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SCATTERING OF SODIUM D PHOTONS BY NEUTRAL GAS IN THE PLANETARY NEBULA BD +30°3639

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ABSTRACT

We report the detection of resonance D lines of Na I ($\lambda\lambda$5890, 5895) formed in neutral material around the planetary nebula BD +30°3639. The circumstellar absorptions, seen against the continuum of the central star, have the same radial velocity as the blue edge of the expanding shell of ionized gas, $v_\odot = -67$ km s^{-1}. The stronger line, λ5890, has a central depth of about 70%. At our spectral resolution, 10 km s^{-1}, the circumstellar features are well separated from low-velocity features due to foreground interstellar material. Applying the doublet-ratio method, we infer a circumstellar column density toward the central star of N(Na I) $= 4 \times 10^{12}$ cm^{-2}. The corresponding neutral hydrogen column density is of order $N(\text{H I} + \text{H}_2) \approx 10^{19-20.5}$ cm^{-2}, where the lower value follows if N(Na I) $= N$(Na) throughout the region, and the higher value is derived assuming that the ionization balance of Na is the same as in typical interstellar clouds. At positions on the nebula located away from the central star, we see the reemerging sodium D photons as emission lines at the systemic nebular velocity of $v_\odot = -31$ km s^{-1}. These are the first observations to show the resonance scattering of Na D photons in planetary nebulae, and demonstrate a new observational tool for studying their neutral envelopes.

Subject headings: nebulae: planetary — stars: circumstellar shells

I. INTRODUCTION

The strong resonance lines of neutral sodium at 5890, 5895 Å (the "D" lines) have long been used as tracers of neutral interstellar gas (e.g., Münch 1968; Hobbs 1978). Due to the low ionization potential of Na I (5.1 eV), we expect these lines to arise in regions shielded from ultraviolet radiation, where the hydrogen is predominantly neutral. The intrinsic strengths of the Na D lines, together with their convenient wavelengths in the optical spectral region, make them sensitive tools for detecting the presence of neutral gas despite the low cosmic abundance of sodium. We therefore undertook a search for circumstellar Na D absorptions against the continua of the central stars of planetary nebulae, in an attempt to detect associated neutral material. We were motivated in part by previous detections of H I 21 cm absorptions in several planetary nebulae (e.g., Taylor and Pottasch 1987; Schneider *et al.* 1987).

In this *Letter*, we present observations of the planetary nebula BD +30°3639, the most dramatic case we have found. This nebula gives a clear illustration of the scattering effects of a circumnebular neutral envelope on resonant line photons, i.e., removal of the photons from the direct line of sight toward the central star and redirection of them toward the observer from positions in the nebula. Further results from a survey of planetary nebulae in Na I and other neutral absorption lines will be presented in a future paper (H. L. Dinerstein and C. Sneden, in preparation).

II. OBSERVATIONS

The observations were made with the coudé spectrograph of the McDonald Observatory 2.7 m reflector, using an 800 × 800 Texas Instrument CCD with 15 μm^2 pixels as the detector. We observed BD +30°3639 twice, on 1988 April 24 and on 1988 June 4. In Figure 1 we show the June spectrum. The integration time was 30 minutes, the spectral coverage about 50 Å, and the spectral resolution 0.20 Å (10 km s^{-1}). We used a projected slit width of 0".46 and a decker of length 30" oriented roughly E-W and extending well beyond the edge of the ionized nebula (radius ≈ 2".5).

The two-dimensional data were reduced using NOAO's IRAF package for the initial operations of bias subtraction and dark subtraction, flat-fielding, and extraction of one-dimensional spectra. A spectral reduction package written for IBM-PC computers (Fitzpatrick and Sneden 1987) was then used to remove cosmic-ray hits, smooth the data, and transform to a telluric wavelength scale. We also removed most of the effects of telluric water vapor lines in this spectral region using a spectrum of the hot star Spica; however, the water lines are much weaker than all of the Na D line components in BD +30°3639, so this correction is not critical to our results.

The unusual shape of the continuum in the vicinity of the Na D lines is due to the Wolf-Rayet nature of the central star, which is of spectral type WC9 (Acker *et al.* 1982 and references therein). The extraordinary optical continuum of this star, also known as "Campbell's star," can best be appreciated by examining the spectrum published by Aller (1968), which shows a veritable forest of broad, overlapping emission lines. The section shown in our Figure 1 includes, from left to right, (1) the relatively sharp nebular He I 5876 Å recombination line, broadened only by the nebular expansion; superposed on (2) the broad, asymmetric stellar He I 5876 Å line, which has a P Cygni profile; (3) an apparent shoulder redward of stellar 5876 Å, identified by Aller as C II 5890 Å; and (4) four narrow absorption lines. The last features are the Na D lines, each member of which is "doubled" by the presence of two distinct velocity components: an interstellar component near zero velocity, and a blueshifted component due to material associated with the planetary nebula. The insert in Figure 1 shows an expanded view of Na I 5890, in which it can be seen that both the main velocity components have resolved structure; the horizontal bar represents our spectral resolution element. In the following sections, we first discuss the absorption lines and

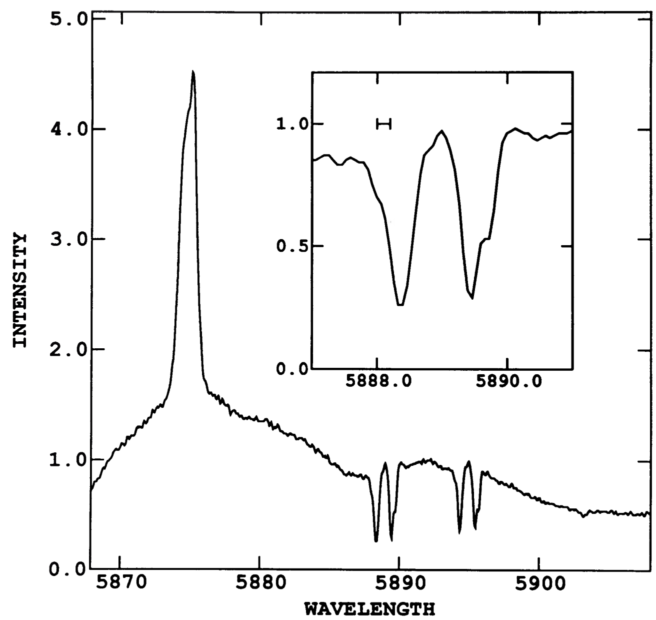

FIG. 1.—The spectrum of the central star of BD +30°3639 in the vicinity of the Na D lines. The continuum shape is dominated by two broad stellar emission lines, He I 5876 Å and C II 5890 Å. Superposed on the broad P Cygni profile of the stellar He I 5876 Å line is a narrower nebular component. Absorptions due to Na I are seen at 5890 and 5895 Å, each composed of two deep features of nearly equal strength. The insert is an expanded view of 5890 Å line, and shows our spectral resolution element (*horizontal bar*). From their Doppler shifts, we identify the blueward components of the Na lines as circumstellar in origin, and the redward components as due to foreground interstellar material (see text).

the implied amount of neutral circumnebular material, and then discuss the nebular Na D emission produced by this scattering process, which is best seen at positions away from the central star.

III. RESULTS

a) The Na D *Absorption Features*

Each of the Na D absorption lines in BD +30°3639 consists of two major components. In Table 1, we list their wavelengths and equivalent widths. We attribute the features near $v = -10$ km s^{-1} to foreground interstellar material ("IS"); they are clearly seen to be blends of multiple velocity components. (Unless indicated otherwise, all velocities are given in a heliocentric frame.) In contrast, we identify the blueshifted component of each line as circumstellar ("CS"). The systemic velocity determined from the nebular emission lines is given by Schneider *et al.* (1983) as $v_{\rm neb} = -31.4$ km s^{-1}. We confirm this value, finding a central velocity from the He I 5876 Å recombination line of $v_{\rm neb} = -31$ km s^{-1}. The double-peaked structure of the He I line is characteristic of all of the ionic emission lines in this nebula, which show line splittings corresponding to expansion velocities of ± 20 to ± 30 km s^{-1} (Sabbadin 1984). Assuming that the neutral layer is moving at a velocity similar to that of the adjacent ionized gas, then the neutral absorption lines should appear near the blue-edge velocity of the expanding ionized shell. The observed minima of the CS features fall at $v_{\rm CS} = -67$ km s^{-1}, as expected in this picture, and correspond to an expansion velocity $v_{\rm exp} = (v_{\rm neb} - v_{\rm CS}) = 36$ km s^{-1}.

This is essentially the same velocity structure as that reported by Pwa, Pottasch, and Mo (1986), who examined the high-resolution *International Ultraviolet Explorer* (*IUE*) spectrum of BD +30°3639, and measured absorption lines of various ions. They find each line to be composed of two components, one near -15 km s^{-1} and the other at -70 (± 5) km s^{-1}, consistent with our two Na I components within the measurement uncertainties. However, Pwa, Pottasch, and Mo point out that these ultraviolet lines come from ions which may be present within the ionized gas. Therefore, although these authors consider the possibility that a neutral region may exist, they conclude that the *IUE* data alone neither confirm nor disprove the presence of neutral gas. Our observations are particularly useful in this context because Na I, with its low ionization potential, is a better tracer of predominantly neutral material. The Na I observations also have the advantages of high spectral resolution and signal-to-noise ratio, which enable us to see that both circumstellar Na D lines have weak blue wings at $v \approx -100$ km s^{-1}. These wings indicate the presence of faster moving material, expanding relative to the central star at ≈ -70 km s^{-1}. Such fast-moving material may indicate acceleration or anisotropy in the nebular expansion.

The Na D lines are particularly useful for determining column densities because they constitute a line pair to which we can apply the classical doublet-ratio method (e.g., Münch 1968). Following the formulation of Spitzer (1968) and substituting the numerical value for the oscillator strength, $f = 0.327$ for 5895 Å (Morton and Smith 1973), we have

$$N\,(\text{Na I}) = 8.8 \times 10^{12}\ W_\lambda(5895)\ [F(C)/C]^{-1}\ \text{cm}^{-2}\ , \quad (1)$$

where N (Na I) is the column density of neutral sodium atoms, $W_\lambda(5895)$ is the equivalent width in angstroms, and C is the line center optical depth for $\lambda 5895$. The functions $F(C)/C$ and

TABLE 1

Na I ABSORPTION LINES IN BD +30°3639

System	True λ[a] (Å)	Observed λ[b] (Å)	$v_\odot$ [c] (km s^{-1})	Central Depth	Equivalent Width (mÅ)
Interstellar ("IS")	5889.950	5889.44	−12	0.68	300 ± 15[d]
	5895.924	5895.43	−11	0.56	250 ± 15[d]
Circumstellar ("CS")	5889.950	5888.36	−67	0.70	290 (330)[e]
	5895.924	5894.34	−67	0.61	220 (230)[e]

[a] Morton and Smith 1973.
[b] Measured on a *geocentric* wavelength scale.
[c] Heliocentric velocity, after correction for a geocentric Doppler shift of $(v_\oplus - v_\odot) = -14$ km s^{-1}.
[d] Total absorption equivalent width (EW); includes contributions from at least two components.
[e] First value is the EW of a single Gaussian profile fitted to the line core; values in parentheses include blue wings. Uncertainties are similar to those for the interstellar components.

$F(2C)/F(C)$ are tabulated by Spitzer, the latter quantity being the ratio of the two line equivalent widths, $W_\lambda(5890)/W_\lambda(5895)$. From Table 1, we have (290 mÅ)/(220 mÅ) = 1.32, using the Gaussian-fitted values which exclude the blue line wings (however, our conclusions are not sensitive to this assumption). The corresponding line center optical depth is $C \approx 2$, yielding a circumstellar column density $N_{\rm CS}$ (Na I) = $4.1(\pm 0.2) \times 10^{12}$ cm^{-2}. To derive an equivalent hydrogen column density, we must assume a value for the neutral sodium fraction. If we adopt a typical interstellar value (e.g., Ferlet, Vidal-Madjar, and Gry 1985), the inferred total hydrogen column density would be $N_{\rm CS}$ (H I + H_2) $\approx 7 \times 10^{20}$ cm^{-2}. However, this number is very uncertain and probably represents an upper limit to the true value. In the diffuse interstellar material from which the relation was derived, the fraction of the Na which is neutral is quite small, of order 1%–2% (e.g., Phillips, Pettini, and Gondhalekar 1984), whereas at least some of the circumstellar Na I in BD +30°3639 is probably within the molecular region known to be present in this nebula (see below). We consider that a reasonable lower bound is $N_{\rm CS}$ (H I + H_2) $\approx 10^{19}$ cm^{-2}, the value which is inferred assuming that *all* of the gas-phase sodium is neutral, i.e., N(Na) $\approx N$(Na I). Also implicit in these estimates is the assumption that the depletion of gas-phase sodium into grains is a factor of 4, as is the case in interstellar clouds of a wide range in densities (Phillips, Pettini, and Gondhalekar 1984).

These values are within an order of magnitude of the average column density through the ionized gas derived by Pwa, Pottasch, and Mo (1986), $N(H^+) = 2.4 \times 10^{20}$ cm^{-2}, suggesting that there may be comparable masses of neutral and ionized material in the overall nebular envelope of BD +30°3639. It is probable that the CS Na D lines are formed at least partly within a predominantly molecular region. Near-infrared emission lines arising from excited vibrational levels of the H_2 molecule were detected in BD +30°3639 by Beckwith, Persson, and Gatley (1978). Further observations by Dinerstein *et al.* (1988*a*, *b*) show that the observed H_2 line intensity ratios imply a radiative rather than collisional excitation mechanism, and that the molecular material is therefore relatively cold. More recently, the 115 GHz CO (J = 1–0) line has been detected as well (H. L. Dinerstein, S. Terebey, and C. R. Masson, in preparation). Previous indicators of neutral atomic, dissociated gas also exist for BD +30°3639. Gathier, Pottasch, and Goss (1986) report a H I 21 cm spectrum with apparent absorption near the nebular velocity, but they did not regard this as a clear detection because of observational uncertainties and confusion by strong interstellar emission (see, however, the discussion in Schneider *et al.* 1987). Another indicator of dissociated neutral material is the observed strength in BD +30°3639 of a major cooling line for warm atomic gas, the [O I] 63 μm fine-structure line (Dinerstein *et al.* 1985).

The interstellar absorption features are difficult to interpret accurately because they are clearly composed of multiple blended components, but we can make at least a rough estimate of the IS column density. Applying the formulae above, we find the following values: $C \approx 4$, $N_{\rm IS}$ (Na I) = 6.7×10^{12} cm^{-2}, and $N_{\rm IS}$ (H I + H_2) $\approx 10^{21}$ cm^{-2}. The last quantity agrees quite well with the value $N_{\rm IS}$ (H I + H_2) $\approx 6 \times 10^{20}$ cm^{-2} inferred by Pwa, Pottasch, and Mo from ultraviolet absorption lines of other species.

b) The Nebular Na D *Emission*

Since the Na D lines are resonance transitions with large Einstein A-values, when a Na D photon is absorbed it will be quickly reemitted in a randomized direction. We therefore expect that photons removed from the direct line of sight will reemerge from the scattering region as apparent emission lines, away from the direction of the central star. Such extended emission due to resonance scattering has been seen in circumstellar shells such as that around α Ori, seen in the K I λ7699 resonance line (Bernat and Lambert 1975). In order to look for this effect, we simulated multiple apertures by extracting spectra at several positions along the slit. In Figure 2, we show spectra for three spatial positions, plotted on a logarithmic scale for convenient comparison. The top spectrum is the same data as shown in Figure 1; it was produced by collapsing 5 pixels, centered on the central star image, along the long axis of our long slit, corresponding to 3".0 on the sky. Labels across the top indicate the CS and IS components of each line. The middle spectrum represents an aperture of the same size, shifted 3".0 east. At this second position both absorptions are still noticeable, but they are partially filled in by an emission feature. The third spectrum was obtained for a narrower aperture (width 1".8) centered at 5" east, in which Na D is seen almost purely in emission. The wavelength of the emission feature corresponds to neither of the absorption features, but instead coincides with

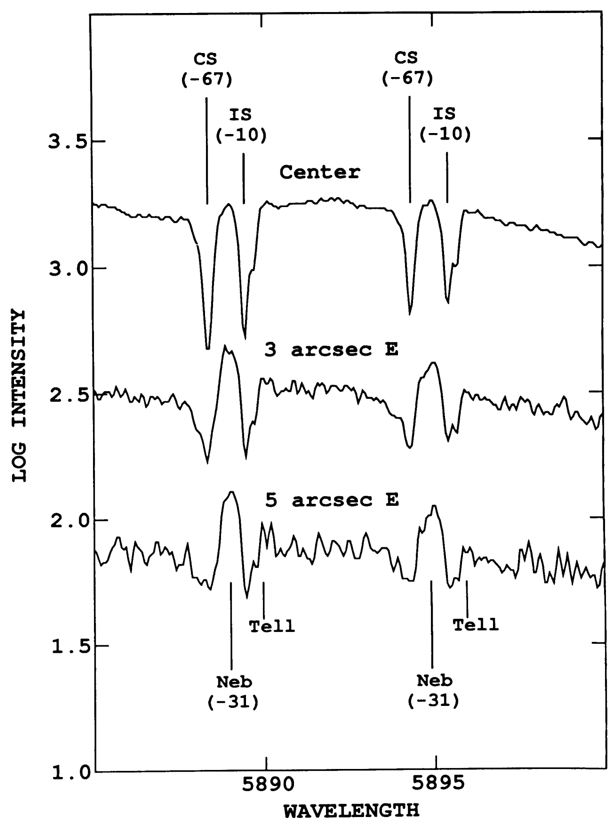

FIG. 2.—Sodium D spectra for three spatial positions in BD +30°3639, plotted on a logarithmic scale. The top spectrum, for a 3" long aperture centered on the ionizing star, is the same as that shown in Fig. 1. Below it are spectra for apertures centered 3" and 5" E of the central star (of length 3" and 1".8, respectively). Along the top we indicate the wavelengths corresponding to the circumstellar (CS) and interstellar (IS) features, with their heliocentric velocities in km s^{-1} given in parentheses. Labels at the bottom mark the wavelengths for the nebular systemic velocity of −31 km s^{-1} (Neb) and zero geocentric, or telluric, velocity (Tell). Strong emission features are seen at the nebular velocity at the 3" E and 5" positions. These emission lines are composed of line photons which have been absorbed and reemitted by the neutral envelope around the ionized core of the planetary nebula (see discussion).

the systemic nebular velocity, $v_{\rm neb} = -31$ km s^{-1}. It is shifted well away from the wavelength corresponding to telluric zero velocity (at which weak night sky emission may be present). The velocity shift makes it certain that this emission feature arises in the nebula and is not an artifact of sky subtraction or due to some extraneous source.

We can compare the Na D emission with the models of Natta and Beckwith (1986), who treat the general problem of resonant line scattering in an expanding circumstellar envelope. For many of their cases, most of the escaping photons have a zero Dopper shift relative to the central star, as is seen in our observations. The surface brightness and radial distribution of the emission are functions not only of the density distribution of scatterers but also of the velocity field, making it difficult to fit a unique model to a given set of observations. In order to estimate the absolute intensity of the emission, we obtained a 10 minute integration of BD +30°3639 through a wide slit (4".6), calibrated by α Lyr. Detectable Na D emission extends to approximately 3"–3".5 from the central star along the E-W axis. Within a factor of 2, the sum of the emergent photons integrated over this large aperture is equal to the number of photons removed by the absorption feature along the direct line of sight to the central star, suggesting that the large aperture includes most of the Na D emission region. If the emission were circularly symmetric, our wide aperture would include about $\frac{3}{4}$ of the total flux, but this assumption clearly does not hold, since at positions 3" and 5" west of the central star, the emission is up to a factor of 2 weaker than at corresponding positions on the east side. The peak surface brightness (near 4"E) is about 5×10^{-16} ergs cm^{-2} s^{-1} per square arcsec for λ5890, and about 3×10^{-16} ergs cm^{-2} s^{-1} per square arcsec for λ5895.

IV. SUMMARY

We have shown that the Na D photons emitted by the central star of BD +30°3639 are scattered by a neutral circumnebular envelope. The presence of this envelope is manifested both in absorption features along the direct line of sight to the central star, and as emission from an extended region away from the central star. These observations demonstrate the utility of optical absorption lines as tracers of the neutral material associated with planetary nebulae. Expansion velocity information is provided by the wavelength shifts of the spectral features, and the spatial distribution of the emission is related to the structure of the neutral region. It would be interesting to obtain narrow-band images of the Na D line emission for BD +30°3639 and other planetary nebulae, as well as further spectroscopic observations. Measurements of resonance lines such as Na D provide a new way to detect and study residual neutral gas around planetary nebulae.

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Note added in proof.—Sodium D absorption lines were reported in the planetary nebula NGC 3918 by R. E. S. Clegg, J. P. Harrington, M. J. Barlow, and J. R. Walsh (*Ap. J.*, **314**, 551 [1987]). However, as noted by those authors, the lines are redshifted rather than blueshifted with respect to the nebular systemic velocity and can plausibly be accounted for as interstellar in origin. In the case of BD +30°3639, not only are the circumstellar absorptions shifted well away from the interstellar lines, but the detection of the reemitted photons provides conclusive proof that the absorption occurs very close to the nebula.

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