BALMER CONTINUOUS EMISSION AND POLARIZATION IN BE STARS

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ABSTRACT

Observations by OAO-2 of two Be stars, Gamma Cassiopeiae and 60 Cygni, are analyzed to show that unpolarized radiation produced by Balmer continuous emission in the extended atmospheres of Be stars is probably a significant factor in explaining the polarization observed shortwards of the Balmer discontinuity. The ratio of the energy flux (normalized at 2200 Å) of Be stars to normal B stars with the same amount of reddening varies from about 1.4 at 3600 Å to 1.05 at 2500 Å. This is interpreted as due to Balmer continuous emission in the Be stars. For γ Cas the polarizations at 3300 and 3600 Å are respectively 0.6 and 0.7 of the values one expects from interstellar polarization. Neutral polarization produced by Thomson scattering and thence modified both by hydrogen absorption and Balmer continuous emission in the extended atmospheres of Be stars is adduced to explain the observed wavelength dependence of the polarization.

I. INTRODUCTION

For some time it has been clear from both the variability of the polarization in Be stars (Coyne and Kruszewski 1969, Serkowski 1970) and from the wavelength dependence of the polarization (Coyne and Kruszewski 1969, Coyne 1971a) that at least some of the observed polarization is produced in the

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extended atmospheres or shells about these stars. The observed polarization differs from that of the interstellar medium in both the blue and red spectral regions: there is a steeper drop in the polarization for the Be stars between 5200 Å and 3300 Å; there is a minimum at about 6600 Å and an increase into the red (see Fig. 4). In the past we have attributed the polarization to scattering from free electrons and subsequent absorption in a hydrogen plasma. A careful analysis, however, shows that the hydrogen absorption is not adequate by itself to explain the wavelength dependence of the polarization. Balmer continuous emission, revealed in the OAO data, must also be an agent.

II. OBSERVATIONS

Spectrophotometric scans with the long-wavelength Wisconsin spectrometer (Code et al. 1970) were obtained for two Be stars, Gamma Cassiopeiae (B0 IVe) and 60 Cygni (B1 Ve) and these results plus scans for two normal stars, Upsilon Orionis (B0 V) and Alpha Crucis (B1 IV), were supplied to me as a Guest Investigator. These data consist of digital counts made at about every 20 Å. A zero point for the wavelengths was determined by identifying the Mg I feature at 2800 Å. This was easily done on all of the scans. The wavelength scale, supplied by the Wisconsin group, was determined by a comparison of the OAO planet data with a smoothed version of the high resolution NRL solar spectrum.

It has already been established that the wavelength dependence of the flux measured with the Wisconsin spectrometers for unreddened B type stars of the same spectral class and of any luminosity class except supergiants is the same (Bless and Savage 1970, Bless and Savage 1972). The reddening for the stars with which we are concerned is small (not greater than +0.08); the color excess, E(B-V), for γ Cas minus that for υ Ori is +0.03, and the color excess for 60 Cyg minus that for α Cru is +0.06. We have, therefore, directly compared the digital output for these respective pairs of stars.

In Fig. 1 the relative fluxes (the ratio of the digital counts for the Be stars to the normal B stars) are plotted versus wavelength. The flux ratios are normalized at 2200 Å. The scans of γ Cas were made on two different orbits; both the flux ratio (with respect to υ Ori) from the individual scans and the mean flux ratio are plotted at the bottom of Fig. 1; at the top the flux ratio for 60 Cyg (with respect to α Cru) is plotted. The flux ratios are the largest (about 1.4) at the Balmer limit and decrease towards shorter wavelengths. This is the kind of wavelength dependence that one would expect from Balmer continuous emission.

There appears to be a difference in the flux from γ Cas as

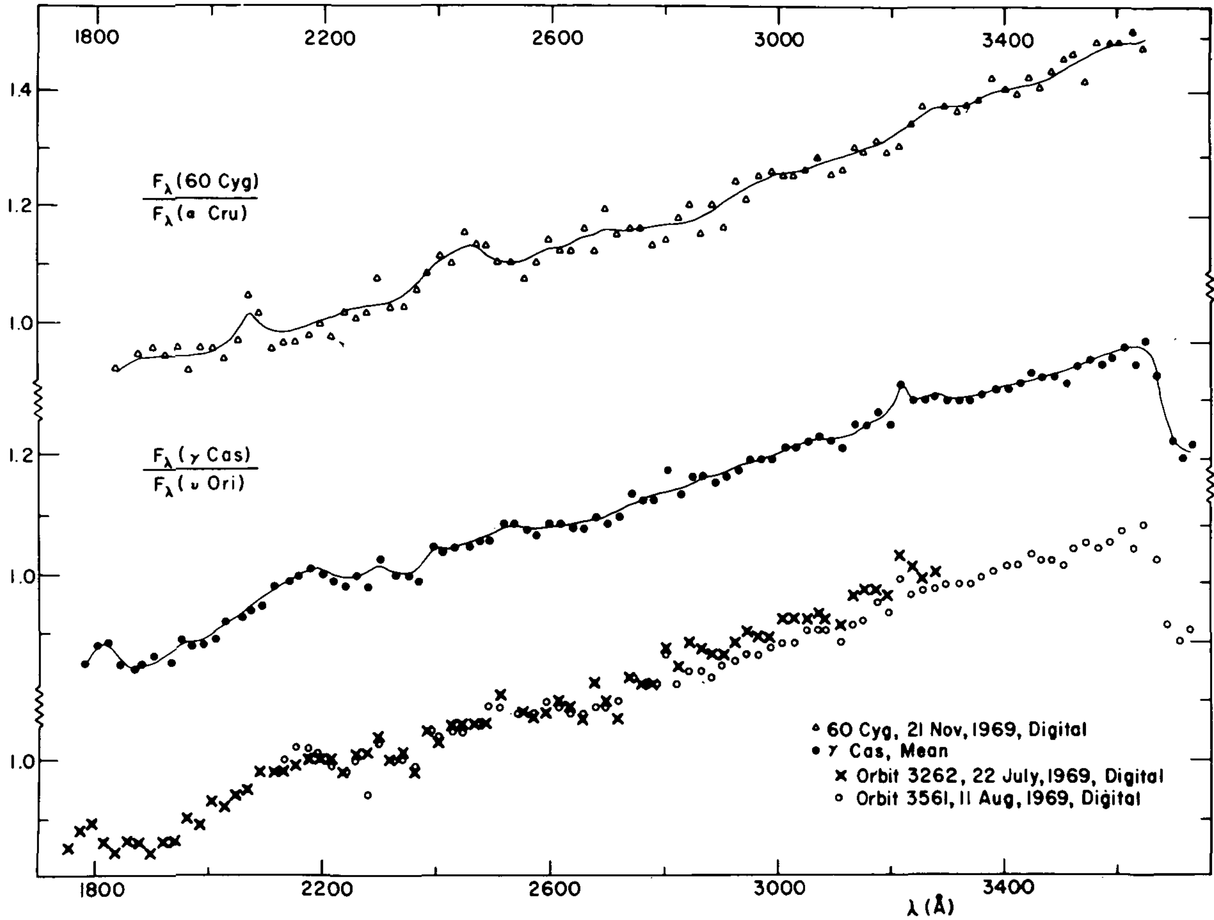

Figure 1.—The ratios of the energy flux in the two Be stars, γ Cas and 60 Cyg, to that in the two respective normal stars, υ Ori and α Cru, are plotted as a function of wavelength. The ratios are normalized at 2200 Å. Both the individual observations for two different orbits and the mean curve for γ Cas are plotted. The energy flux in the Be stars exceeds that in the normal B stars, the excess being the greatest at the Balmer limit (3647 Å) and decreasing to shorter wavelengths. This is interpreted as being due to Balmer continuous emission in the Be stars.

compared to that from 60 Cyg. In Fig. 2 we present a check of the response of the system to the two respective comparison stars, υ Ori (B0 V) and α Cru (B1 IV) by plotting the respective counts for each star at the same wavelength. The spectral energy distribution and the response of the system are the same for the two comparison stars.

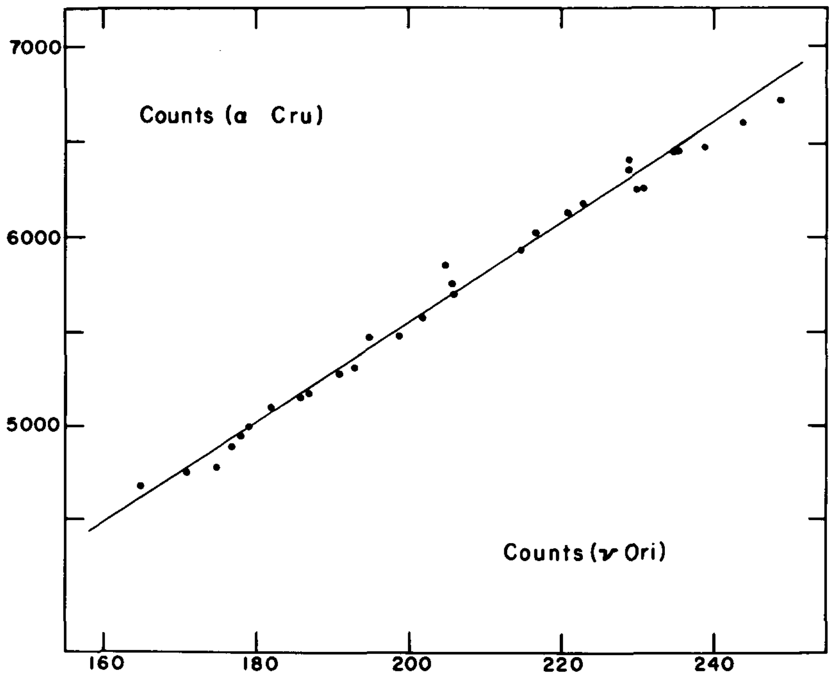

Figure 2.—The digital counts for the two comparison stars, υ Ori and α Cru, at each wavelength are compared. The difference in the reddening, E(B-V), for these two stars is only $0^m.02$. The relative spectral energy distributions are the same in the region of the spectrum covered.

In Fig. 3 we show the relative flux of the two Be stars as a function of the wavelength (normalized at 3000 Å). We see that the flux from γ Cas is relatively less at longer wavelengths. Apparently the spectral gradient of the Balmer continuous emission varies among the Be stars.

III. DISCUSSION

At the University of Arizona we have detailed polarization measurements on several Be stars (Coyne 1971b), especially on γ Cas, and these shall now be discussed in terms of the Balmer continuous emission indicated by the OAO data.

Fig. 4 shows the mean polarization of γ Cas contrasted with the mean polarization for the interstellar medium (Coyne and Gehrels 1967). The polarization of γ Cas varies with time with an amplitude of about 0.5% (Coyne 1971b). Here are plotted the mean of all the observations at each filter. The inverse effective wavelengths for our seven filters and the location of the Balmer and Paschen limits are indicated on the

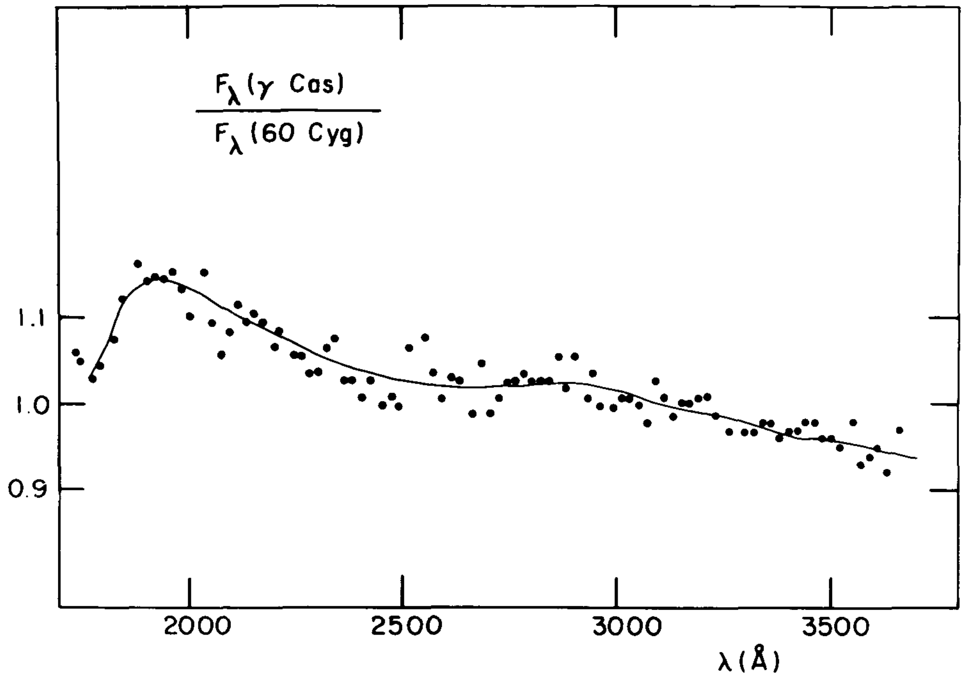

Figure 3.—The ratio of the energy flux, normalized at 3000 Å, in γ Cas to that in 60 Cyg as a function of wavelength. Since from Fig. 2 the spectral energy distribution is the same for the two comparison stars, we may interpret this curve as due to real differences in the energy distribution from these stars.

abscissa scale. The interstellar curve is normalized to the curve for γ Cas at the B filter. The typical wavelength dependence of the polarization in Be stars (see description in § I) is shown by γ Cas.

The location of the filters is important for a discussion of both hydrogen absorption and Balmer continuous emission in Be stars. In Fig. 5 we have plotted the detailed spectral response of the various filter-phototube combinations (right hand ordinate scale) and the hydrogen absorption coefficient for an electron temperature, $T_e = 10{,}000$°K and an electron density, $N_e = 10^{12}\text{cm}^{-3}$ (left hand ordinate scale). The response of the various filters has been determined by ourselves, but the manufacturer's mean curve is used for the phototube response. The response curves are determined for white light (which approximates the flux for B stars) through 1.3 airmasses of atmospheric extinction. [The color system is described in detail by Coyne and Gehrels (1967.] The hydrogen absorption coefficient, which is a function of the inverse cube of the frequency between successive discontinuities, var-

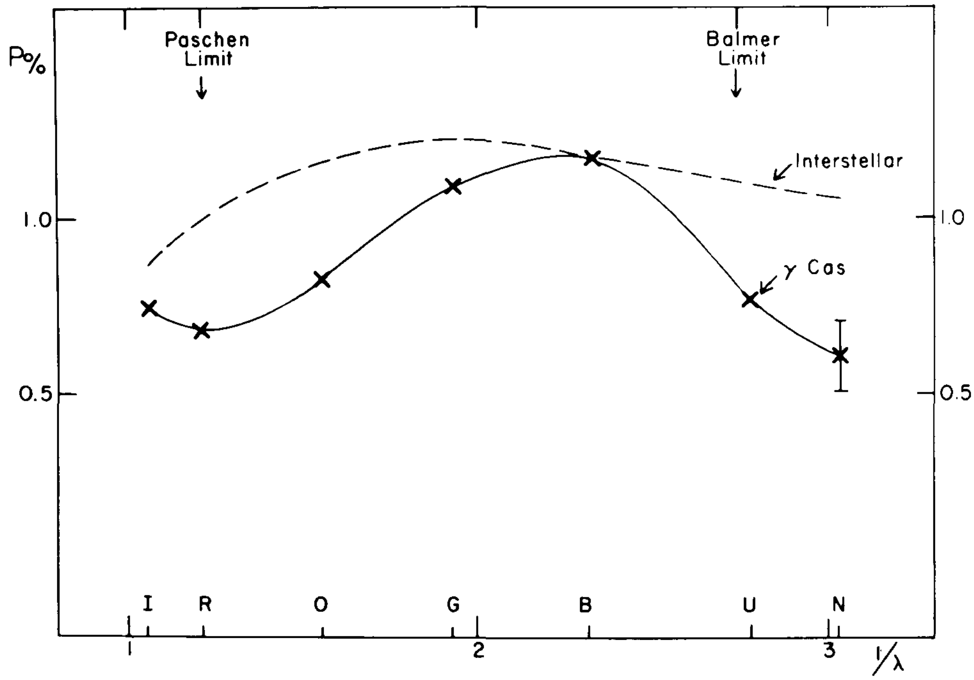

Figure 4.—The mean polarization for γ Cas and that for the interstellar medium are plotted versus inverse wavelength. The interstellar curve is adjusted to the curve for γ Cas at the B filter. The inverse effective wavelengths of the various filters and the location of the Balmer and Paschen limits are indicated on the abscissa scale.

ies significantly over the wavelength band of the respective filter-phototube response curves, especially over the U, N and R filters. In our past discussion of the polarization in Be stars (Coyne and Kruszewski 1969) this has not been considered quantitatively. In order to make some quantitative comparison between the intrinsic polarization and hydrogen absorption, we do the following. For each response curve an effective hydrogen absorption coefficient is determined by evaluating from Fig. 5 the integral $1/2 \int S_{\bar{\nu}}\, a_{\bar{\nu}}\, d\bar{\nu}$ over the wavelength band of the respective filter-phototube response curves, where $S_{\bar{\nu}}$ is the filter-phototube response, $a_{\bar{\nu}}$ the hydrogen absorption coefficient and $\bar{\nu} = 1/\lambda$ is the wavenumber. As a measure of the wavelength dependence of the intrinsic polarization in γ Cas the ratio P(γ Cas)/P(interst.) is determined for each of our filters.

In Fig. 6 we plot the ratio of the polarization of γ Cas to that of the interstellar medium as a function of the effective hydrogen absorption coefficient, defined in the previous para-

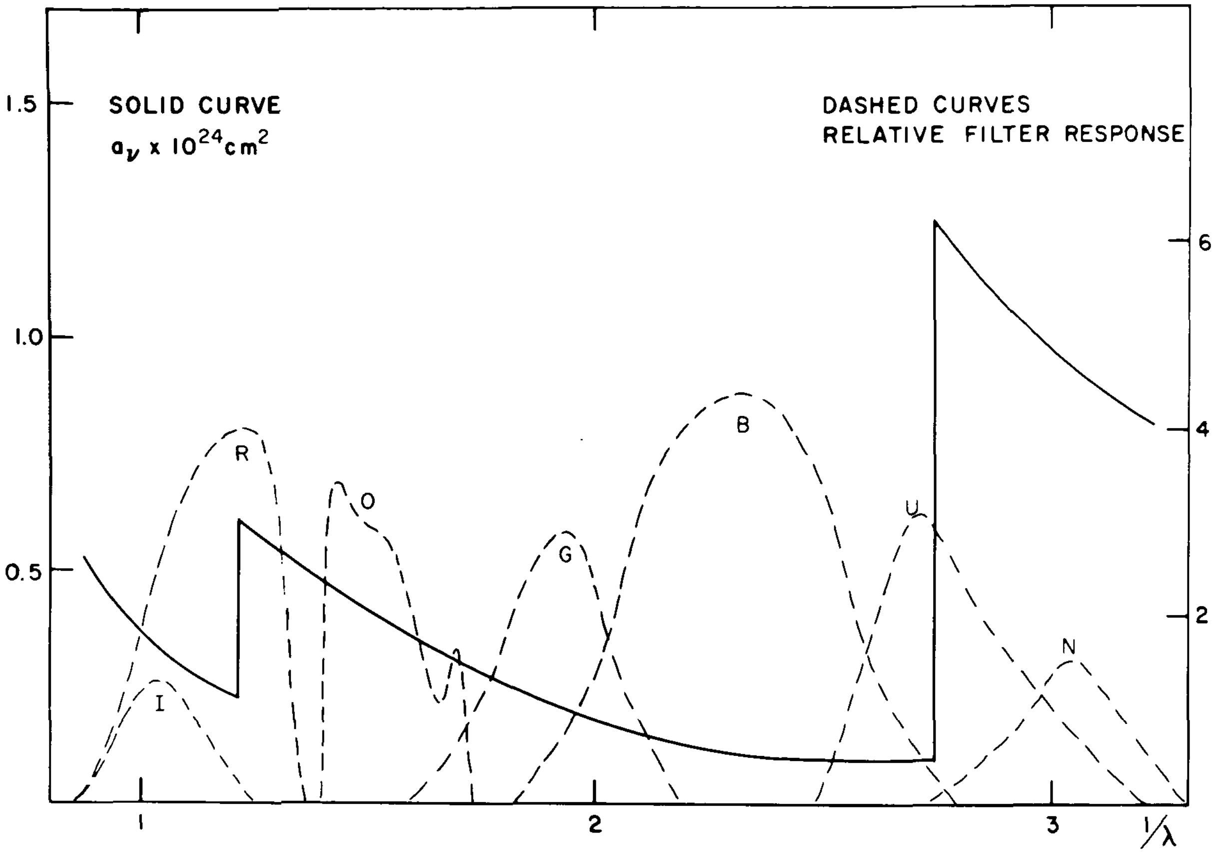

Figure 5.—The solid curve (left hand ordinate scale) gives the absorption coefficient as a function of inverse wave-length for hydrogen gas at an electron temperature of 10000°K and an electron density of $10^{12} cm^{-3}$. The dashed curves (right hand ordinate scale) give for the various filter-phototube combinations the relative distribution of radiant energy received from B stars through 1.5 air-masses of atmospheric extinction.

graph. There is, in general, a correlation of the hydrogen absorption and the polarization, but it is precisely the filters at the Balmer and Paschen discontinuities which do not fit this correlation well. If we accept the hypothesis that it is only hydrogen absorption which causes the wavelength dependence of the polarization, then we should observe even less polarization in the N, U and R filters than that actually observed. There will, of course, be a gradient in the electron temperature and electron density with the height of the absorbing and scattering layers above the photosphere and therefore, a similar gradient in the hydrogen absorption coefficient.

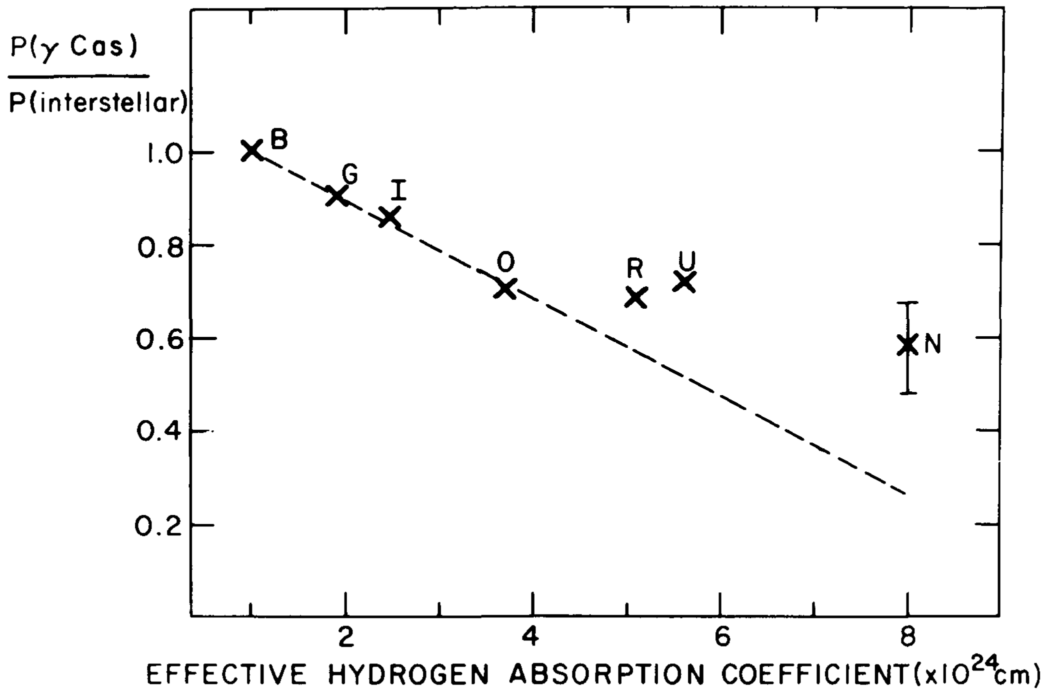

Figure 6.—The ratio of the mean polarization in γ Cas to that in the interstellar medium is plotted for each filter as a function of the effective hydrogen absorption coefficient defined as 1/2 $\int S_{\bar{\nu}}\, a_{\bar{\nu}}\, d\bar{\nu}$ (see Fig. 5 and text). The polarizations at the R, U and N filters, which lie at or near the Paschen or Balmer limits, do not fit as well as do the polarizations for the other filters.

Assuming also that the absorption and scattering will vary differently with height for different spectral regions, we cannot expect that there will be a strict correlation between the polarization and the effective hydrogen absorption coefficient, determined for one specific temperature for all filters. Nevertheless, it seems fortuitous that only those filters which lie at or near the Balmer and Paschen discontinuities require a hydrogen gas at a lower temperature and electron density.

Since the OAO data shows that there is Balmer continuous emission in Be stars, this must also be considered as a possible agent in suppressing the polarization in the U and N filters. Unpolarized Balmer continuous emission would decrease the polarization in the U and N filters while not affecting the other filters. Paschen continuous emission might be present, of course, and this would affect the polarization especially in the R and I filters. It appears, therefore, that the intrinsic polarization in Be stars is due to three mechanisms: (1) scattering of light from electrons in a flattened disk or ring of partly ionized hydrogen; (2) self-absorption in the hydrogen gas before and after scattering; (3) unpolarized radiation from Balmer and, perhaps, Paschen continuous emission.

The physical model is the following. There is a flattened disk with a thickness at least several times smaller than the star's radius in order to have the asymmetry required to produce the observed intrinsic polarization. This disk consists of a partly ionized hydrogen gas with a mean electron temperature of about 10,000°K and a mean electron density of about $10^{12} cm^{-3}$. A path length of at least 20 $R_\odot$ (about 3 stellar radii) is required in order to have enough scattering to produce the observed polarization. This path length is equivalent to unit optical thickness for Thomson scattering under the stated electron temperature and density conditions. Within this disk extending at least 2 or 3 stellar radii from the star there is, of course, a gradient of the electron temperature and density. The current polarimetric data are not sufficient to specify with precision at which levels in the disk each of the three mechanisms enumerated in the previous paragraph plays a major role. It would seem, however, that the major part of the scattering and the production of neutrally polarized radiation takes place in the inner parts of the disk where the electron density is higher and that the Balmer continuous emission, producing unpolarized radiation, is concentrated to the outer regions of the disk where the electron density is lower.

This model is not inconsistent with what is otherwise known about the extended atmospheres of Be stars. From emission line intensities in Be stars it is estimated that the radius of the emitting region is about 10 stellar radii with an electron density of $10^{13} cm^{-3}$ (Burbidge and Burbidge 1956). From the rotational broadening of the absorption lines, it is deduced that the main body of the gas lies 2 or 3 stellar radii from the star. The region extending out to about 10 stellar radii beyond this main concentration of gas would presumably be the region in which the major part of the Balmer continuous emission occurs. As unpolarized radiation it would suppress the polarization (observed in our N and U filters) produced by Thomson scattering in the inner parts of the disk. This polarized radiation would have also been modified by absorption in the hydrogen gas.

I wish to thank Dr. A. Code and his colleagues at the University of Wisconsin, especially Dr. Blair Savage, for transmitting to me the OAO data and for discussions concerning this data.

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