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THE 1984 SUPERNOVA IN NGC 3169: EVIDENCE FOR A SUPERWIND

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ABSTRACT

Optical spectra of the Type II supernova in NGC 3169 obtained near maximum light on 1984 April 1.484 UT and April 2.563 UT show a double P Cygni structure in the Balmer lines. The high-velocity component suggests a velocity of expansion of the photosphere of 15,500 km s^{-1} whereas the helium lines give a somewhat lower velocity, 13,500 km s^{-1}. From the size of the Balmer discontinuity and from the ratio of continuum fluxes at 4861 Å and at 6563 Å, a photospheric temperature of 15,500 $\pm$ 1800 K is derived. The photospheric radius was larger than or approximately equal to 3×10^{14} cm.

The narrow P Cygni profiles seen in Hα to Hδ suggest that the precursor star underwent a strong episode of mass loss immediately prior to the supernova event and that this wind material was outflowing at a velocity close to 3000 km s^{-1} at the time of observation.

Subject headings: galaxies: individual — spectrophotometry — stars: supernovae — stars: winds

I. INTRODUCTION

The supernova in NGC 3169 was discovered independently by Kiyomi Okazaki, Yamagata, Japan; Nataliya Metlova, Sternberg Crimean Station, U.S.S.R.; and Robert Evans, Maclean, Australia (see *IAU Circulars* 3931 and 3936). The very sparse photometric data given in these *IAU Circulars* suggests that at the time of discovery the supernova was still approaching maximum luminosity. Gaskell of the McDonald Observatory classified it as a Type II supernova on the basis of CCD spectra taken between March 30 and April 2, and he drew attention to the unusual (or unique) narrow Balmer lines seen in this object.

This *Letter* describes spectrophotometric observations made at the Anglo-Australian Observatory on April 1 and April 2, which show that these narrow Balmer lines display, in fact, a P Cygni structure which is most simply interpreted as due to an episode of very strong mass loss in the precursor star prior to the supernova event itself.

II. OBSERVATIONS AND REDUCTIONS

The optical spectra were obtained under photometric conditions at the Anglo-Australian 3.9 m Telescope on 1984 April 1.484 UT (1000 s exposure) and on April 2.563 UT (500 s exposure). The Royal Greenwich Observatory Spectrograph was used with its 25 cm camera and the Image Photon Counting System (IPCS; Boksenberg 1972) as the detector. A grating of 250 lines mm^{-1} blazed in the blue was used in its first order to give a continuous coverage in wavelength from 3400 Å to 7600 Å. This grating has the useful property that its second-order leakage is negligibly small, thus obviating the need to make additional observations with order-blocking filters to obtain flux-calibrated data. The slit width of 400 μm (2".65 on the sky) was significantly wider than the seeing disk (1".4–1".6 FWHM) enabling absolute spectrophotometry at a resolution of 11 Å (FWHM). The external memory was formatted to 50 spectra $\times$ 2044 pixels.

In reduction, pixel-to-pixel variations in sensitivity of the detector were removed by dividing the data by a normalized flat field obtained from several long exposures of a tungsten lamp in third-order red. The spatial response along the slit, which varies slightly due to vignetting in the optics and sensitivity variations in the detector, was removed by division of each spectrum by a normalizing function determined from the mean counts in the strong night sky [O I], 5577 Å line in each spectrum. After rebinning the data to absolute wavelength, those spectra judged to be free of galaxy or stellar contamination were then averaged and subtracted from all spectra in the map. Each spectrum was then converted to absolute flux [$F(\lambda)$] using observations of the Oke (1974) white dwarf standard L745–46A. The data were checked for internal consistency against secondary standards. Finally, the spectrum was reduced to one-dimensional form by co-adding all the spectra (or spatial increments) which contained significant signal.

III. RESULTS AND DISCUSSION

Neither the absolute flux nor the shape of the spectra showed strong night-to-night variation. At visual wavelengths, the two spectra agree to within 2% in absolute flux. This is well within the expected measurement error (10%), suggesting that the supernova was near its maximum luminosity in V. Using the flux-calibrated spectrum averaged over the two nights to extract mean magnitudes in the B and V passbands, we find $B = 14.6 \pm 0.2$ and $(B - V) = -0.15 \pm 0.05$. From the galaxian radial velocity (1240 km s^{-1}; Sandage and Tammann 1981) we derive a distance modulus of 31.0 ($H_0 =$

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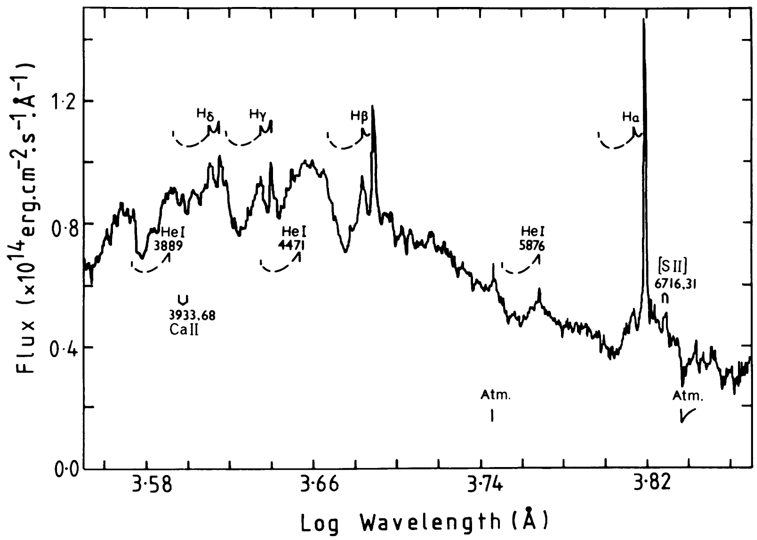

FIG. 1.—The average April 1–2 spectrum of the 1984 supernova in NGC 3169. Note the broad H I and He I absorption and the narrow double-peaked emission in Hα to Hδ.

75 km s^{-1} Mpc^{-1}). These numbers therefore imply a (reddening-uncorrected) absolute B luminosity of $M_B = -16.4 + 5\log(H_0/75$ km s^{-1} Mpc$^{-1})$, which is typical of Type II supernovae near maximum light (Tammann 1978).

Blueward of Hβ, the April 2 spectrum was systematically fainter, and below the Balmer limit it was 20% fainter. If the size of the Balmer jump may be used as a temperature indicator (e.g., Mihalas 1970), this change is indicative of a decrease in the photospheric temperature. For the April 1 spectrum $F(\lambda 3650^+)/F(\lambda 3650^-) = 1.98 \pm 0.10$, and for the April 2 spectrum this flux ratio $= 2.35 \pm 0.20$. These values imply photospheric temperatures of $15{,}800 \pm 1500$ K and $13{,}500 \pm 2000$ K, respectively. The slope of the continuum can also be used to estimate the photospheric temperature, on the assumption that the continuum follows a blackbody distribution. Using the average spectrum (Fig. 1), the ratio of the continuum flux at 6400 Å and 5000 Å implies a photospheric temperature greater than, or about equal to, $15{,}500 \pm 1500$ K. These temperatures are high and similar to those observed in other Type II supernovae near maximum (Kirshner and Kwan 1974).

Because of the similarity of the two spectra, we have co-added them to improve signal-to-noise ratio, and the result is shown in Figure 1 on an $F(\lambda):\log(\lambda)$ plot (which gives a linear velocity scale. Lines of both He I and H are prominent in the spectrum as is typical for a Type II supernova at this phase. However, the most extraordinary feature of the spectrum is the narrow emission P Cygni profile superposed on a much broader absorption or P Cygni structure in all four Balmer lines, Hα to Hδ.

The broad component is associated with the material ejected by the supernova event. A full interpretation of the line shape would require both a density and velocity profile in the atmosphere. However, the maximum velocities observed in absorption and emission are of interest in setting limits on the velocity of ejection. Redward emission is clearly seen only in Hα where it is truncated by the atmospheric OH absorption band. The maximum redshift in Hα (with respect to the galaxy) is $+14{,}000 \pm 2000$ km s^{-1}. High-velocity blueshifted absorption is weakly visible at Hα but is very strong in Hβ to Hδ. The maximum velocity of approach with respect to the galaxy is $-15{,}500 \pm 500$ km s^{-1}. In the helium lines, a broad P Cygni profile is evident in He I 5876 Å, the others showing only blueshifted absorption. The maximum approach velocity in these lines with respect to the galaxy is less than in the Balmer lines; $-13{,}500 \pm 800$ km s^{-1}. This is to be expected since the optical depth in the Balmer lines is greater than in the helium lines at any point in the atmosphere, so the Balmer absorption is weighed to zones higher in the atmosphere in faster moving material (Branch *et al.* 1981).

The "narrow" emission P Cygni structure, unique to this supernova, is seen in Hα to Hδ. The most prominent emission peak has a velocity only slightly different from that of the galaxy; $+1290 \pm 120$ km s^{-1} compared with $+1240$ km s^{-1}. A narrow emission peak is also seen weakly in He I 5876 Å. There is certainly some contribution to these narrow emission lines by a nearby or associated H II region, since the [S II] 6717, 6731 Å doublet is weakly detected at the same redshift. However [O III] and [O II] are not seen, suggesting that this H II region is either very low excitation or else is very highly reddened. In the first case, the contamination of the narrow Hα will be weak, and in the second case, contamination of the higher Balmer lines will be unimportant. The observed Balmer decrement is not grossly differently from that expected in recombination under case B conditions (see Osterbrock 1974), which in view of the above discussion suggests that the narrow Balmer features are intrinsic to the supernova.

The subsidiary "narrow" emission peak seen in Hα to Hδ is blueshifted with respect to the galaxy, and the overall structure of the "narrow" emission features can be understood as a broader emission encompassing both main and subsidiary peaks with a relatively narrow P Cygni absorption notched into the blue side of the emission (Fig. 2). Such a structure is obtained in extended optically thick outflowing winds. If the limit of the blueshifted absorption is indicative of the terminal velocity, this wind is flowing out at 3000 ± 600 km s^{-1}. The profile at Hα is in some respects reminiscent of SS 433 (Dopita and Cherepashchuk 1981).

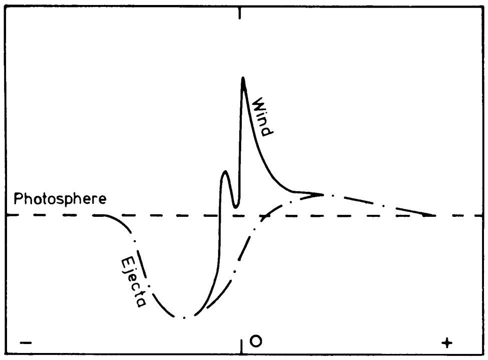

FIG. 2.—A schematic picture showing the observed line profile can arise from two components, inner high-velocity P Cygni–absorbed ejected material and an outer, self-absorbed, emission in a lower velocity wind material.

Among observed Type II supernovae, only 1979c in M100 showed any features even slightly resembling this narrow P Cygni structure in the Balmer lines (Branch *et al.* 1981). This supernova also showed a shell of gas emitting in the UV which was presumably ionized by a pulse of ionizing radiation from the supernova event (Panagia *et al.* 1980). In order to produce a narrow P Cygni profile on top of the broader photospheric P Cygni feature, the "wind" region must clearly lie outside the supernova photosphere. The 3000 km s^{-1} velocity in the wind may either be the result of the initial velocity of ejection, or else of acceleration by the intense initial burst of ionizing radiation, as suggested by Panagia *et al.* (1980). Furthermore, the Balmer emission may either by the result of collisional excitation in this "wind" material or else the result of radiative recombination. The mechanisms will each place different limits on the presupernova mass loss.

The flux in the narrow features at Hα and Hβ are, respectively, $(2.3 \pm 0.6) \times 10^{-13}$ and $(1.0 \pm 0.4) \times 10^{-13}$ ergs cm^{-2} s^{-1}. Adopting a distance of 16 Mpc ($H_0 = 75$ km s^{-1} Mpc^{-1}) to NGC 3169 implies an Hα luminosity of 6.6×10^{39} ergs s^{-1} and an Hβ luminosity of 2.9×10^{39} ergs s^{-1}.

In a wind of constant velocity, the particle density falls as the inverse square of the radius. The flux in a hydrogen line is then

$$F_{\rm H} = 4\pi\alpha_{\rm H}^{\rm eff} h\nu_{\rm H} n_{\rm phot}^2 r_{\rm phot}^3,$$

where $\alpha_{\rm H}^{\rm eff}$ is the effective rate for the transition due to either collisional excitation or recombination, $h\nu_{\rm H}$ is the energy of the transition, and $n_{\rm phot}$ is approximately equal to the hydrogen density at the photosphere; radius $r_{\rm phot}$.

Since the supernova was less than 2 weeks old when observed, and the expansion velocity ~ 15,000 km s^{-1}, $r_{\rm phot} \le 1.8 \times 10^{15}$ cm. From the flux of 6.4×10^{-14} ergs cm^{-2} s^{-1} Å^{-1} measured at 5400 Å, a photospheric radius

$$r_{\rm phot} = 3 \times 10^{14} e\left(H_0/75 \text{ km s}^{-1} \text{ Mpc}^{-1}\right) \text{ cm}$$

is implied, where e is the gray body emissivity (= 1.0 in a blackbody). Normalizing then to a radius of 3×10^{14} cm, $(r_{14.5})$, the density at this radius $n(r_{14.5})$ lies in the range $4 \times 10^9 \le n(r_{14.5}) \le 11 \times 10^9$ cm^{-3}, assuming radiative recombination, that the plasma is fully ionized and using the rates given in Osterbrock (1974) for a plasma temperature of 15,000 K. If, on the other hand, the plasma is collisionally ionized and excited at the photospheric temperature, then

$$6 \times 10^8 \le n(r_{14.5}) \le 4 \times 10^9 \text{ cm}^{-3}.$$

The mass loss, $\dot{M}$, is given by

$$M \approx 4\pi n r^2 M_{\rm H} V_{\rm wind}$$

or

$$\dot{M} = 3 \times 10^{-6} n_9 v \ M_\odot \text{ yr}^{-1},$$

where n_9 is the density of the wind at $r = 10^{14.5}$ cm in units of 10^9 cm^{-3}. This mass loss estimate varies only as the square root of the assumed photospheric or emission radius and is therefore fairly accurate, within the assumptions.

For a precursor wind with a velocity of 3000 km s^{-1}, the mass loss implied lies in the range

$$5 \times 10^{-3} \le \dot{M} \le 0.1 \ M_\odot \text{ yr}^{-1},$$

and for a precursor red giant wind at 10 km s^{-1}, $\dot{M}$ would lie in the range

$$2 \times 10^{-5} \le \dot{M} \le 3 \times 10^{-4} \ M_\odot \text{ yr}^{-1}.$$

These mass loss figures can only be reconciled with "normal" mass loss rates for supergiants at the lower limit. Therefore we are forced to conclude that the supernova in NGC 3169 was the victim of a "superwind" immediately prior to explosion. We shall not enter into speculation as to the cause of this but instead refer the reader to the discussion of the possible scenarios in the case of 1979c by Branch *et al.* (1981).

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