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EVIDENCE FOR A BIPOLAR NEBULA AROUND THE PECULIAR B[e] STAR HD 45677 FROM ULTRAVIOLET SPECTROPOLARIMETRY

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ABSTRACT

We report the first ultraviolet spectropolarimetry of the peculiar B-type emission-line star with infrared excess HD 45677. The observations were obtained during the 1990 December *Astro-1* space shuttle mission with the Wisconsin Ultraviolet Photo-Polarimeter Experiment, WUPPE, and cover the spectral range 1400–3220 Å. We also present the first optical spectropolarimetry, extending from the atmospheric cutoff to ~7600 Å. The observed UV/optical linear polarization displays a strong increase toward shorter wavelengths indicative of scattering by circumstellar dust. The position angle of the intrinsic polarization flips by 90° in the near-UV as expected from a bipolar reflection nebula.

Subject headings: polarization — stars: individual (HD 45677) — stars: emission-line, Be — stars: mass loss

1. INTRODUCTION

HD 45677 is a B2 IV star (Burnichon et al. 1967) exhibiting infrared excess due to thermal emission of circumstellar dust (Low et al. 1970; Swings & Allen 1971). Although the presence of cool dust around this hot star is an enigma, it does provide a laboratory to study the formation and destruction of cosmic grains in a high-temperature environment. HD 45677 has been observed extensively from space with ESRO *TD-1* (Thompson et al. 1978), *ANS* (Savage et al. 1978), *IUE* (Sitko & Savage 1980; Selvelli & Stalio 1980; Sitko, Savage, & Meade 1981), and *IRAS* (Olnon et al. 1986).

Savage et al. (1978) showed that the interstellar extinction toward HD 45677 is very small. From a comparison of its spectral energy distribution with that of slightly reddened B stars, Sitko & Savage (1980) suggested that circumstellar dust absorption (2.1 mag at 1500 Å) is responsible for the deficiency of UV and optical radiation, and that it could account for the IR-excess emission. Sorrell (1989) used detailed radiative transfer calculations to show that the energy distribution of HD 45677, the strength of the 2200 Å dip, and the strength of the 10 and 18 μm silicate emission features could indeed be explained by absorption and reemission of stellar radiation in a massive spherical dust shell containing comparable amounts of carbon and silicate dust with a power-law grain size distribution having an upper size limit of ~1 μm. Sorrell recognized, however, that dust-shell geometry could be a potential problem with his model. There have also been observations indicating that the circumstellar envelope of HD 45677 is not spherical. Swings (1973) interpreted the optical emission-line spectrum as having originated in a disk-shaped stellar wind. Coyne & Vrba (1976, hereafter CV) showed that the optical and near-IR radiation of HD 45677 is linearly polarized by dust scattering. An unresolved spherical dust shell yields net polarization only if the particles are elongated and aligned. Although the star might have a magnetic field of 1600 G (Babcock 1958), CV argued that the field strength would be inadequate for efficient grain alignment at such distances from the star where dust could be expected to survive. They offered an alternative interpretation in which the polarization is produced by arbitrarily shaped and oriented dust grains in a nonspherical scattering geometry. CV suggested that scattering by dust clouds in a ring with radius ~45 AU surrounding the inner, plasma disk could explain both the wavelength and time variations of the polarization. Sorrell, however, pointed out that this dust ring proposed by CV does not contain enough mass, by a factor of 1000, to account for the observed IR emission. The massive, spherical shell of his model has a radius of >200 AU or an angular size of 5''.8. Yet, unpublished imaging of HD 45677 by R. Puetter et al. (private communication) indicates that HD 45677 is indistinguishable from a stellar point source at 20 μm (FWHM of ~3''.4).

The controversial geometry of the circumstellar material around HD 45677 made it a prime candidate for a study with WUPPE.

2. OBSERVATIONS

WUPPE, a 0.5 m telescope designed to measure polarization in the ultraviolet from about 1400 to 3300 Å at a maximum resolution of 6 Å, was flown on the space shuttle Columbia during the *Astro-1* mission. HD 45677 was observed on 1990 December 6 (JD 2,448,231.59) through the 6'' × 12'' aperture, in a single pointing of 1536 s. The data were calibrated using both preflight and in-flight measurements (Nordsieck et al. 1992a). Due to poor pointing stability, the fluxes should not be considered as absolute. Since the Stokes Q and U parameters and their errors are calculated from least-squares fits to the count-rate modulations in three pairs of half-wave plates with different orientations of their fast axes, they are prone to systematic errors when count rate variations occur faster than the rate at which the plates are swapped. However, after sorting the subintegrations by image position within the aperture, we found that the scatter in the Stokes parameters was within 3 σ

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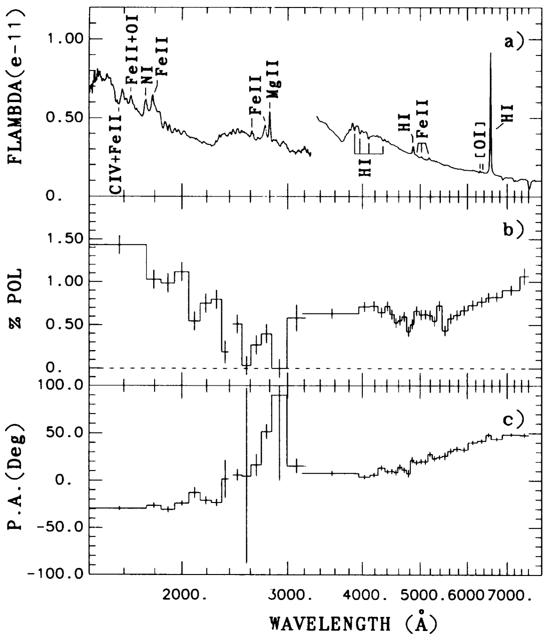

FIG. 1.—Ultraviolet and optical (PBO) flux in units ergs cm^{-2} s^{-1} $Å^{-1}$ (*a*), percentage polarization (*b*), and position angle (*c*) of HD 45677 as a function of logarithmic wavelength. The offset between the UV and optical fluxes is due to errors in the absolute flux calibration of this WUPPE observation due to pointing problems. The polarization was binned to constant errors, 0.1% for the UV, 0.06% for the optical data. The optical data represent a mean of two nights. The gap in UV coverage near 2400 Å in (*b*) and (*c*) is due to polarization data that were removed because a detector flaw produced spurious results.

of the calculated errors. The mean (combined) polarization over the WUPPE wavelength range using an error-weighted, pixel-by-pixel average (excluding an area from 2394 to 2431 Å in which the detector photocathode is flawed) is $P = 0.53\%$ ($\pm 0.03\%$), at position angle $\Theta = 161°$.

Contemporaneous optical observations were obtained on 1990 December 11 and 12 at the 0.9 m telescope of Pine Bluff Observatory (PBO) (Nordsieck et al. 1992b). The data range from 3170 to 7600 Å at a resolution of 25 Å. Since these nights were not photometric, we shifted the optical spectrum to $V = 8.16$, a value interpolated from photometry by Halbedel (1991). The UV and optical data are shown in Figure 1. The combined optical data exhibit a polarization of $P = 0.57\%$ ($\pm 0.01\%$) at $\Theta = 24°$. HD 45677 was also monitored at PBO on seven other occasions between 1989 February 17 and 1992 March 24. (These data are not shown in Fig. 1.)

We observed HD 45677 on 1991 November 25 and 26 with the 3.9 m Anglo-Australian Telescope (ATT) at a higher spectral resolution of ~9 Å. The mean polarization from 4120 to 6870 Å is $P = 0.48\%$ ($\pm 0.01\%$) at $\Theta = 25°$. The systematic error was estimated to be $\pm 0.05\%$.

Finally, we also acquired near-simultaneous, high-resolution *IUE* spectra on 1990 December 5.

3. RESULTS

The *IUE* spectrum of HD 45677 was described by Selvelli & Stalio (1980) and Sitko & Savage (1980). The WUPPE UV spectrum, with a resolution similar to *IUE* low-resolution mode, shows strong emission lines of Mg II, Fe II, and N I, as well as numerous weak Fe II lines longward of 2200 Å, absorption lines of C IV, Al III, copious Fe III lines around 1900 Å, and the 2200 Å extinction bump. The Mg II lines exhibit intricate P Cygni profiles in our *IUE* high-resolution spectrum. There is a previously unidentified emission feature at about 1642 Å which Selvelli & Stalio say is not He II λ1640. Our optical spectra do not show emission of He II λ4686, which supports this suggestion. We propose to identify this feature as a blend of Fe II (68), Fe II (42) and possibly O I (146), all with laboratory wavelengths near 1642 Å (Carpenter, Wing, & Stencel 1985). Our optical spectra show strong emission lines at Hα and Hβ, Fe II (42) and [O I], as well as numerous weak metallic lines in the region around 5300 Å; the higher members of the Balmer series up to H10 and the Balmer jump are seen in absorption.

The percentage polarization exhibits a minimum at ~2800 Å; it rises steeply toward shorter wavelengths and increases gradually toward longer wavelengths. The position angle rotates smoothly across the observed spectral range, crossing zero in the same wavelength region where the polarization is a minimum. The polarization does not change across the 2200 Å feature, in the Mg II lines (2.5 σ result), or across the Balmer jump, within the observational errors. It does vary across the Hα line in both AAT observations (the signal-to-noise ratio in the PBO data was insufficient to detect this). The line polarization with the continuum removed is 0.69% ($\pm 0.04\%$) at 46° while the polarization of the continuum is 0.53% ($\pm 0.04\%$) at 35° in the combined data.

A *Q-U* diagram of our data is presented in Figure 2. There is

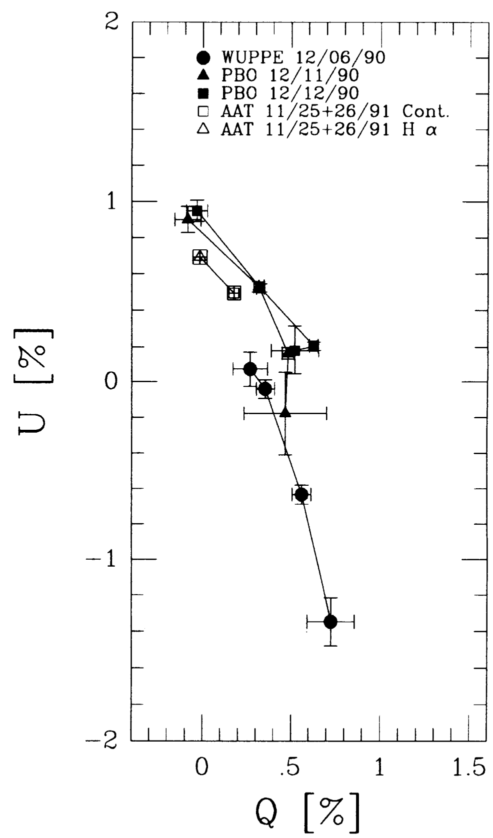

FIG. 2.—*Q-U* diagram of the observed ultraviolet and optical polarization. The WUPPE and PBO data were each binned into four passbands to illustrate the color behavior of the continuum polarization. The upper left points are the reddest of the optical data, whereas the point in the lower right of the diagram is the bluest of the ultraviolet data. The AAT data were used to extract the polarization in the Hα line and underlying continuum.

a general trend of the data to follow along a slightly curved *Q-U* track as a function of wavelength. The polarization crosses into a different quadrant in the near-UV, which is indicative of a flip of the intrinsic position angle by 90° (a rotation in *Q-U* space by 180° corresponds to an actual variation on the sky by 90°). The Hα continuum-to-line vector is co-aligned with the optical continuum color vectors. There is a displacement between the optical and the UV data where the polarization attains its minimum. Since the optical polarization did not vary significantly between the two PBO nights, the difference between the UV and optical *Q-U* paths is probably not caused by temporal variations. (CV also noted that broad-band polarization variations in HD 45677 tend to occur on time scales of several weeks to months.)

CV found that the optical polarization was more variable in the red than in the blue (see their Table 2). Our optical data from 1989 to 1992 confirm this behavior. CV interpreted the color variations by assuming that the observations at shorter wavelengths represent the constant, interstellar component of the polarization. They suggested an interstellar polarization with the following parameters: $P_{max} = 0.65\%$, $\lambda_{max} = 0.5\ \mu m$, and $\theta = 170°$. After removing it, CV found that the intrinsic polarization rose into the red; they proposed that the polarization might be due to scattering from large-size grains with diameters of about 1 μm located in a circumstellar ring. Variability in the red was accounted for by an inhomogeneous dust distribution in the ring.

The model of CV explains the optical polarization behavior of HD 45677 very well. We suggest that it can also provide a basis for interpreting the UV polarization if there exists an orthogonal component of polarization that peaks in the UV. Based on the WUPPE data, we propose that the "constant" polarization in the blue corresponds to that wavelength at which the two orthogonal intrinsic polarization components cancel. The observed polarization at that wavelength can therefore be understood as the interstellar polarization component. Using the parameters of CV, and assuming the interstellar-polarization dependence follows a Serkowski law (there are no sight lines observed with WUPPE with less polarization than that expected from an extrapolation of a Serkowski law; see Clayton et al. 1992), we separated the interstellar and intrinsic components at each wavelength. The resulting *Q-U* diagram of the intrinsic polarization now shows a wavelength track which is almost linear and in which the displacement between the UV and optical data has also become much smaller, with Hα being more polarized than the adjacent continuum. The intrinsic polarization versus wavelength is shown in Figure 3. The flip in position angle is now 90°. This is the polarization signature one would expect from a bipolar nebula, as we now discuss.

4. DISCUSSION

The WUPPE UV polarization data provide strong evidence for a bipolar picture of HD 45677 (see Fig. 4 [Pl. L9]). Polarization in bipolar reflection nebulae around central stars was modeled by Daniel (1982). The important features of this model are an equatorial disk of large optical depth in dust scattering and polar lobes of smaller optical depth. Photons emitted in equatorial directions scatter in the thick disk with the resultant polarization along the polar axis, whereas photons scattered in the polar envelopes produce a competing polarization along the equatorial axis. At short wavelengths, the equatorial disk blocks out the direct starlight while itself generating very small polarization. The polarization is dominated by light scattered from the polar lobes and can be quite large. At long wavelengths, the polarization is dominated by scattering in the equatorial disk. A flip in position angle occurs at that wavelength where both components are of equal strength. Daniel achieved good fits with his model to the polarization of several late-type stars in which reversals have been observed.

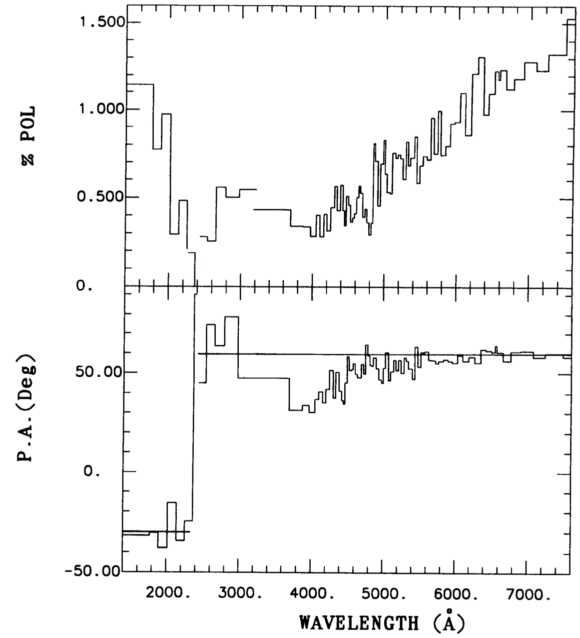

FIG. 3.—*Intrinsic* percent polarization and position angle of HD 45677 as a function of wavelength. The data were binned to a constant error of 0.1%. The horizontal lines show the 90° difference in position angle to either side of the polarization reversal.

The polarization in a bipolar model is maximized when the system is viewed equator-on. Swings & Allen (1971) determined a projected rotational velocity of ∼200 km s^{-1}—confirmed by Swings (1973)—from the width of photospheric He I lines and suggested that HD 45677 is most probably seen nearly equator-on. A high-resolution CCD spectrum obtained by A. Fitzsimmons & E. Little which recently appeared in Gemini (issue 34, Fig. 2) shows Balmer line profiles of similar width which also display narrow shell absorption features, suggestive of a high inclination if the emission region is confined to a Be-type gas disk.

The intrinsic polarization rises more steeply into the UV than it rises into the red. Daniel models the polar grains as small, Rayleigh-scattering grains, whereas the disk grains are assumed to be larger, Mie scatterers. This could account for the sharper rise of the UV polarization component. However, it may not be necessary to invoke two distinct grain-size distributions, because the polarization on either side of the reversal is also controlled by the variation of the optical depth in the disk with wavelength.

We assume that there is a dust-free region of ionized gas in which the emission-line spectrum is formed (Swings 1973), and which could also explain the elevated intrinsic polarization in Hα. The continuum star light and Hα emission are scattered by grains in the dust ring causing polarization in both components with similar position angles. The dust ring must be located sufficiently far from the star such that the star is seen as

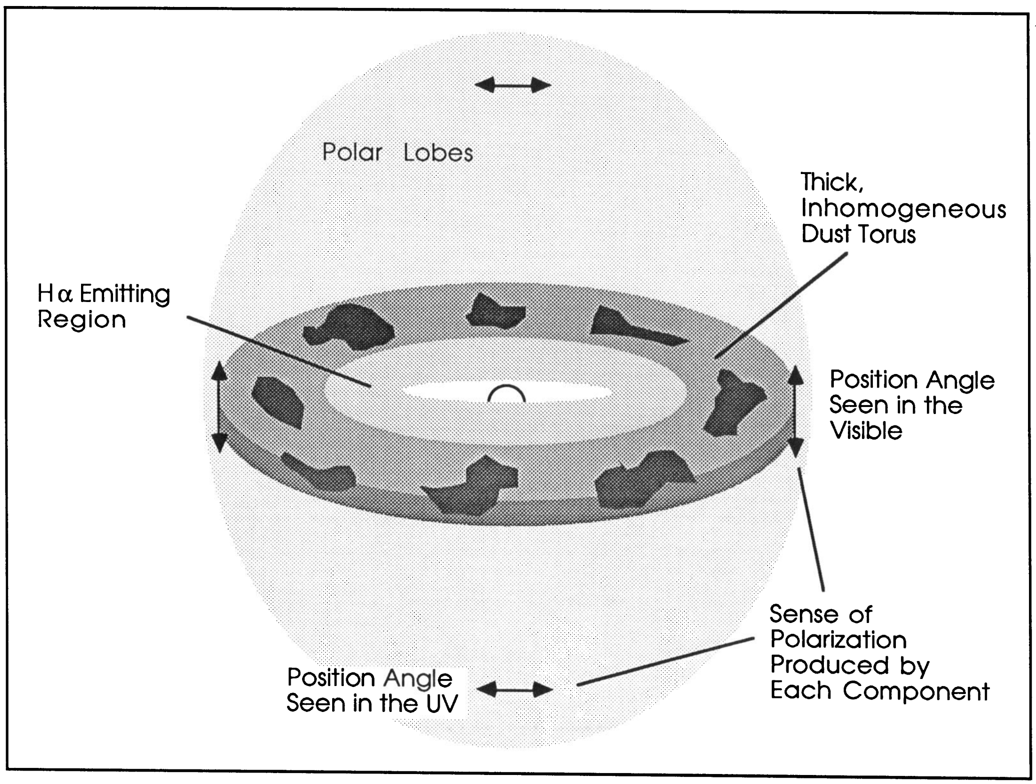

FIG. 4.—A schematic picture of the proposed circumstellar environment around HD 45677

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a point source; the continuum polarization is then just proportional to the solid angle of the ring (the polarization is largest for a solid angle of 1 radian; beyond this, geometrical dilution begins to decrease it). The polarization of the Hα region would be increased by being located relatively closer to the inner boundary of the dust ring, as long as the apparent angular thickness of the dust ring as seen by the emission-line region is also smaller than 1 radian. Another indication for the existence of a geometrically thick ring comes from the position angle variations of the red polarization, from which CV inferred a disk height of ~ 15 AU.

The geometry of the dust torus combined with the grain size distribution and composition determine the spectral energy distribution of HD 45677 as well as the resulting polarization. Note that since, in a nonspherical geometry some scattered photons are removed from the beam, models of the energy balance between the UV and the IR will change because the same *extinction* of UV/optical flux can be achieved with less absorption. While qualitatively the UV/optical extinction seems to be sufficient to explain both the UV polarization and the IR excess, the feasibility of our picture should be examined with radiative transfer calculations. The IR emission could perhaps originate from an extension of the circumstellar dust ring to larger radii. If the dust torus could be imaged in the IR, and if its orientation was perpendicular to the position angle of the red polarization, this would strongly argue for a common origin of both.

The following observations could also verify our picture. First, at that wavelength where the linear polarization is zero due to cancellation, there should be a strong circular polarization caused by rescattering of disk light in the polar lobes. HD 45677 was observed in circular polarization by Serkowski (1973) with a null result, but the measurement was taken at a wavelength of 9700 Å, well outside the spectral region where we would expect to find circular polarization. An observation of circular polarization just longward of the atmospheric cutoff could easily be obtained with a filter polarimeter and would provide an excellent test. Second, optical depth variations in the equatorial disk should change the amount of blocking of the direct starlight and are thus expected to produce correlated variations of the UV polarization in the bipolar model. Specifically, one would expect the UV polarization to increase as the visual polarization decreases while the polarization reversal point should remain within a narrow wavelength range. Additional contemporaneous measurements of the linear polarization from the UV through the IR could be used to investigate this variability behavior and could be carried out during the *Astro-2* mission.

5. CONCLUSIONS

We presented and discussed the first UV spectropolarimetry of HD 45677. The UV polarization shows a near-UV position angle flip by 90° plus a steep rise in the percentage polarization toward shorter wavelengths. This provides compelling evidence for a bipolar geometry of the circumstellar dust around HD 45677.

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