First multicolour polarimetry of TeV γ-ray binary HESS J0632+057 close to periastron passage

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ABSTRACT
We present the results of UBVRI polarimetry of the TeV γ-ray binary HESS J0632+057 obtained on 2015 March 24 (JD 2457106) and 2015 December 12 (JD 2457369). The detected polarisation values of HESS J0632+057, just after periastron passage (March 24), are higher than all previously published values ($p_V \sim 4.2$ per cent) and the position angle ($\Theta_{\text{obs}} \sim 171^\circ - 172^\circ$) is also different by $\sim 6^\circ - 10^\circ$ from previously published values. The data obtained just before the subsequent periastron passage (December 12) show statistically lower polarisation in all photometric bands ($p_V \sim 3.9$ per cent) and a different position angle $\Theta_{\text{obs}} \sim 167^\circ - 168^\circ$. From observations of a nearby field star, the interstellar component of the measured polarisation was estimated as $p_V \sim 0.65$ per cent and $\Theta_{\text{is}} \sim 153^\circ$. This estimate was used with the previous $V$-band estimation by “field-stars method” ($p_V \sim 2$ per cent and $\Theta_{\text{is}} \sim 165^\circ$) of Yudin (2014) to identify the wavelength dependence of the intrinsic polarisation in HESS J0632+057. It was found that after subtraction of the interstellar component (for both $p_V$ estimates), the wavelength dependence of the intrinsic polarisation in HESS J0632+057 is essentially flat. We propose that the formation of an additional source of polarisation or some perturbation of circumstellar material at this orbital phase can explain the changes in the level of polarisation in HESS J0632+057 close to periastron passage.

Key words: circumstellar matter - polarisation: stars: individual: HESS J0632+057.

1 INTRODUCTION
HESS J0632+057 (MWC148; HD250440) is one of the most interesting TeV γ-ray binaries [Aharonian et al. 2007; Skilton et al. 2009; Casares et al. 2012]. The optical star is known to be a B0 emission line star, though the nature of the compact companion (a neutron star or a black hole) remains uncertain (Moritani et al. 2015; Maier 2015). The object displays periodic variations on several different timescales. The most pronounced variations, derived from X-ray data, were detected with a period of 315 ± 4 days (Aliu et al. 2014) which is considered to be the orbital period of the binary system. Other variability includes:

- $H_\alpha$ line variations with a period of $\sim 60^d$ detected by Aragona et al. (2010), possibly attributed to a spiral density wave in the circumstellar disc,
- γ-ray variability on time-scales of the order of one to two months, possibly linked to the X-ray outburst that occurs about 100 days after periastron passage (Aleksic et al. 2012),
- clear evidence of strong X-ray variability on multiple timescales, with the measured flux doubling on time-scales as short as $\sim 5$ days (Falcke et al. 2010).

Although the object has been intensively studied across a wide range of the electromagnetic spectrum, polarimetric data of HESS J0632+057 is very limited (see later discussion in Sect. 3). There are no published multicolour polarimetric data covering the optical region from $\sim 0.3\mu m$ to $0.9\mu m$. The only data published several decades ago by Serkowski et al. (1964) were obtained with large errors in the red ($\sigma_p > 0.2$ per cent at wavelengths $\sim 0.8-0.9 \mu m$, see Table 1). This does not allow one to identify the true wavelength dependence of the observed HESS J0632+057 polarisation. Moreover, without these data and estimates of the interstellar component of polarisation in all optical photometric bands, the wavelength dependence of intrinsic polarisation can not be determined. Finally, taking into account uncertainties in the orbital period determination ($\pm 5$ days), it is not possible to...
associate previous sparse polarimetric data with a specific orbital phase by extrapolating the modern ephemerides back several decades. However, we expect that the long-term polarimetric variability previously noted by Yudin (2014) can be attributed to the orbital motion of the binary.

We have performed new multicolour polarimetric observations of HESS J0632+057 and one nearby field star, revealing the precise wavelength dependence of the source’s intrinsic polarisation and confirming the association between the variability of the polarisation and the orbital phase of the binary.

2 OBSERVATIONS

Multicolour optical polarimetry (linear and circular) of HESS J0632+057 was carried out in two Sets (Set "I": 2015 March 24 (JD 2457106) and Set "II": 2015 December 12 (JD 2457369)) at the South African Astronomical Observatory (SAAO). SAAO’s high speed polarimeter, HIPPO (Potter et al. 2011, 2010), was used to conduct all Stokes mode photopolarimetry of HESS J0632+057 on the SAAO 1.9m telescope. Observations were made with Johnson UBVR I filters. In addition, observations of a field star (GSC 00158-01500) were performed in the same mode during JD 2457106. This A0V star (mV ≈ 12.1; "star in cluster") is located very close to HESS J0632+057 (2 arcmin) and was used to estimate the interstellar polarisation. The FK5 coordinates (ep=1200 eq=2000) for GSC 00158-01500 are 06 32 55.51 +05 49 29.9, while for HESS J0632+057 the coordinates are 06 32 59.254 +05 48 01.18. The resulting polarisation measurements for HESS J0632+057 are presented in Table 2.

Assuming the orbital phase 0 is at T0=MJD 2454857 (Aliu et al. 2014), the date of Set "I" observations correspond to an orbital phase of 0.140 (if the period is 315 days),

Table 1. Multicolour polarimetric data of Serkowski et al. (1969). No exact JD date and $\sigma_\Theta$ are available. Observations were made in 1966.

| $\lambda_\nu$ (µm) | 0.33 | 0.36 | 0.43 | 0.52 | 0.64 | 0.83 | 0.94 |
|-------------------|-----|-----|-----|-----|-----|-----|-----|
| p±$\sigma$        |     |     |     |     |     |     |     |
| $\Theta_{obs}$    | 159.7 | 164.6 | 165.2 | 165.9 | 163.1 | 164.5 | 166.0 |
### Table 2. Multicolour polarimetry for HESS J0632+057 from this work (Set "I" and Set "II") and polarimetric data of "UBV" monitoring early published by Yudin & Evans (1998). \( \sigma_{\mu} \) and \( \sigma_{\varphi} \) are the errors derived from photon counting statistics.

| Source/JD | JD    | Filter | Integration time, (s) | \( p \pm \sigma, (\%) \) | \( \sigma_{\mu} \) \( \Theta_{\text{obs}} \pm \sigma \) | \( \sigma_{\varphi} \) \( \varpi_{\text{circ}} \pm \sigma, (\%) \) |
|-----------|-------|--------|-----------------------|-------------------|-----------------|-----------------|
| JD 2457106.0+ (Set "I") | .28903603 | "U" | 1593 | 3.43±0.15 | 0.08 | 170.5±3.0 | ±2.4 | 0.05±0.059 |
| JD 2457369.0+ (Set "II") | .44839849 | "U" | 989 | 3.22±0.15 | 0.09 | 166.4±3.0 | ±2.5 | -0.17±0.062 |
| JD 2449745.0+ | .36950 | "U" | 240 | 3.75±0.20 | 0.16 | 163.5±2.6 | ±0.6 | 0.01±0.060 |
| JD 2449751.0+ | .38290 | "V" | 180 | 3.87±0.09 | 0.07 | 164.5±2.6 | ±0.7 | 0.08±0.060 |
| JD 2449753.0+ | .35980 | "B" | 180 | 3.80±0.20 | 0.16 | 165.5±2.6 | ±0.6 | 0.01±0.060 |
| JD 2449755.0+ | .28690 | "U" | 240 | 3.54±0.21 | 0.17 | 165.3±2.6 | ±0.7 | -0.03±0.070 |

Yudin & Evans (1998)
3 DISCUSSION

3.1 Observed polarisation in HESS J0632+057

As we noted in Sect. 1, previously published polarimetric data for HESS J0632+057 are very limited. The first observations made by Hiltner (1951) at wavelength $\lambda = 5400\ \AA$ (i.e. close to the photometric band V) observed polarisation to be $p=4.0$ per cent at $\Theta = 164^\circ$. Later, values of $p=3.9$ per cent at $\Theta = 166^\circ$ were published by Hoag & Smith (1959) without any indication of the wavelength used. We will assume further, that this data corresponded to the V-band.

The first multi-band measurements of polarisation were presented by Serkowski et al. (1969), but with large errors in the red ($\sigma_p > 0.2$ per cent at wavelengths $\sim 0.8-0.9\ \mu m$). For these observations, the position angle ($\Theta$) was also found to be between $163^\circ$ to $166^\circ$. The most recent polarimetric data were published by Yudin & Evans (1998) and showed polarisation ranging from $p=3.5$ per cent to $p=3.9$ per cent with $\Theta = 162^\circ$ to $166^\circ$ (see Table 2).

As shown by our Set "I" data, the object displayed statistically higher polarisation than all previous measurements ($p_V = 4.21$ per cent). In addition, the value of detected polarisation in the red ($p_I \sim 3.8$ per cent) and in the blue ($p_U \sim 3.4$ per cent) were around 0.5 per cent higher than noted by Serkowski et al. (1969). At the same time, the position angle ($\Theta_{\text{obs}} = 171^\circ - 172^\circ$) is also different by $\sim 6^\circ - 10^\circ$ from previously published values. The polarised standard star, HD154445 (Hsu & Breger 1982; Bastien et al. 1988) was observed in order to calculate the position angle offsets and efficiency factors. Unpolarised standard stars were used to measure any instrumental polarisation ($0.4$ per cent, $0.3$ per cent, $< 0.1$ per cent, $< 0.1$ per cent, $< 0.1$ per cent in UBVRI correspondingly). These values of instrumental polarisation were vectorially subtracted from the observation values. Background sky polarisation measurements were also taken at frequent intervals during the observations. Thus, we can confidently rule out any instrumental effects and conclude that the increase in polarisation and shift in the observed position angle are real and intrinsic to the source.

Our Set "II" data show statistically lower polarisation values (by around 0.2-0.4 per cent) in all photometric bands compared to Set "I" (see Fig. 1 and Table 2). The position angle also changed from $\sim 172^\circ$ (for Set "I") to $\sim 167^\circ$.

The wavelength dependence of the observed polarisation for both of our datasets was also different from that of Serkowski et al. (1969) (see Fig. 1). According to Serkowski et al. (1969) the maximum polarisation occurred at $\lambda = 0.62\ \mu m$, while in our data the maximum is in the "V"-band for both of our datasets.

The difference between our data and that previously published is even more pronounced on a qu-diagram of Stokes' parameters (Fig. 2). It is immediately obvious that our Set "I" data are concentrated well outside the group of previously published values. The Set "II" data are located in

![Figure 2. qu-diagram of Stokes' parameters for HESS J0632+057. Data from Yudin & Evans (1998) - filled diamonds for UBV bands. Data from Serkowski et al. (1969) - open point-up triangles. Data from Hoag & Smith (1959) - cross. Data from Hiltner (1951) - filled circle. Data from this work: open squares (Set I, JD2457106) and open circles (Set II, JD2457369). Positions of interstellar polarisation (in V-band) taken from Yudin (2014) and from this work are indicated by dashed and dashed-dotted circles respectively. Dashed line on the plot represent the linear fit for the unweighted data as a whole.](image-url)
toward the object. First is the estimate by Yudin (2014) –
to date, we have two estimates of interstellar polarisation

3.2 Wavelength dependence of intrinsic polarisation in HESS J0632+057

To date, we have two estimates of interstellar polarisation
toward the object. First is the estimate by Yudin (2014) – p$_{is}$≈2 per cent and $\Theta_{is}$≈165° (using the "field star method" for 28 field stars in 3° vicinity of HESS J0632+057) and second is the data obtained for the nearby field star (GSC 00158-01500) in this work. This field star is located just 2° from HESS J0632+057 (see Fig. 3) and was not included in the previous interstellar polarisation estimate by Yudin (2014). The nearest star from Heiles (2003) catalogue used by Yudin (2014) for his interstellar polarisation estimate (HD 45910) is located ~40° away from HESS J0632+057.

V-band measurements obtained on the same date (JD 2457106.3413561) indicate the degree of polarisation of $p_V = 0.64 \pm 0.20$ per cent with $\Theta \approx 153° \pm 6°$. Unfortunately, as this field star is relatively faint ($m_{B,V,R} \approx 12.6:12.1:12.7$ respectively), the detected degree of polarisation does not exceed the 3σ level in the "BRI" bands. Nevertheless, the degree of polarisation detected in the "BRI" bands is less than 0.6 per cent.

In order to obtain the wavelength dependence of the intrinsic polarisation of the source, the interstellar component, $p_{is}$, needs to be subtracted in all photometric bands. We can do this by using both estimates of $p_{is}$ for our observing data of two epochs reported above - Set I and Set II. For the data of Yudin (2014), we assume that $p_{is}^{max}$=2 per cent, $\Theta_{is}=165°$ and $\lambda_{is}^{max}=0.55\mu$m. The values of interstellar polarisation in other photometric bands were calculated using the standard "Serkowski’s Law” (Serkowski et al. 1975). Vectorial subtraction of these values of interstellar polarisation from the observed ones allow us to re-construct the wavelength dependence of the intrinsic polarisation (see Fig. 4). Note, that only $V$- band measurements for 28 field stars used by Yudin (2014) for the estimate of interstellar polarisation are available in Heiles (2003). Therefore, some uncertainty in $\lambda_{is}^{max}$ value may occur. However, changing of $\lambda_{is}^{max}$ value from 0.55$\mu$m to 0.7$\mu$m will change the resulting intrinsic $p(\lambda)$ dependence insignificantly (see dotted line in Fig. 4 as an example).

Using this estimation of $p_{is}$, the average values of the intrinsic polarisation for HESS J0632+057 are $p\approx1.8$ per cent to 2.2 per cent and $\Theta \approx 175° \pm 5°$.

In Fig. 4 we also plot the wavelength dependence of the intrinsic polarisation calculated by vectorial subtraction of...
the field star observed during this work, using the above described procedure. We assume that $p_{\text{pol}}^{\text{max}} = 0.65 \text{ per cent}$, $\Theta_{\alpha} \approx 153^\circ$ and $\lambda_{\text{max}} = 0.55 \mu \text{m}$. In this case, the average values of the intrinsic polarisation for HESS J0632+057 are $p \approx 3 \text{ per cent}$ to $3.5 \text{ per cent}$ and $\Theta \approx 173^\circ \pm 4^\circ$. Note that in either case, the intrinsic $p(\lambda)$ dependence is essentially flat, without noticeably decreasing in the red. Similar $p(\lambda)$ distributions are often observed in classical Be stars and are attributed to scattering in flattened circumstellar gaseous discs and/or jets around them (see also the polarimetric study of the microquasar LS I +61°303 by Nagae et al. (2006)). We propose that Thomson scattering in a gaseous disc (see, for example, the discussion of optical polarisation in the high-mass X-ray binary LS 5039 by Combi et al. (2004)) may be the dominant mechanism for producing the polarisation behaviour in HESS J0632+057 (at least close to periastron passage). Another possibility is discussed by Russell et al. (2011) in the context of synchrotron emission from jets launched close to black holes or neutron stars in low-mass X-ray binaries. In this case, however, strong polarimetric variability can be expected in the near-IR.

4 CONCLUSIONS

We have shown that the observed polarisation in HESS J0632+057, close to periastron passage, is statistically different from previously published measurements. The detected polarisation degree, just after periastron, is higher than previously observed with a shift of 6°-10° in position angle. We propose that these changes arise from the interaction of the compact object with a circumstellar disc near periastron passage, and/or some redistribution of the material within the circumstellar disc. According to Zamanov et al. (2016), the compact object moves deeply through the circumstellar disc during periastron passage, in the zones associated with $H_{\alpha}$, $H_{\beta}$, $H_{\gamma}$ line formation, i.e. crossing dense regions of the disc (Moritani et al. 2013). At this orbital phase, different events may occur, such as: the interaction of the stellar wind with the wind or jet of the compact object; a strong flow of matter from the Be star can be captured by the compact object resulting in the formation of an accretion disc or gaseous tail; the disruption of the circumstellar disc by the compact object etc. (see Hoeflich et al. (1996), Moritani et al. (2015), Zamanov et al. (2016)). Therefore, some perturbation of circumstellar material at this orbital phase or the formation of an additional source of polarisation cannot be surprising. On the other hand, the Be disc can be misaligned with the orbital plane (Martin et al. 2009). In this case, the formation of a tilted accretion disc, formation of a jet which is non-orthogonal to the Be disc, or formation of a tail from gas captured by a compact object may result in a shift in the position angle of the observed polarisation, as detected here.

If the polarimetric variations reported here (especially for Set "T") are linked to some form of perturbations in the circumstellar disc or the formation of an additional source of polarisation started just after the periastron passage, then we can expect further increase of polarisation at phases up to $\sim 0.3-0.5$. In this context, the object exhibits a main outburst, at TeV and X-rays, at orbital phases $\sim 0.3$ and a secondary lower outburst at orbital phases $\sim 0.7$ (Aliu et al. 2014). Therefore, one might expect the geometry of the circumstellar envelope to also change during these phases.

Depolarisation across the $H_{\alpha}$ line, which is often observed in many early-type objects, can be used as a method for independently deriving the interstellar polarisation (Hoeflich et al. 1996; Oudmaijer et al. 1999; Patat et al. 2011) and circumstellar envelope geometry. Therefore, spectropolarimetry around $H_{\alpha}$ would be very helpful.

Finally, higher-precision polarimetric measurements over the orbital period are needed to study the HESS J0632+057 behavior in the qu-plane. To date, our limited observations do not allow us to make definitive conclusions about the geometry of the system, or the mechanisms responsible for the detected polarimetric variations. Most extensive polarimetric data were obtained by Yudin & Evans (1998) in "$U,B,V$" bands. Lack of polarimetric data in "$R,I$" does not allow to analyze the object in a whole spectral region. Near-IR polarimetric data would also be strongly desirable.

Therefore, additional multi-epoch and multi-colour polarimetric observations covering the entire orbit are strongly desirable to verify potential orbital phase variations in the polarisation degree and to map the geometry of the HESS J0632+057 system.

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