or, in the case of the absorption lines, relative to a template whose velocity is determined by the emission lines, we caution that this could introduce a systematic offset between these new results and C12 results. However, plotted against orbital phase the radial velocities are decreasing, which is also consistent with the M18 solution, but not the C12 solution.

4. Discussion and conclusions

The inconsistency between the solutions proposed in C12 and M18 has complicated the interpretation of how the non-thermal emission is produced in HESS J0632+057. Since the compact object is not detected, the radial velocity must be measured from optical spectroscopy of the massive companion. However, since the massive companion is a Be star, emission line features from the circumstellar disc obscure the Balmer absorption lines. The radial velocity must then be measured either from the weaker He and metal absorption features (as in C12) or from the emission lines produced by the circumstellar disc (as in M18). However, as the circumstellar discs of Be stars are known to be variable, this may trace structures in the disc, as opposed to the central star. Here we have reported on initial results from our campaign using SALT to obtain high resolution optical spectra to measure the radial velocity from both the absorption and emission line features.

Our initial results show a better agreement with the solution presented by M18. This implies that the regions of highest emission may be associated with the compact object interacting with the circumstellar disc, as the peaks in the light curves do not occur near the proposed phase of periastron (see e.g. [8]). However, our observations currently cover a small part of the orbital phase, and further observations are required. In particular observations to cover the time around the possible periastron will be important to constrain the solution.

Acknowledgments

All of the optical observations reported in this paper were obtained with the Southern African Large Telescope (SALT) under programme 2020-2-MLT-007 (PI: B van Soelen).

References

[1] G. Dubus, *Gamma-ray binaries and related systems*, A&A Rev. **21** (2013) 64 [1307.7083].

[2] M. Chernyakova, D. Malyshev, A. Paizis, N. La Palombara, M. Balbo, R. Walter et al., *Overview of non-transient γ-ray binaries and prospects for the Cherenkov Telescope Array*, A&A **631** (2019) A177 [1909.11018].

[3] S. Johnston, R.N. Manchester, A.G. Lyne, M. Bailes, V.M. Kaspi, G. Qiao et al., *PSR 1259-63: A Binary Radio Pulsar with a Be Star Companion*, ApJ **387** (1992) L37.

[4] A.G. Lyne, B.W. Stappers, M.J. Keith, P.S. Ray, M. Kerr, F. Camilo et al., *The binary nature of PSR J2032+4127*, MNRAS **451** (2015) 581 [1502.01465].

[5] S.-S. Weng, L. Qian, B.-J. Wang, D.F. Torres, A. Papitto, P. Jiang et al., *Radio pulsations from a neutron star within the gamma-ray binary LS I +61° 303*, *Nature Astronomy* **6** (2022) 698 [2203.09423].

[6] G. Dubus, *Gamma-ray binaries: pulsars in disguise?*, A&A **456** (2006) 801 [astro-ph/0605287].

[7] S.D. Bongiorno, A.D. Falcone, M. Stroh, J. Holder, J.L. Skilton, J.A. Hinton et al., *A New TeV Binary: The Discovery of an Orbital Period in HESS J0632+057*, ApJ **737** (2011) L11 [1104.4519].

[8] C.B. Adams, W. Benbow, A. Brill, J.H. Buckley, M. Capasso, A.J. Chromey et al., *Observation of the Gamma-Ray Binary HESS J0632+057 with the H.E.S.S., MAGIC, and VERITAS Telescopes*, ApJ **923** (2021) 241 [2109.11894].

[9] M. Chernyakova, D. Malyshev, B. van Soelen, S. O'Sullivan, C. Sobey, S. Tsygankov et al., *Multi-Wavelength Properties of the 2021 Periastron Passage of PSR B1259-63*, *Universe* **7** (2021) 242 [2106.03759].

[10] J. Casares, M. Ribó, I. Ribas, J.M. Paredes, F. Vilardell and I. Negueruela, *On the binary nature of the γ-ray sources AGL J2241+4454 (= MWC 656) and HESS J0632+057 (= MWC 148)*, MNRAS **421** (2012) 1103 [1201.1726].

[11] Y. Moritani, T. Kawano, S. Chimasu, A. Kawachi, H. Takahashi, J. Takata et al., *Orbital solution leading to an acceptable interpretation for the enigmatic gamma-ray binary HESS J0632+057*, PASJ **70** (2018) 61 [1804.03831].

[12] D. Malyshev, M. Chernyakova, A. Santangelo and G. Pühlhofer, *Decade-long X-ray observations of HESS J0632+057*, *Astronomische Nachrichten* **340** (2019) 465 [1711.05001].

[13] Y.M. Tokayer, H. An, J.P. Halpern, J. Kim, K. Mori, C.J. Hailey et al., *Multiwavelength Observation Campaign of the TeV Gamma-Ray Binary HESS J0632 + 057 with NuSTAR, VERITAS, MDM, and Swift*, ApJ **923** (2021) 17 [2110.01075].

[14] A.M. Chen and J. Takata, *Modelling the correlated keV/TeV light curves of Be/gamma-ray binaries*, A&A **658** (2022) A153 [2112.00345].

[15] J. Kim, H. An and K. Mori, *Investigation of the Broadband Emission of the Gamma-Ray Binary HESS J0632+057 Using an Intrabinary Shock Model*, ApJ **936** (2022) 32 [2208.01189].

[16] L.A. Crause, R.M. Sharples, D.G. Bramall, J. Schmoll, P. Clark, E.J. Younger et al., *Performance of the Southern African Large Telescope (SALT) High Resolution Spectrograph (HRS)*, in *Ground-based and Airborne Instrumentation for Astronomy V*, vol. 9147 of Proc. SPIE, p. 91476T, July, 2014, DOI.

[17] D.A.H. Buckley, G.P. Swart and J.G. Meiring, *Completion and commissioning of the Southern African Large Telescope*, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 6267 of Proc. SPIE, p. 62670Z, June, 2006, DOI.

[18] A.Y. Kniazev, V.V. Gvaramadze and L.N. Berdnikov, *MN48: a new Galactic bona fide luminous blue variable revealed by Spitzer and SALT*, MNRAS **459** (2016) 3068 [1604.03942].

[19] M.J. Kurtz and D.J. Mink, *RVSAO 2.0: Digital Redshifts and Radial Velocities*, PASP **110** (1998) 934 [astro-ph/9803252].

[20] R. Manick, B. Miszalski and V. McBride, *A radial velocity survey for post-common-envelope Wolf-Rayet central stars of planetary nebulae: first results and discovery of the close binary nucleus of NGC 5189*, MNRAS **448** (2015) 1789 [1501.03373].

[21] I.M. Monageng, V.A. McBride, L.J. Townsend, A.Y. Kniazev, S. Mohamed and M. Böttcher, *The Orbit of the Gamma-Ray Binary 1FGL J1018.6-5856*, ApJ **847** (2017) 68 [1708.07886].

[22] B. van Soelen, N. Komin, A. Kniazev and P. Väisänen, *The orbital parameters of the gamma-ray binary LMC P3†*, MNRAS **484** (2019) 4347 [1901.08911].

[23] T. Rivinius, A.C. Carciofi and C. Martayan, *Classical Be stars. Rapidly rotating B stars with viscous Keplerian decretion disks*, A&A Rev. **21** (2013) 69 [1310.3962].