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ON THE PRESENCE OF A SCATTERED CONTINUUM IN THE PLANETARY NEBULA BD+30°3639

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ABSTRACT

A measurement of the strength of Hβ relative to that of the nebular continuum in the planetary nebula BD+30°3639 is reported. The equivalent width of Hβ alone, exclusive of the central star, is found to be 1000 $\pm$ 200 Å, while the theoretical value at T_e = 10,000° K is $\sim$2000 Å. It seems likely that the excess continuum flux is due to starlight that is scattered by particles within the nebula. The scattering optical depth of these particles probably lies between 0.05 and 0.10, depending on T_e.

Subject heading: planetary nebulae

I. INTRODUCTION

Recent infrared observations of the planetary nebula BD+30°3639 (Gillett, Merrill, and Stein 1972; Willner, Becklin, and Visvanathan 1972) have shown that this object is one of several planetaries that emit excess radiation longward of 1.65 μ. The standard explanation for this excess (which is $\sim$100 times that expected from recombinations at 10 μ) is that it is thermal radiation from dust particles heated by resonantly trapped Lα photons and light from the central star. It would be of interest to establish the existence of these particles by a method independent of the infrared observations. Since the central star of BD+30°3639 is moderately bright, the possibility exists that the nebular continuum contains a component of starlight that is scattered by the postulated dust particles as has been demonstrated for Orion (O'Dell and Hubbard 1965).

In order to test this hypothesis we have measured the strength of Hβ relative to the continuum *in the nebula alone*. The resulting equivalent width of Hβ, W(Hβ), is insensitive to interstellar reddening or air-mass corrections.

II. OBSERVATIONS

The observational procedure consists of measuring the strength of Hβ and the continuum flux on either side of this line in different-sized apertures centered on the central star. The effects of scattered light due to seeing effects and the telescope/scanner combination are calibrated and effectively eliminated by observing a standard star and the planetary under nearly the same conditions of seeing and transparency. Thus the nebular continuum and line fluxes are found for annuli surrounding the central star. The fluxes from these annuli would contain no spurious component of continuum due to the seeing disk of the central star if (*a*) all of the continuum arose from the star and (*b*) the seeing calibration were perfect.

The observations were carried out on a good photometric night in 1972 September, with the Cassegrain scanner (described by O'Dell 1963) attached to the 100-inch (254-cm) Hooker telescope on Mount Wilson. A star-sky chopping system was used throughout, and all observations were made near meridian transit. The sizes of the entrance apertures and exit slots were chosen so that there was no contamination of

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the continuum channels by Hβ or any other nebular line, and all the Hβ flux entering the aperture was accepted by the exit slot. First, a standard star at the same right ascension and 12° S of BD+30°3639 was measured with apertures having diameters of 3″.5, 5″, 7″, and 10″, at the wavelengths 4800, 4860, and 4900 Å. The planetary was then measured several times in each aperture at the same wavelengths. The standard star was then remeasured in the same way, so that the average sidereal time of observation was the same for each wavelength, aperture, and source (star or planetary).

The data were reduced in the following manner. First all fluxes were found by using the standard-star counting rates measured with the 10″ aperture. The standard-star continuum counting rates measured with the smaller apertures were then used to find the flux of starlight (scattered by seeing effects) in each annulus, relative to the total standard-star flux. The true (continuum) flux from the central star of BD+30°3639 was found by assuming that all the light entering the 3.5″ aperture is starlight, and then scaling this flux to the 10″ aperture. A correction of 3 percent was then applied to account for the nebular continuum entering the 3.5″ aperture. The flux of continuum from the central star of BD+30°3639 that is scattered by seeing into each annulus was then found by using the corresponding values found for the standard. Table 1 lists the standard star "seeing" fluxes and the uncorrected continuum fluxes for BD+30°3639, for each annulus. The standard star fluxes for the average seeing (mean of two measurements) were normalized to the continuum flux from the star in BD+30°3639, for ease in making comparisons.

The Hβ surface brightness was found to be approximately uniform for BD+30°3639, and thus no corrections for seeing were applied to the Hβ fluxes.

In the period between the two sets of observations of the standard star there was a deterioration in the seeing quality, which amounted to a loss of 12 percent of the light measured in the smallest aperture. For this reason, the above reduction was performed for both sets of observations of the standard, as well as for the averaged data. For the most reliable data (those obtained with apertures of 5″, 7″, and 10″) the spread in values of the annular continuum fluxes was found to be comparable to the uncertainties from counting statistics. However, since the standard is 12° S of the planetary, it is expected that the multiaperture calibration will not undercorrect but may overcorrect for seeing. This results in an underestimate of the continuum fluxes in the annuli, and thus should give a conservative estimate, i.e., an overestimate, of *W*(Hβ).

Note that the presence of stellar emission lines in BD+30°3639 does not affect the results significantly, because all the light from the central star has been removed when

TABLE 1

EQUIVALENT WIDTH OF Hβ IN BD+30°3639

Aperture Annuli (arc sec)		Continuum Fluxes (10^{-29} W m^{-2} Hz^{-1})			
Outer	Inner	Average for Standard	BD+30°3639	Hβ Flux (10^{-29} W m^{-2} Hz^{-1})	W(Hβ) (Å)
10.......	7	3	15	251	835 ± 240*
10.......	5	8	38	668	890 ± 175*
10.......	3.5	24	65	1182	1156 ± 145
7.......	5	5	21	417	1040 ± 230*
7.......	3.5	20	50	931	1240 ± 225
5.......	3.5	16	27	514	1860 ± 1200
10.......	0	235	281	1731	

* Most reliable data.

the annular fluxes are considered. Also, as may be seen from table 1, an error as large as 10 percent in the flux from the central star of BD+30°3639 does not affect the resulting annular fluxes significantly.

Data for the apertures of 3″.5 and 7″ were obtained on another night, but since the standard star was not measured twice, the 3″.5 data were discarded. The 7″ data agreed to within 2 percent on the two nights and were averaged in. Figure 1 displays the observed fluxes of BD+30°3639 corrected for the effects of seeing.

III. RESULTS

Since the purely stellar component of flux entering each aperture was calibrated for seeing, the flux of direct starlight should be the same for each aperture, and is thus effectively removed from the flux entering an annulus. The quantity (Hβ/continuum) $\times$ (exit-slot bandwidth) then gives W(Hβ).

The results are given in table 1, where the uncertainties are 1 σ of the mean and were found from the scatter in the individual measurements. The uncertainties are large, of course, because the central star dominates the continuum emission. The equivalent widths show a marginal increase toward the central star. The most reliable data indicate that the equivalent width of Hβ in the nebular gas of BD+30°3639 is in the range 800–1300 Å. A value of 1000 $\pm$ 200 Å is assumed to be typical. Note that any seeing corrections to the Hβ flux would not significantly affect the resulting equivalent width.

The calibrated data are plotted in figure 1, which shows that the ratio of the Hβ flux to the continuum flux decreases somewhat away from the central star.

The total line flux is found to be $\log F(\mathrm{H}\beta) = -10.057 \pm 0.008$ ergs cm^{-2} s^{-1}. This compares well with O'Dell and Terzian's (1970) value of -10.01 ± 0.03, which, when renormalized to the Oke and Schild (1970) absolute calibration, becomes -10.05 ± 0.03.

This work also shows that the angular diameter of BD+30°3639 is not 5″, the value used by O'Dell and Terzian (1970), but rather 8″ $\pm$ 1″ (cf. fig. 1). This agrees with the size estimated visually while the photoelectric observations were being made.

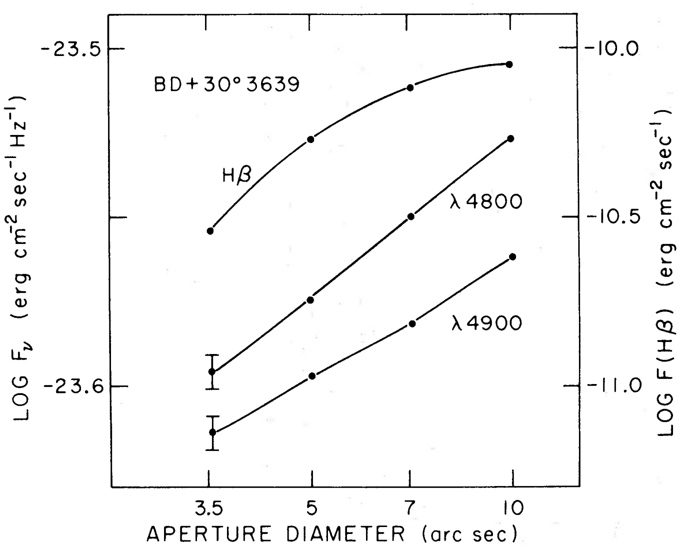

FIG. 1.—Plot of flux versus aperture (plotted logarithmically) for the continua (*left-hand scale*) and Hβ (*right-hand scale*). Typical 1 σ errors are shown for the continua.

IV. DISCUSSION

The measured value of $W(\mathrm{H}\beta)$ may be compared with theoretical equivalent widths found by using the continuum recombination coefficients tabulated by Brown and Mathews (1970). An important point to consider in using these tables is the possible conversion of Lα to the two-photon continuum. Capriotti's (1967) transfer calculations for planetary nebulae indicate that a mean Lα proton will escape from the nebula in the line wings long before it is "quenched" (converted to the two-photon continuum). Also, one could argue that unless a large fraction of the incident stellar flux is absorbed on particles the Lα resonance flux must be destroyed on grains in order to provide the infrared flux, which comprises a sizable fraction of the total energy output. Thus it is very likely that the mean lifetime of a Lα photon within the nebula is $\gtrsim 100$ times shorter than the lifetime against quenching. It is assumed, therefore, that conversion of Lα contributes nothing to the two-photon continuum.

Figure 2 shows a plot of $W(\mathrm{H}\beta)$ versus T_e for a range of electron density in a nebula that is optically thin to Hβ. The label $N_e \to \infty$ means that the two-photon continuum is completely suppressed. Helium abundances of $N(\mathrm{He}^+)/N(\mathrm{H}^+) = 0.15$ and $N(\mathrm{He}^{++})/N(\mathrm{H}^+) = 0$ were assumed, although the exact values of these parameters are not required to calculate $W(\mathrm{H}\beta)$ to sufficient accuracy.

This plot demonstrates that the nebular continuum flux is significantly larger than that expected from recombinations unless (*a*) $T_e \sim 20{,}000°$ K, or (*b*) the nebula is optically thick to Hβ. Both these possibilities are rendered very unlikely by the radio observations reported by O'Dell and Terzian (1970), however. First, a high temperature is unlikely because an increase in the angular diameter from 5″ to 8″ reduces the electron temperature derived from the 1-GHz flux to a value of $T_e \sim 4300°$ K. If this low temperature is characteristic of at least the outer regions of the nebula (cf. Thompson 1968), the interstellar absorption coefficient $c = \Delta \log(\mathrm{H}\beta)$, derived from the 10-GHz/Hβ flux ratio, increases from 0.22 to 0.50, a value in better agreement with the optically derived value of 0.7 ± 0.1. This brings in point (*b*). If the nebula were

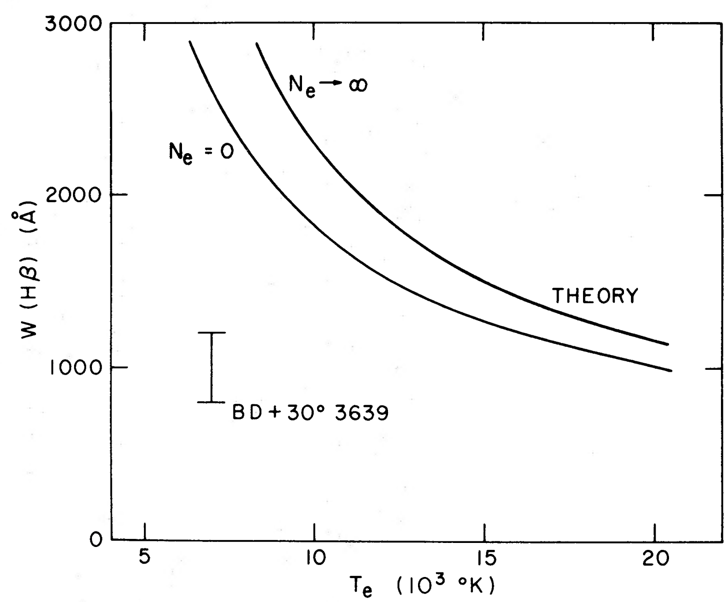

FIG. 2.—Theoretical equivalent width of Hβ versus electron temperature in a nebula optically thin to Hβ. The labels $N_e = 0$ and $N_e \to \infty$ indicate regions wherein the two-photon continuum has its maximum or minimum strength respectively. The observed value of $W(\mathrm{H}\beta)$ is arbitrarily plotted at 7000° K.

optically thick to Hβ, then a correction for this effect would lower the 10-GHz/Hβ flux ratio, and would thus lower 10^c in the same proportion. However the value of c derived from this ratio is lower than the optically derived value. In other words, Hβ is already too strong (c is too small) to accommodate any corrections for optical depth. Furthermore, the measured values of N_e in BD + 30°3639 are in the range 8×10^3 to 2×10^4 cm^{-3} (O'Dell and Terzian 1970), values that are too low for optical-depth effects in the lower Balmer lines to be important.

Thus it seems reasonable to assume that T_e is not as high even as 11,000° K, and that the nebula is optically thin in Hβ. Therefore a likely interpretation of the observed strength of the nebular continuum relative to Hβ is that it is due to starlight scattered by particles within the nebula. From the strength of the scattered continuum relative to the stellar continuum, the radial optical depth due to scattering is found (for $N_e = 10^4$ cm^{-3}) to be $\tau_s = 0.09$ at 7000° K and $\tau_s = 0.05$ at 10,000° K.

Since the optical depth to electron scattering is not expected to exceed 4×10^{-3} in BD + 30°3639, the particles are probably the same dust particles that emit the infrared radiation.

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