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Polarimetric variability of the Herbig Be star HD 100546

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Abstract. High accuracy polarimetric observations made on three nights are reported for the Herbig Be star HD 100546 revealing changes both in the linear and circular components. Continuous monitoring over windows ~ 2 hrs reveal no variation or secular change in p at levels ~ 0.0002 but night-to-night changes ~ 0.0010 are clearly recorded. The $p(V)/p(B)$ ratio indicates an interstellar polarization component. Accounting for this by consideration of field stars does not, however, provide an intrinsic value for this ratio that is explained by electron scattering and it is concluded that the basic polarigenic mechanism is scattering by dust within the circumstellar environment.

Key words: polarization – stars: circumstellar matter – stars: individual: HD 100546 – stars: pre-main sequence

1. Introduction

It is well known that Be stars display linear polarizations $(p \sim 1\%)$ with a characteristic wavelength dependence dominated by the influence of hydrogen opacity in the extended atmosphere (e.g. see the review of Coyne (1976)). Once the contamination of any interstellar component is removed from the raw measurements, the $p(\lambda)$ data are usually distributed along a line – the intrinsic line – in the normalised Stokes parameter (q, u) plane, with the vector angle related to the inclination of the stellar equatorial disk. Many Be stars display temporal variability on a range of time-scales from hours to months, the mapped behaviour in the q, u plane sometimes being related to the intrinsic line. A classic example for the behaviour of $p(\lambda)$ and its temporal changes is the Be star, γ Cas – see Clarke (1990).

For young Herbig AeBe stars (HAEBE), temporal polarimetric variability is also observed, both on the short and long terms. The polarigenic mechanisms are quite different from classical Be stars, being connected with dust particles in non-spherical shells. There is no unique behaviour of $p(\lambda)$ for these young stars as the resultant involves the combinations of dust types, degrees of clumpiness, etc. (see Voshchinnikov and Karjukin 1994). Polarimetry, being more sensitive to the geometrical configurations and physical conditions, may help to explore these stars.

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The southern hemisphere Be star HD 100546, spectral type B9Vne, has been included in the list of HAEBE stars of Thé, et al. (1994). It has also been selected for investigation as a young star by Henning et al. (1994) who discussed the presence of a disk-like dust component around it. Short-term variability of the Hα and He line profiles on time scales of days and probably hours has been reported by Vieira et al. (1998). According to SIMBAD, ten papers have already been published in 1998 on different observational aspects of this remarkable star. It was therefore decided to extend the observational diagnostic study by performing polarimetry with a view to determining the star's basic geometry and aspect. A preliminary polarimetric study was made by Yudin & Evans (1998) and with uncertainties in $p \sim \pm 0.1\%$ for each reported measure, they suggest there is clear evidence of variability on time-scales of days to minutes. We report on new measurements obtained during an observational run in May 1996 at the South African Astronomical Observatory, Sutherland, using the polarimeter of the University of Cape Town (see Cropper, 1985).

2. The measurements

Measurements were made on three nights, each covering about 2 hours. Alternate B and V band integrations (180 s) were obtained and later reduced to remove the instrumental polarization and to relate the Stokes parameters to the celestial equatorial frame, using the calibrations described in a previous paper – see Clarke, Smith and Yudin (1998). The nightly mean values of the polarization are summarised in Table 1 and displayed in Fig. 1.

At face value, the measurements suggest that HD 100546 displays a small polarization $\sim 0.25\%$. The main question for this peculiar star is the origin of the intrinsic polarization. If we assume that the polarization of the radiation is Thomson scattering in the gaseous shell, the only possibility to explain the $p(V)/p(B)$ ratio being larger than the usual Be star (i.e. > 1) is a contamination of interstellar polarization. Taking into account the value of the measured interstellar absorption [$(A_V \approx 0.^m28$ (see Ancker et al. 1998)] and the canonical relation $p_{IS} \leq 3A_V$, (see Serkowski, et al. 1975) the value for $p_{IS} \leq 0.9\%$ for HD100546. According to Hipparcos data, the distance to this star is 103 ± 5 pc. Inspection of Centre de

Table 1. The measurements of the Be star, HD 100546, according to the commencing Julian Date and the filter passband. The headings q, u correspond to the mean normalised linear Stokes parameters with the standard error (1σ) attached; uncorrected circular polarization measurements with their associated error are listed under the heading v_o. The number of integrations is designated by N, each with integration time of 180 seconds.

JD 2450000+	Band	q	u	σ	v_o	N
227.272	B	-0.00077	$+0.00180$	±0.00014	-0.00020 ± 0.00010	11
227.274	V	-0.00086	$+0.00311$	±0.00012	-0.00027 ± 0.00009	11
229.286	B	-0.00039	$+0.00156$	±0.00010	$+0.00007 \pm 0.00007$	17
229.288	V	-0.00113	$+0.00227$	±0.00009	-0.00017 ± 0.00007	17
230.324	B	-0.00084	$+0.00082$	±0.00013	$+0.00046 \pm 0.00009$	12
230.326	V	-0.00165	$+0.00232$	±0.00011	-0.00030 ± 0.00008	12

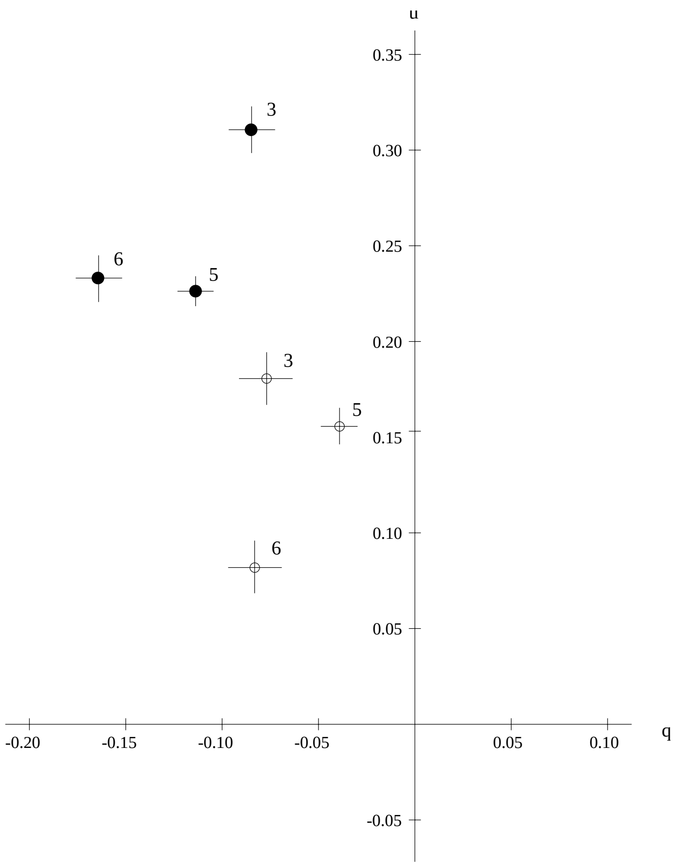

Fig. 1. The Stokes parameter plot (q and u in %) depicts the mean polarimetric values for HD 100546 for each of the three nights (3 ≡ JD 227, 5 ≡ JD 229, 6 ≡ JD 230) of observation for the B(○) and V(●) passbands. The error bars correspond to $\pm1\sigma$ values.

Données Astronomiques de Strasbourg – Polarisation Catalogue (1978) and the data of Klare and Neckel (1977) reveals that there are no field stars within 3°. By expanding the field to 7°, there are four stars at similar distances which show $p \sim 0.05\%$ with $\theta \sim 135°$. However, as noted by Hu et al. (1989), the star's co-ordinates match those of a dark cloud (DC 296.2–7.9) covering a field ~ 15 arcmin. There are a few stars within 2.°5 of HD 100546 which are 2 to 3 times more distant, providing substantial interstellar polarizations (see Table 2).

Table 2. Values of the V-band interstellar polarization of stars within 2.°5 of HD 100546, the data taken from Mathewson & Ford (1970)

HD Number	Angular Sep (°)	$p(\%)$	θ (°)	d(pc)
102839	1.4	1.44	118	446
98695	2.1	1.90	115	233
99264	2.17	2.36	120	270
96706	2.32	1.37	116	346
99872	2.32	3.03	117	233

From Table 2 we may estimate $p_{IS} \approx 2\%$ with $\theta \approx 117°$ for the distance ~ 300 pc. Assuming a linear growth with distance, the value of p_{IS} at 100 pc would be 0.6% which is in agreement with the estimate obtained from the extinction value. However, consideration of such an interstellar polarization does not rectify the anomalous $p(V)/p(B)$ ratio. From this we can conclude that electron scattering can be excluded as the primary source of the intrinsic polarization.

The temporal variability of p discussed here clearly indicates an intrinsic origin for the polarization. An explanation for the observed behaviour of HD 100546 may be found through scattered radiation by dust particles in the circumstellar envelope. The star is known to have a large IR excess ($E_{(V-L)} \approx 2\overset{\mathrm{m}}{.}5$ or $E12\,\mu\mathrm{m} \approx 8\overset{\mathrm{m}}{.}6$) which is explained by the presence of a dust disk surrounding the star and viewed edge-on (see, for example, Malfait et al., 1998) and is like many other young HAEBE objects. Such excesses indicate the presence of cool and hot dust in their environments. If the circumstellar dust is the main agent for the polarization of HD 100546, the wavelength dependence may have a form like that of the canonical Serkowski Law. In most cases HAEBE stars show $p(\lambda)$ which differs from the Serkowski Law in the sense that p does not decrease in the red. This fact can be explained in terms of non-selective absorption in circumstellar shells due to the presence of large dust particles. The existence of both selective and non-selective components affecting the polarization of some HAEBE stars has been discussed recently by Beskrovnaya et al. (1998) and Beskrovnaya et al. (1999). Moreover, the objects which were considered (HD 163296 and HD 36112) are very analogous to HD 100546 taking into account their photometric and spectroscopic char-

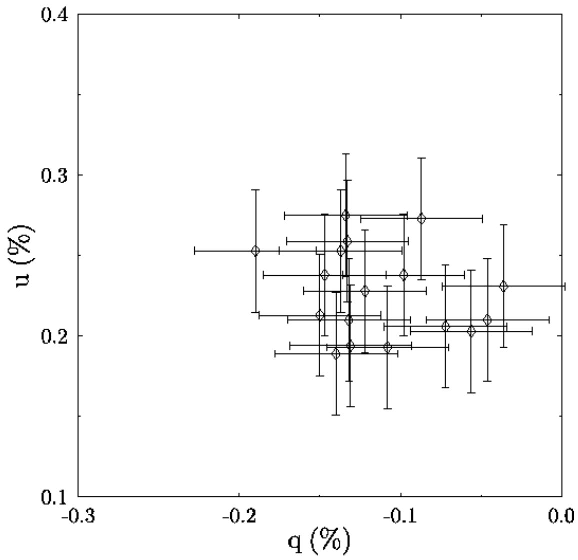

Fig. 2. The Stokes parameter plot depicts the individual V-band polarimetric records for HD 100546 for the night of JD 245 0229.

acteristics. According to Grady et al. (1997) the spectroscopic behaviour of HD 100546 and the presence of accreting gas profiles led them to conclude the existence of star-grazing bodies resembling either comets or asteroids. They also noted a similarity of HD 100546 with two other HAEBE stars HD 104237 and HD 163296 and with more evolved stars such as β Pic. The prominent mm flux from HD 100546 is also consistent with the presence of comparatively large circumstellar grains (Henning et al., 1994).

3. The temporal variability

The method of data logging, with repeated measurements (N) of $p(\mathrm{B})$ and $p(\mathrm{V})$, is ideal for applying statistical tests to explore short term polarimetric flickering and night-to-night changes. For each night, tests (see Brooks et al., 1995) showed that the assembly of q and u values for both passbands could be considered as being Normally distributed with a variance that was no larger than expected as a result of the experimental noise. Time plots of the data in the q, u plane also revealed random paths through the distribution. No distinctions could be made between measurements made at the beginning of each night relative to the data recorded towards the end of each 2hr run. Each set of nightly values appeared to be consistent as being repeated measurements of a constant underlying value. A typical set of measurements from a single night is depicted in Fig. 2. Thus no flickering in p at a level of $\sim \pm 0.0002$ was observable on any of these nights with a total observation coverage of about 6 hours.

Welch tests (see Brown and Forsythe, 1974) reveal that for both the B and V passbands, the three q means for each night are indistinguishable and can be considered as coming from the same underlying parent constant value. The u parameter, however, does show movement. On JD 0230, the B band measurements are significantly displaced from the values of the other two nights and, on JD 0227, the V band measurements are significantly displaced relative to the other two nights, the differences being clearly seen in Fig. 1. Unfortunately the observing run was too short to obtain hints of any systematic changes in the q, u plane that would allow the major principal axis or intrinsic line (see Clarke and McGale, 1987) to be determined.

Although the circular polarization measurements have not been treated properly for effects of instrumental polarization, it does appear that a change in the B band is detectable over the observing run. Welch tests show that on JD 0230 the underlying value is different from the other two nights, possibly associated with the noted change of the linear polarization on the same night. At this stage it is impossible to say whether this circular polarization is generated in the stellar atmosphere or whether it is the intrinsic linear component being partially converted to circular by the birefringent interstellar medium. The three mean records for the V band are indistinguishable and although they provide a systematic non-zero value, reference to data from other stars (see Clarke, Smith and Yudin, 1998) would suggest that it is an instrumental effect and that its mean value is essentially zero. To explain their spectroscopic data, Vieira et al. (1998) suggested the presence of an optically thick dust cloud in the edge-on disk-like envelope of the star. Such a geometry may result in the appearance of circularly polarized radiation at least from time-to-time.

4. Discussion and conclusion

Three nights of observation have revealed night-to-night polarimetric changes in HD 100546, both linear and circular. Over windows of $\sim$ 2 hours, however, no polarimetic variation either secular or of a more stochastic nature was detected with measurement uncertainties in $p \sim \pm 0.02\%$. No hint of the temporal behaviour, as reported by Yudin & Evans 1998, was detected over a total monitoring time $\sim$ 6 hours, even though our new measurements were recorded with experimental uncertainties which were some 5 times smaller. Comparison of the data of Yudin and Evans shows that the $p(\mathrm{V})$ values occupy a similar region in the q, u plane but that the $p(\mathrm{B})$ are displaced as a result of u values being negative. Thus the ratio $p(\mathrm{B})/p(\mathrm{V})$ has changed significantly between the data sets of Yudin and Evans and those presented here. Such a variation may be brought about by a change in the average opacity in the stellar disk or by a change in the contribution of the circumstellar dust component.

The variability on time scales of days reported here and on a long time scale, following comparison with the data presented by Yudin & Evans (1998), is not surprising. As noted earlier, the star is a spectroscopic variable (e.g. see Grady, et al., 1996). Vieira et al. (1998) pointed out that both accretion and stellar wind are the sources of activity in HD 100546. Moreover, they have noted the occurrence of Algol-like photometric minima with small ($\approx 0\overset{\mathrm{m}}{.}06$) brightness variation and discussed this behaviour in terms of variable extinction by inhomogeneities in the circumstellar disk. Hipparcos photometry of the star (see van den Ancker et al., 1998) indicates a photometric variation with amplitude $\delta H_p \approx 0\overset{\mathrm{m}}{.}19$.

There is a significant difference between stars like HD 100546, HD 31648, HD 36112 and HD 163296 and young HAEBE stars with Algol-like minima of brightness like UX Ori, BF Ori, etc. (UXOrs). Both stellar groups are characterised by the presence of circumstellar disks viewed edge-on and inhomogeneous dust clouds rotating in the plane of the disk. The amplitude of the photometric and polarimetric variability is small for the first group ($\Delta m_V < 0.^m2$, $\Delta p < 0.3\%$) whereas for UXOrs, the scale of variability of the observed parameters is significantly larger ($\Delta m_V \approx 3^m$; $\Delta p \approx 6$ to 7%). It is safe to suggest that in both cases this variability results from reductions of the dust cloud dilution effect of the unpolarized stellar radiation, and because of the cloud sizes, this is more important for UXOrs than the above HAEBE stars. This suggestion goes hand in hand with the notion that these subgroups have different ages with the HAEBE stars above, being considered in the past as members of Vega-type stars and "Baby" β Pic stars (see Sitko et al., 1999) or in terms of circumstellar evolution of objects in a transition stage between young HAEBE stars and young main sequence Vega-type stars. Small amplitude variability on time scales of days is typical for this sub class of young stars Beskrovnaya et al. (1998, 1999). In the framework of dust condensations rotating around a star, polarimetric variability of UXOrs results from changes in the ratio between the polarized and non-polarized fluxes from the circumstellar envelopes, while for the stars like HD 100546, variability is generated by scattering within the small inhomogeneities. If the initial dust disk is compressed along the direction of the local magnetic field, it should be oriented normally to the interstellar polarization (i.e. position angle $\approx 117° - 90° = 27°$. The estimates of intrinsic polarization of HD 100546 leads to a V-band value $\theta_{intr} = 35°$, i.e. the vector of intrinsic polarization is roughly parallel to the disk plane. Contrary to the optically thin case, such a situation may occur if the dust inhomogeneities are optically thick. The conclusion that the scattering is from optically thick dust inhomogeneities is also consistent with the possible detection of circular polarization in HD 100546.

It is important that this star should be monitored more extensively to explore the nature of the variation in p and to investigate the circular polarization further with a view to confirming its origin. It is important to obtain measurements of p as it is undergoing change and to record the rate at which the night-to-night variations in p, occur. If, for example, the change is smooth and progressive through the 24 hr period, then its cause might be ascribed to a general global development. For more rapid changes, localised variations in the optical depth are required, these being produced by stellar wind events or in a more permanent structure which is revealed through co-rotation of the circumstellar structure. Monitoring of the temporal signatures variations would help determine the 'degree of clumpiness' in the extended atmosphere of this star. Measurements made with a broader range of wavelength coverage would also be useful to distinguish between electron scattering and Mie scattering from the dust in the stellar environment and to investigate the presence of very small and very large dust particles.

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