Implications for gamma-ray production from updated orbital parameters for LMC P3 with SALT/HRS

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Abstract. The recently discovered LMC P3 is the most luminous gamma-ray binary detected to date. The source was discovered with *Fermi*-LAT gamma-ray observations which showed a 10.301 ± 0.002 d period. The gamma-ray emission is associated with the previously detected point-like X-ray source CXOU J053600.0-67350, within the supernova remnant DEM L241, and this binary was previously classified as a high mass X-ray binary where the optical companion is a O5III(f) star. The source has also been detected at very high energies with the H.E.S.S. gamma-ray telescope, though in only one phase bin. We have used the High Resolution Spectrograph (HRS) with the Southern African Large Telescope (SALT) to obtain the best binary solution so far for this source, showing that source is slightly eccentric (~ 0.4) and constrained the phases of superior and inferior conjunction. The *Fermi*-LAT and H.E.S.S. results are discussed in relation to the new binary solution.

1. Introduction

Gamma-ray binaries are a rare class of high mass binaries which emit the majority of their radiation in the gamma-ray regime; see e.g. Dubus [1] for a review of these sources. The systems all show orbitally modulated non-thermal emission from radio up to very high energy gamma-rays. So far only seven sources have been discovered, all of which consist of a compact object (in the mass range of a neutron star or black hole) orbiting around an O or Be star. For only two sources, namely PSR B1259-63 and PSR J2032+4127, has the nature of the compact object been confirmed as a neutron star due to the detection of pulsed emission [2, 3]. Assuming all the systems contain a pulsar, the non-thermal emission is produced at the shock that forms between the pulsar and stellar winds, where particle are accelerated and then subsequently cool via synchrotron and inverse Compton scattering. Gamma-ray binaries, therefore, provide a unique case for studying particle acceleration around compact objects.

The gamma-ray binary LMC P3 is the first gamma-ray binary discovered outside of the Milky Way Galaxy [4]. *Fermi*-LAT observations showed a 10.301 ± 0.002 d period and subsequent optical, radio and X-ray observations showed variability on the same period. However, the radio and X-ray light curves are in anti-phase with the *Fermi*-LAT observations. Such an anti-correlation is also seen in, for example, LS 5039 [5, 6, 7]. The source has also been detected by the H.E.S.S. telescope, though only in one phase bin, which is also in anti-phase with the *Fermi*-LAT observations [8].

The anti-correlation between the GeV and TeV emission could be the result of $\gamma\gamma$ absorption of the photons, see e.g. H.E.S.S. Collaboration [8]. When the pulsar is near to superior conjunction, the observed GeV flux is a maximum, due to the favourable scattering angle for inverse Compton emission. However, this is also the position for maximum $\gamma\gamma$ absorption, and therefore, the TeV emission is a maximum near inferior conjunction.

We have recently undertaken observations of this binary with the Southern African Large Telescope (SALT), and have improved on the orbital parameters. In this paper we briefly discuss the consequences of the updated parameters for gamma-ray production in the system.

2. SALT observations

LMC P3 was observed with the High Resolution Spectrograph (HRS) [9, 10, 11] on SALT [12] between 2016 September 14 and 2017 February 06 in Low Resolution Mode ($R = 14\,000$). The radial velocity was determined using cross-correlation with the IRAF/RVSAO package, against a template created from the observations. The adopted solution shows an eccentricity of $e \approx 0.4$ and places inferior conjunction near phase $\phi \approx 0.24$ and inferior conjunction near $\phi \approx 0.98$, with periastron at $\phi \approx 0.13$ [13]. This confirms that the maximum in the *Fermi*-LAT light curve (at $\phi = 0$) is near superior conjunction, while the maximum in the H.E.S.S. light curve (between $\phi = 0.2 - 0.4$) is near inferior conjunction.

3. Point source modelling

In order to investigate the consequences of this updated orbital parameters, we have modelled the anisotropic inverse Compton and $\gamma\gamma$ absorption from the system, using a point-source approximation, i.e. the optical companion is treated as a point source. The gamma-ray emission is also assumed to originate from a point centred on the pulsar. The binary separation is calculated assuming the mass of the compact object to be $M_X = 1.4\,\mathrm{M}_\odot$, and the mass of the optical companion $M_{\mathrm{star}} = 33.5\,\mathrm{M}_\odot$, and the scattering angles are calculated for a binary inclination of $i = 45^\circ$.

The anisotropic inverse Compton emission has been calculated using the analytical approximations presented in Khangulyan et al. [14] as implemented using the NAIMA package [15]. A constant electron spectrum, with an index of $p = 2$ was assumed at all phases, and the target photon energy density was calculated by approximating the star as a black-body emitter with a temperature of $T_{\mathrm{star}} = 39\,400\,\mathrm{K}$. The $\gamma\gamma$ absorption was calculated using the point-source approximation given in Dubus [16].

In addition, we considered the influence of mild Doppler boosting on the emission, since numerical simulations have suggested the flow at the outer regions of the shock may become mildly relativistic, see e.g. Bogovalov et al. [17].

4. Results

Figure 1 shows the H.E.S.S. light curve compared to the point-source approximation modelling. Since we are initially only investigating the shape of the light curve, the modelled flux has been normalized to the H.E.S.S. measurement. The inverse Compton emission peaks around phase $\phi = 0.1$, slightly after superior conjunction because of the increasing photon energy density nearer to periastron. This is more favourable with the *Fermi*-LAT light curve, but is not consistent with the H.E.S.S. observations. The introduction of $\gamma\gamma$ absorption shifts the peak in the emission closer to phase $\phi \approx 0.2$ which is more consistent with the H.E.S.S. observations. A similar result is obtained for mild Doppler boosting ($\Gamma = 2$), though the rise and fall time of the emission is much faster, an effect that will become stronger for larger values of Γ.

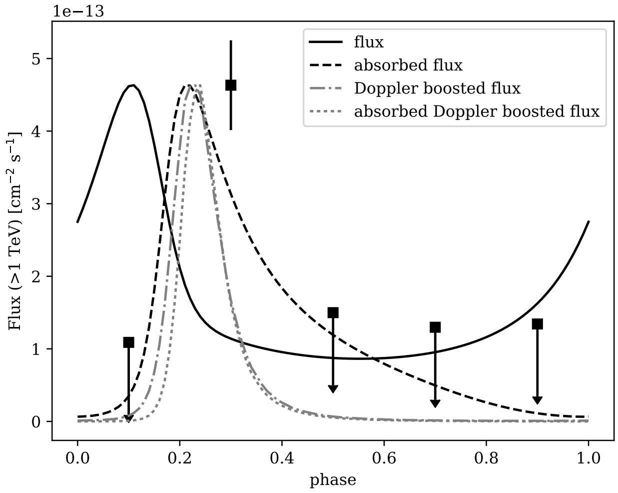

Figure 1. Modelled light curves compared to the H.E.S.S. observations [8]. The inverse Compton flux (solid line) is modified by $\gamma\gamma$ absorption (dashed line), Doppler boosting (dot-dashed line) and both absorption and Doppler boosting (dotted line). In all cases the maximum modelled flux is normalized to the H.E.S.S. measurement.

5. Discussion

The preliminary modelling shows that the updated parameters can shift the peak in the TeV light curve closer to the observed light curve. However, it should be noted that since the source is faint, the peak in the H.E.S.S. light curve is confined to a wide phase bin $\phi = 0.2 - 0.4$. Further observations will help to refine the exactly phase at which the light curve peaks. In addition, a wider range of binary parameters (e.g. inclination angle) as well as particle injection and Doppler boosting should be investigated.

6. Conclusion

The gamma-ray binary LMC P3 has recently been detected in the Large Magellanic Cloud. The multi-wavelength observations show the *Fermi*-LAT light curves are in anti-correlation with the radio, X-ray and TeV gamma-ray light curves, with H.E.S.S. only detecting the source in one phase bin. We have undertaken SALT/HRS observations and have updated the orbital parameters, showing the system is slightly eccentric, with inferior conjunction lying close to the period of maximum TeV emission. We have undertaken preliminary gamma-ray modelling of the system assuming a point source approximation and analytical approximations. We show the combined effect of $\gamma\gamma$ absorption and/or Doppler boosting of the emission can help to explain the H.E.S.S. observations, but that more detailed modelling is required.

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