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THE SPECTRAL DEVELOPMENT OF NOVA CYGNI 1975

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ABSTRACT

Optical and near-infrared (0.3–2.5 μm) observations of Nova Cygni 1975 made at Steward Observatory during the period 1975 August 30 to 1975 December 11 are reported. The persistent strength of O I $\lambda\lambda$8446, 11287 is shown to be due to Lβ fluorescence in clouds with high ($>10^3$) Hα optical depth. A simple model of the nova ejecta is presented and shown to be consistent with the observed evolution of the nova spectrum.

Subject headings: stars: individual — stars: novae

I. INTRODUCTION

The present paper is concerned with the spectrum of Nova Cygni 1975 (V1500 Cygni), which reached a maximum visual magnitude of ~1.8 mag on 1975 August 30. Apart from being the brightest nova in decades, Nova Cygni is of special interest because of (1) its extreme range in brightness ($\Delta m_v > 19$), and (2) its rapid development. We wish to report spectroscopic observations of Nova Cygni made at Steward Observatory during the period 1975 September–December, and will focus our attention on the evolution of the O I spectrum.

Although most O I lines remained relatively weak, the O I λ8446 feature was comparable with Hα throughout much of September and October, but had declined in relative intensity by an order of magnitude by December. The O I λ11287 line was observed at similar strength throughout September and provides strong evidence that Lβ fluorescence is responsible for the prominence of these features. The similar profiles of Hα and O I imply the existence of (at least) four discrete clouds of high Hα optical depth which contribute most of the observed Hα emission. The Lβ fluorescence hypothesis requires that the optical depth in Hα is large [$\tau(\text{H}\alpha) \gtrsim 10^3$], presumably owing to population of the $n = 2$ level of hydrogen by trapped Lα photons. It is suggested that the ionization by Lα of hydrogen in this level determines the Lα photon density. A highly simplified model of the nova ejecta is shown to be consistent with this picture and with the general evolution of the nova spectrum. The origin of certain weaker O I and N I lines is also discussed.

II. OBSERVATIONS

Numerous observations of Nova Cygni were made at Steward Observatory during the period 1975 August 30–December 15 as part of a general monitoring program. These observations were mainly spectrographic and were carried out with various grating and detector configurations of the Cassegrain spectrograph at the Steward Observatory 2.3 m telescope. Photographic image-tube data are the most numerous and permit study of the spectral evolution of the nova. More quantitative data were obtained in the red spectral range on 1975 September 13, October 19, and December 7, using the Steward Observatory digital TV system (Gilbert *et al.* 1975). In addition, 1–2.5 μm infrared scans were obtained on September 9, 24, and 28 with the Lunar and Planetary Laboratory Fourier Transform Spectrometer (FTS) and on September 21 with the Steward Observatory FTS system. Some further spectrometric data were obtained on December 11 with the new single-channel scanner (Angel, McGraw, and Stockman 1973).

Figure 1*a* shows a composite of two TV scans taken on 1975 October 9. One observation was taken through increased neutral density filtering to obtain the strengths of O I λ8446 and Hα + [N II], and this scan was scaled (via the strength of He I λ7065) to an observation taken through less filtering. The data shown in Figure 1 have been reduced to a relative flux scale, using a calibration based on the standard star EG 148 (Oke 1974). As can be seen from this figure, O I λ8446 is roughly one-third the strength of Hα + [N II]; the profiles of the lines are very similar. Also shown in Figure 1 are the λ7772 line of O I ($3s\ ^5S^0$–$3p\ ^5P$) and a line that has been identified by Fehrenbach and Andrillat (1975*a*, *b*) as O I λ8222 ($3s'\ ^3D^o$–$3p'\ ^3D$) and by Tomkin, Woodman, and Lambert (1976)

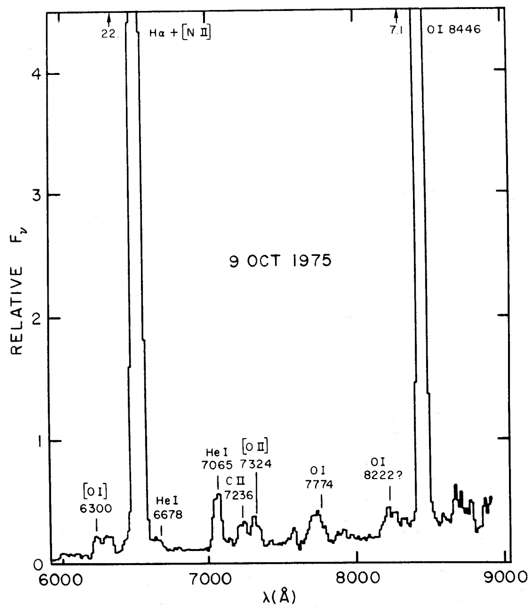

FIG. 1*a*

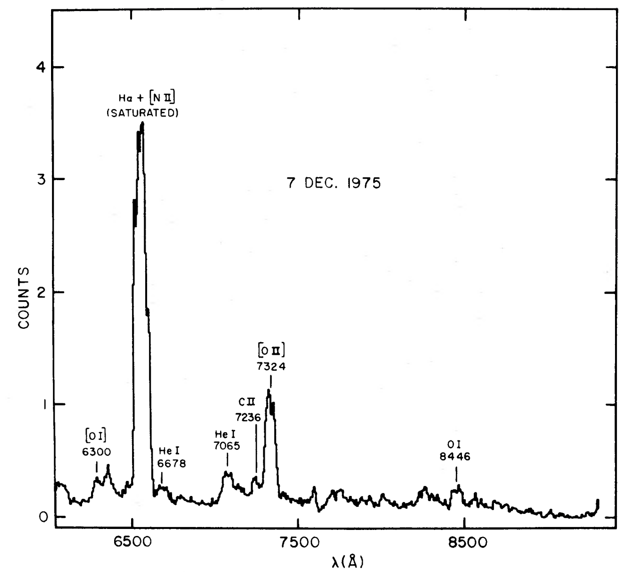

FIG. 1*b*

FIG. 1*a*.—Spectrum of Nova Cygni 1975 from 6000 to 9000 Å obtained on 1975 October 9 with the Steward Observatory Digital TV system. Note extreme strengths of the Hα and O I λ8446.

FIG. 1*b*.—Spectrum of Nova Cygni 1975 from 6200 to 9000 Å obtained on 1975 December 7 with the Steward Observatory Digital TV system. The Hα line saturated the detector, but the strength of O I λ8446 has diminished drastically compared with earlier phases.

as N I λ8212 ($3s\ ^4P$–$3p\ ^4P^o$). Our results, including the image-tube data on the earlier phases, are consistent with the spectral development noted by Tomkin, Woodman, and Lambert (1976) for the period from outburst until 1975 September 18. The profiles of Hα and O I λ8446 appear to contain four dominant velocity components at relative velocities of approximately −1200, −600, +200, and +600 km s^{-1}, respectively. As the nova faded, the line wings of the features became steadily sharper, leading one to conjecture that the individual components may have been far better resolved at higher dispersion. The anomalous strength of O I λ8446, relative to other O I lines, was clearly established by September 4. It is also clear, both from the data presented by Tomkin *et al.* and from our own observations, that the sharpness in the structure of O I λ8446 develops much earlier than in, for example, Hα.

The early evolution of a selected region in the IR spectrum is shown in Figure 2. We note that the O I λ11287 line figures prominently on September 9 and has a profile similar to, but probably not identical with, O I λ8446 (unfortunately, this region of the spectrum is confused by strong atmospheric absorption due to H_2O, so that the precise profile of λ11287 is difficult to determine). No significant emission is present, however, at O I λ13146. The September 9 profiles of Pβ and of Pγ + He I 10830 appear considerably "broadened" with respect to O I λ11287, and, in particular, appear to be extended longward. By September 24, however, all IR lines had developed similar, sharp-winged structure. This behavior is similar to that noted above in comparing O I with Hα. A list of other possible IR features is given in Table 1; agreement with the low-resolution data published earlier by Grasdalen and Joyce (1976) is fair.

Our image-tube spectrum-monitoring program recorded a steady increase in ionization through October and November with the development of prominent features of [O III], [Ne III], and [Ne V]. The strength of O I λ8446, on the other hand, began to decline rapidly with respect to Hα, the line ratio being ~1/50 by 1975 December 11, according to the scanner data shown in Figure 3. The December 7 TV data shown in Figure 1*b* also illustrate this point. We note that even at this late stage, the structure in the O I λ8446 line appears sharper than though similar to that in Hα. Parallel infrared monitoring was, unfortunately, not possible because of the rapid decline in overall brightness of the object.

III. PRODUCTION OF O I λ8446, λ11287

a) *The* Lβ *Fluorescence Mechanism*

O I λ8446 has been observed in H II regions, planetary nebulae, Seyfert galaxies, and QSOs, as well as in Nova Cygni. Grandi (1975*a*, *b*, 1976) has shown that starlight-continuum fluorescence is the excitation mechanism for λ8446 and the other O I lines observed in the Orion Nebula and in planetary nebulae. Oke and Shields (1976)

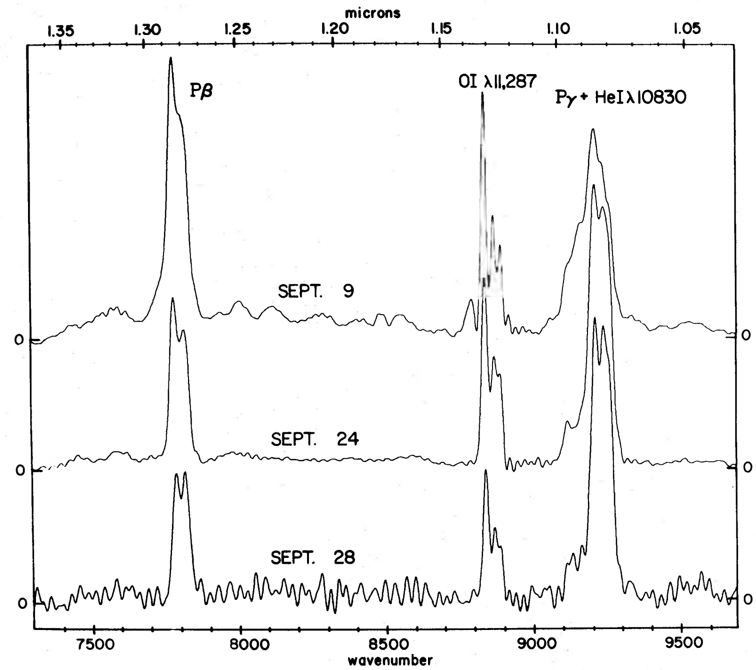

FIG. 2.—Near-infrared spectra of Nova Cygni 1975 from 1.03 to 1.37 μm obtained on 1975 September 9 (*above*), September 24, and September 28 with the Lunar and Planetary Laboratory Fourier Transform Spectrometer. The spectral features are Pβ, O I λ11287, and Pγ + He I λ10830. There is no evidence for a strong feature corresponding to O I λ13164. Note the strong line wings in the early spectra and the subsequent tendency to sharpness. The profile of O I λ11287 is strongly influenced by atmospheric (H_2O) absorption and is therefore less reliable.

TABLE 1

POSSIBLE IR LINES

Sept. 9	Sept. 20	Sept. 24	Sept. 28	Adopted	μm	Comments
4160 w......	...	...	...	...	(2.43)	
4320 w......	...	...	...	...	(2.31)	
4610 s......	4617 s	4620 m	4590 m	4607	2.17	Bγ
4730 w......	...	...	...	...	(2.11)	
4840 m......	*	4870 w	...	4855	2.06	He I λ20581
5010 w......	...	...	...	...	(1.99)	
5120 w......	...	5125 w	...	5123	1.95	Bδ
5310 w......	...	5335 s	...	5324	1.87	Pα (in variable H_2O absorption)
5745 m......	5750 m	5760 w	5740 w	5748	1.74	B10
5920 m......	5930 m	5950 w	5925 w	5932	1.68	B11
6070 w......	...	...	...	...	(1.65)	B12
6180 w......	6200 m	...	...	...	(1.62)	B13
6840 m......	...	...	...	...	(1.46)	
7780 vs......	7790 vs	7800 s	7780 s	7786	1.28	Pβ
8020 mw....	...	...	...	...	(1.25)	
8175 w......	...	...	...	...	(1.22)	
8385 w......	...	...	...	...	(1.19)	
8535 w......	...	...	...	...	(1.17)	
8785 w......	...	...	...	...	(1.14)	
8850 s.......	8855 s	8870 s	8830 s	8850	1.13	O I λ11287
9110 m......	9130 m	9140 m	9125 w	9125	1.09	Pγ
9210 vs......	9220 vs	9230 s	9220 s	9220	1.08	He I λ10830
9250 w......	...	...	...	...	(1.08)	
9570 w......	...	...	...	...	(1.07)	
9745 w......	*	...	...	...	(1.05)	
9920 m......	*	9960 w	...	9940	1.07	
10820 w......	*	...	...	...	(0.94)	
11080 m......	*	11100 w	10080 w	10090	0.991	

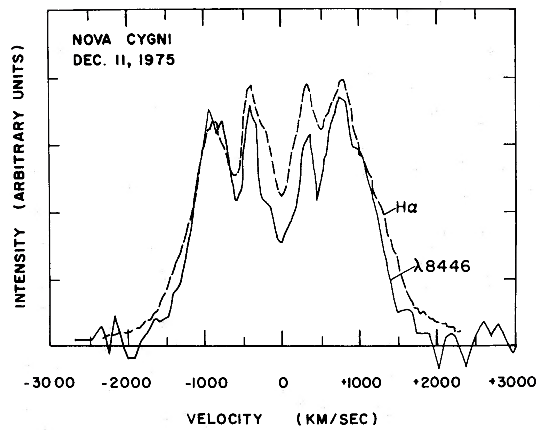

FIG. 3.—Line profiles of Hα and O I λ8446 on 1975 December 11. The total fluxes of Hα and λ8446 were, respectively, 2×10^{-10} and 4×10^{-12} ergs cm^{-2} s^{-1}. The plotted intensities have been scaled to appear approximately equal so that the profiles can be easily compared. The instrumental resolution was 180 km s^{-1} at Hα and 260 km s^{-1} at λ8446. Note that λ8446 shows narrower wings and a deeper central depression, even though the resolution is better at Hα. The velocities are relative values from the line center.

favor a similar continuum fluorescence model for the Seyfert galaxies II Zw 136 and I Zw I, and the QSO 3C 273.

The other possible excitation mechanism for λ8446 is fluorescence of the $3d\,^3D^o$ level of O I by Lβ photons. This coincidence between Lβ and the O I resonance line $2p\,^3P_2$–$3d\,^3D^o{}_{321}$ was first pointed out by Bowen (1947). In typical nebular environments, however, O I and Lβ photons are confined to different parts of the nebula because neutral hydrogen atoms degrade the Lβ photons produced during recombination and prevent them from reaching the O I zone of the nebula (Morgan 1971; Grandi 1975*a*). In other environments, where the $n = 2$ levels of H I are significantly populated, the Lβ photons can be generated in regions where O I is prevalent by conversion of Hα photons. Shields (1974), Shields and Oke (1975), Oke and Shields (1976), and Netzer and Penston (1976) have discussed such a process in connection with Seyfert galaxies and QSOs.

Our data clearly show that Lβ fluorescence is the dominant excitation mechanism for O I. Both the O I λ8446 and the λ11287 lines are quite strong, while O I λ13164 ($3p\,^3P$–$4s\,^3S^o$) is not seen at all. Specifically, our observations show that the strength of O I λ13164 was less than 1/20 of O I λ11287 between September 9 and September 28. If continuum fluorescence were significant, we should expect $W(\lambda 13164)/W(\lambda 11287) \gtrsim 1$ (Grandi 1976), as well as significant contribution to such lines as λ7254 ($3p\,^3P$–$5s\,^3S^o{}_5$) and λ7002 ($3p\,^3P$–$4d\,^3D^o$). Recombination can also be excluded as the dominant mechanism, since, for example, the λ7774 ($3s\,^5S^o$–$3p\,^5P$) line should be roughly 5/3 the strength of λ8446. This is clearly inconsistent with the observations after, say, September 3 (cf. Tomkin, Woodman, and Lambert 1976); we shall return to the question of the early strength of O I λ7774 in § IV.

b) *Optical Depth in* Hα

If it is accepted that Lβ fluorescence is responsible for the O I spectrum, the observed line ratio between Hα and O I λ8446 demonstrates that there must be a large optical depth in Hα. If $\epsilon_{\rm H\,I}$ and $\epsilon_{\rm O\,I}$ are the efficiencies for turning a Lβ excitation of H I and O I into Hα and λ8446, respectively, the line ratio (measured in photon units) between Hα and λ8446 should, in the optically thin case, be

$$\frac{I_{\rm H\alpha}}{I_{\lambda 8446}} = \frac{N_{\rm H\,I}(1s\,^2S)}{N_{\rm O\,I}(2p\,^3P)}\frac{\epsilon_{\rm H\,I}}{\epsilon_{\rm O\,I}}, \qquad (1)$$

where

$$\epsilon_{\rm H\,I} = A({\rm H}\alpha{:}\ 2s\text{–}3p)f_{{\rm L}\beta}/[A({\rm H}\alpha{:}\ 2s\text{–}3p) + A({\rm L}\beta)] \approx 0.0095\,, \qquad (2)$$

and

$$\epsilon_{\rm O\,I} = A(\lambda 11287)f_{\rm O\,I}/[A(\lambda 11287) + A({\rm O\,I}\ \lambda 1025)] \approx 0.0038\,. \qquad (3)$$

The symbols f and A denote the oscillator strengths and Einstein spontaneous transition probabilities, respectively. This line ratio is a lower bound, since other contributions to the strength of Hα (such as recombination) are ignored. Williams (1973) has shown that, owing to charge exchange, the abundance ratios $n_{\rm O\,II}/n_{\rm O\,I}$ and $n_{\rm H\,II}/n_{\rm H\,I}$ are approximately equal. In regions where oxygen is only neutral or once ionized, this implies that $n_{\rm O\,I}/n_{\rm H\,I} = n_{\rm O}/n_{\rm H}$.

If we assume that the population of the O I ground-state fine-structure levels is according to statistical equilibrium and that population of excited Rydberg levels is relatively small, it follows that

$$\frac{n_{\rm H\,I}(1s\,^2S)}{n_{\rm O\,I}(2p\,^3P)} = \frac{9}{5}\frac{n_{\rm H}}{n_{\rm O}}, \tag{4}$$

and the predicted value of $I_{\rm H\alpha}/I$ λ8446 ≈ 7.5 × 10^3, assuming a normal abundance of O I. Even if it is assumed that there is a negligible contribution[1] of [N II] λλ6548, 6583 to Hα, the observed ratio $I_{\rm H\alpha}/I$ λ8446 is approximately 3. Since other O I lines are weak, there is little reason to suspect a gross overabundance of oxygen relative to hydrogen. Although a modest increase in oxygen abundance (≲10) cannot be excluded, it is, in our opinion, more probable that the anomalous O I λ8446/Hα line ratio is due to high Hα optical depth. A minimum value, based on negligible optical depth in O I λ8446 and on normal composition, is

$$\tau_{\min}({\rm H}\alpha) = \frac{I_{\rm O\,I}{}^{\rm obs}}{I_{\rm H\alpha}{}^{\rm obs}}\frac{I_{\rm H\alpha}{}^{\rm pred}}{I_{\rm O\,I}{}^{\rm pred}} = 2.5 \times 10^3\,. \tag{5}$$

If the optical depth in O I λ8446 is significant, $\tau({\rm H}\alpha)/\tau(\lambda 8446)$ may be set equal to the above value of $\tau_{\min}({\rm H}\alpha)$. This value is, in any case, sufficiently high to require a significant optical depth in the O I transition, if the composition is normal.

The high Hα optical depth required to account for the prominence of O I λ8446, together with the four-component line profile, strongly suggests the presence of four discrete, partially ionized clouds. The relative intensities of the corresponding components in Hα and O I would depend on Hα optical depth if O I λ8446 were optically thin. The close similarity in total line profile observed in late September and October suggests, therefore, that the clouds were optically thick in both transitions.

c) *Population of the n = 2 Level by Trapped* Lα *Photons*

The high optical depth in nonresonance lines requires explanation. We propose that, in the case of Hα, it is due to population by trapped Lα photons. If we assume that other processes are negligible, it follows that, in a quasi-steady state,

$$\frac{n_2{}^{\rm H}}{n_1{}^{\rm H}} = \frac{cn_\alpha}{\Delta\nu}\left(\frac{\pi e^2}{m_e c}\right)\frac{f_{12}}{A_{21}}, \tag{6}$$

where $n_1{}^{\rm H}$, $n_2{}^{\rm H}$ are the populations of the $n = 1, 2$ levels of hydrogen, respectively, n_α is the number density of Lα photons, $\Delta\nu$ is the line width in frequency units,[2] and other symbols have their usual meaning. If we adopt a line width per component of $\sim 10^2$ km s^{-1},

$$\frac{n_2{}^{\rm H}}{n_1{}^{\rm H}} = 1.7 \times 10^{-12} n_\alpha/\Delta\nu_2\,. \tag{7}$$

d) *Ionization*

In order to proceed further, we shall make certain assumptions about the nova explosion and will check subsequently for self-consistency. The total line width suggests an outflow velocity $v \approx 10^3$ km s^{-1}. Studies of novae indicate an inverse correlation between speed of development and ejected mass. We accordingly adopt the relatively low value $\Delta m \approx 10^{-5}\,M_\odot$ for the mass of the ejecta. After a time $t \approx 1$ month, the material will be at radius $r = 2.5 \times 10^{14} v_3 t_1$ cm and will have a line-of-sight column density

$$N = \Delta m/4\pi r^2 m_{\rm H} \approx 1.5 \times 10^{23}(\Delta m_4/v_3{}^2 t_1{}^2)\ {\rm cm}^{-2}\,. \tag{8}$$

The density is rather more difficult to estimate, but a reasonable lower limit may be obtained if we assume quasi-homologous expansion from a shell of thickness $\sim 10^{-1}$ of its radius—the original stellar mass configuration. We then obtain

$$n_{\min} \approx 2 \times 10^{10}(\Delta m_4/v_3{}^3 t_1{}^3)\ {\rm cm}^{-3}\,. \tag{9}$$

If the relative expansion in any direction is thermal, the above density estimate must be increased by the ratio of the homologous expansion velocity to that of sound. In the following discussion, we shall assume that $n = n_{\min}$.

[1] We note that [N II] λ5755 is seen in spectra of Nova Cygni taken in 1975 October. Some contribution from [N II] λλ6568, 6583 is expected but is strongly density-dependent.

[2] The adopted value of $\Delta\nu$ represents a compromise between the total observed line width and estimates of local physical conditions in the clouds that suggest low temperature and modest macroscopic random motions.

We will deal throughout with mean properties of the gas only, although it is clear from the line profiles that a "lumpy" medium is present.

On the basis of data for other novae (see Gallagher and Starrfield 1976, and references therein), we will also assume that the central remnant has a constant luminosity $L \approx 10^4 L_\odot$ and is comparatively hot ($T_{\rm eff} \approx 5 \times 10^4$–$10^5$ K). Ionization balance, assuming that the nebula is ionization-bounded,[3] implies a mean electron density given by

$$n_e \approx 5 \times 10^8[L_4F(T)/t_1{}^3v_3{}^3]^{1/2} \tag{10}$$

and a mean relative ionization

$$\frac{n_e}{n} \approx \frac{5 \times 10^{-2}[L_4F(T)t_1{}^3v_3{}^3]^{1/2}}{\Delta m_4}, \tag{11}$$

where F is a function taking into account the distribution of ionizing photons. For $t_1 \approx 1$, equations (9) and (11) show that the nebula is nearly density-bounded, and lines from higher ionization states should be increasing rapidly in the spectrum; this is consistent with observation. We should emphasize that this is a mean result and that considerable variation is expected between different parts of the nebula; in particular, the inner edge and intercloud medium should be much more highly ionized than the principal clouds. For $t_1 \approx 1$, however, the mean fraction, P, of neutral hydrogen should not differ greatly from unity.

e) *Estimate of the Trapped* Lα *Photon Density and* Hα *Optical Depth*

The number of ionizing photons emitted by the central source is approximately

$$N \approx 5 \times 10^{54}[L_4F(T)t_1]. \tag{12}$$

In principle, each of these should result in the creation of at least one Lα photon. The high column density (eq. [9]) and modest mean ionization (eq. [11]) imply a very large Lα optical depth,

$$\tau(\mathrm{L}\alpha) \approx 6 \times 10^8P(\Delta m_4/v_3{}^2t_1{}^2\Delta\nu_2), \tag{13}$$

where P is the fraction of hydrogen which is neutral. The comparatively high density indicates that Lα scattering should take place with considerable frequency redistribution which, coupled with the high optical depth, makes escape through random walk in frequency space unlikely. A random walk in physical space would be accomplished in a minimum time

$$t = \tau(\mathrm{L}\alpha)(R/C) \approx 2.4 \times 10^{13}P(\Delta m_4/v_3t_1\Delta\nu_2)\ \mathrm{s}, \tag{14}$$

i.e., long compared with the age of the nova. For these reasons, no strong Lα emission would be expected from the nova, which is consistent with the null results obtained from *Copernicus* (Jenkins *et al.* 1977). The mean density n_α of Lα photons in the nebula, assuming complete trapping, would be

$$n_\alpha{}^{\max} \approx 4 \times 10^{10}[L_4F(T)]/(v_3{}^3t_1{}^2)\ \mathrm{cm}^{-3}, \tag{15}$$

which would be sufficient to populate the $n = 2$ level to a degree comparable with the ground state (cf. eq. [7]). We note, however, that Lα itself can ionize a hydrogen atom from the $n = 2$ level, a process which limits the buildup of Lα photon density (cf. Osterbrock 1964). Each ionization from the ground state requires two Lα absorptions and returns only one such photon on recombination. The energy is lost through free-free emission and higher-level recombination-line radiation. An estimate of the Lα photon density may be obtained by equating the loss rate of Lα photons to their creation rate owing to absorption of Lyman-continuum photons from the central source. We then obtain

$$\begin{aligned} 1.3 \times 10^{48}[L_4F(T)] &\approx 5.8 \times 10^{-19}cn_\alpha n_2{}^{\rm H}V, \\ &\approx 1.0 \times 10^{-30}cn_\alpha{}^2n_1{}^{\rm H}V/\Delta\nu_2, \\ &\approx 1.0 \times 10^{-30}cn_\alpha{}^2N_{\rm H}4\pi r^2/\Delta\nu_2, \\ &\approx 3.6 \times 10^{33}(\Delta m_4P/\Delta\nu_2)n_\alpha{}^2. \end{aligned} \tag{16}$$

Thus

$$n_\alpha \approx 1.7 \times 10^7[L_4F(T)\Delta\nu_2/\Delta m_4P]^{1/2}. \tag{17}$$[4]

[3] The rate of supply of ionizing photons has been set equal to the total rate of recombination in the nebula.

[4] Note that this equation is appropriate only so long as the nebula is ionization bound and $n_\alpha \lesssim n_\alpha{}^{\max}$.

It therefore follows from equation (7) that

$$\frac{n_2^{\mathrm{H}}}{n_1^{\mathrm{H}}} = 3 \times 10^{-5}[L_4 F(T)/\Delta m_4 P \Delta\nu_2]^{1/2}\,, \tag{18}$$

and hence that the optical depth in Hα is

$$\tau(\mathrm{H}\alpha) = 1.7 \times 10^4 [P\Delta m_4 L_4 F(T)]^{1/2}/[V_3{}^2 t_1{}^2 (\Delta\nu_2)^{3/2}]\,. \tag{19}$$

This implies a substantial optical depth in the Balmer continuum in the clouds of

$$\tau_{\mathrm{BC}} \approx 1 \times 10^2 [P\Delta m_4 L_4 F(T)/\Delta\nu_2]^{1/2}/(V_3{}^2 t_1{}^2)\,, \tag{20}$$

measured at the absorption edge. While the optical depth in the Balmer continuum is not known with any certainty at present, it is known that, after the third or fourth day, the Paschen continuum arose mainly from free-free emission in an optically thin gas (Gallagher and Ney 1976). The population of the $n = 3$ level of hydrogen is likely to be much less than that of the $n = 2$ level by a factor as great as the $n_1{}^{\mathrm{H}}/n_2{}^{\mathrm{H}}$ ratio (see § III*f*). This would be consistent with the observations and the estimates given above. A minimum value of the Balmer-continuum opacity is $\tau_{\mathrm{BC}} \approx 1$ if the optical depth in Hα is to have the minimum value $\tau_{\min}(\mathrm{H}\alpha)$ given in equation (5).

f) *The* O I *Fluorescence Spectrum and the* Lβ *Photon Density*

As noted above, the ionization of oxygen and that of hydrogen are very similar. The Lα ionization process is capable of producing recombination photons of Lβ even in a gas which is well shielded from direct Lyman-continuum photons. In addition, the high optical depths in Lβ and Hα ensure that an essentially photon-conservative process occurs until a Lβ photon is absorbed by O I (Balmer-continuum ionization is 10^4 times less effective in the present circumstances). This assumes that *l*-state (Brocklehurst 1972) mixing occurs reasonably efficiently in the $n = 2$ and $n = 3$ levels. At densities greater than 10^9, the time scale for mixing is substantially faster than those involved in other hydrogen line-loss processes.[5]

We note that, given the Lα optical depth (eq. [13]), the O I resonance lines must also be highly opaque. On the basis of normal composition, we estimate that, at $t_1 = 1$, $\tau(\lambda 1302) \approx 3 \times 10^4$ and the random walk escape time $\sim 3 \times 10^8$ s, again long compared with the age of the nebula when the *Copernicus* observations were made. The absence of O I λ1302 in the observed spectrum can, therefore, be understood despite the strength of O I λ8446, the feed transition.

Some estimate of the Lβ and O I λ1302 photon densities is now required. The creation rate for Lβ–Hα photons should be approximately the same as that for direct recombination to the $n = 2$ level, that is, to the creation rate of Lα photons. This is approximately equal to the recombination rate and hence to the rate of ionization by Lα in the Balmer continuum (eq. [16]). The effective steady-state equation for the Lβ photon density n_β is

$$n_e n_{\mathrm{H\,II}} \approx \left(\frac{\pi e^2}{mc}\right)\frac{f_{1026} n_1{}^{\mathrm{O\,I}} c n_\beta}{\Delta\nu} + 3 \times 10^{-19} n_2{}^{\mathrm{H}} c n_\beta\,, \tag{21}$$

where it has been assumed that the Lβ–Hα system is conservative and where the respective terms represent recombination, O I absorption, and Balmer-continuum ionization. From equation (18) and the assumption of normal composition, it is clear that the O I loss term is dominant. Because of the quasi-conservative nature of the Lβ–Hα system when the optical depth in Hα is high, most Lβ photons must be converted to O I λ1302 photons via the fluorescence mechanism and emission of O I $\lambda\lambda$11287 and 8446 photons. The number density of O I λ1302 photons should therefore increase rapidly until limited, presumably, by the rate of ionization of $n = 2$ level hydrogen atoms. Since the creation and destruction rates for O I λ1302 are thus virtually identical to those for Lα, the O I λ1302 photon density, n_{1302}, must be comparable with n_α. If so, the ratio of O I atoms in the $3s\ {}^3S^o$ level to those in the ground state should be comparable with that given in equation (18). The optical depth in O I λ8446 should then be

$$\tau(\lambda 8446) \approx 6\{[P\Delta m_4 L_4 F(T)]^{1/2}/[V_3{}^2 t_1{}^2(\Delta\nu_2)^{3/2}]\}\,. \tag{22}$$

This may account for the similarity in profile between O I λ8446 and Hα during September and October and the relative decline in O I λ8446 thereafter (i.e., when the optical depth in λ8446 falls below unity).

The Lβ photon density n_β in a quasi-steady state may be deduced from equation (21). If we set the recombination term equal, approximately, to the Lα ionization rate, we obtain

$$\frac{n_\beta}{n_\alpha} \approx 1.0 \times 10^{-4}\left[\frac{L_4 F(T)}{\Delta m_4 P}\right]^{1/2}. \tag{23}$$

[5] For the Lα photon density given in eq. (17), losses due to two-photon emission are not entirely negligible compared with the Balmer ionization rate and, strictly speaking, should be included in the calculation. The problem becomes more severe as n_α declines because of the quadratic dependence on the ionization losses (eq. [16]).

Since mixing of l-states proceeds on a time scale short compared with the O I loss rate, and Hα photons are also trapped, the Hα photon density $n_{H\alpha}$ should be comparable with n_β. From equation (23) it therefore follows that the Lβ induced population n_3^H of the $n = 3$ level of hydrogen satisfies $n_3^H/n_2^H \approx 1 \times 10^{-4}$. The optical depth at the Paschen-continuum edge is therefore

$$\tau_{PC} = 1.0 \times 10^{-2}[L_4 F(T)]/[V_3^2 t_1^2 (\Delta\nu_2)^{1/2}] . \tag{24}$$

Thus $\tau_{PC} \approx 1$ when $t_1 \approx 0.1$, which is again consistent with the observations. Pα should, on this basis, have become optically thin after $t_1 \approx 3$. (The effects of collisional excitation have not been included in this calculation, since for the $n = 2$–3 transitions they are strongly temperature-dependent. Except perhaps in the very earliest nebular phase of the nova, there is little evidence for strong collisional population of excited states.) Similarly, the optical depth at $t_1 = 1$ in λ11287 or other lines arising from the $3p\ ^3P$ or $3d\ ^3D^o$ levels in O I should be $\lesssim 10^{-3}$.

IV. THE O I QUINTET LINES AND THE C I AND N I SPECTRA

The behavior of other O I lines requires some comment. The observations of Tomkin *et al.* clearly show that the quintet lines λ7774 ($3s\ ^5S^o$–$3p\ ^5P$) and probably λ9265 ($3p\ ^5P$–$3d\ ^5D^o$)[6] are comparable with O I λ8446 on September 2 although they diminished in relative strength very rapidly thereafter. No other quintet lines except perhaps λ6158 and λ6455, or any other triplet lines, achieved detectable strength, thus ruling out recombination or continuum fluorescence. The observed quintet lines are in fact the analogs of λ8446 and λ11287 and are strong at a time when all the O I lines have a fairly broad P Cygni profile (Tomkin, Woodman, and Lambert 1976). As they decline, they develop a four-component structure similar to λ8446 but with much lower intensity. One possible explanation of the change in profile is that, in the early phases, essentially the whole circumstellar cloud is sufficiently opaque to cause fluorescence, whereas later only the four basic clouds fulfill the required conditions (see below). An alternative explanation at least for the O I λ7774 line is that a substantial population is built up in the $3p\ ^5S^o$ metastable level leading to P Cygni or collisionally excited emission.

According to Tomkin *et al.*, however, certain N I quartet lines ($\lambda\lambda$7472, 8211, 8691) and C I triplet lines ($\lambda\lambda$9087, 9640, 10695) also appear with moderate P Cygni profiles which decline at a rate comparable with O I λ7774. We have been unable to account for the strength of these lines by any plausible fluorescence mechanism. On the other hand, they arise from the lowest excited state of the atom in question ($3s\ ^4P$ in N I, $3s\ ^3P^o$ in C I) that is connected by a permitted transition to the ground state. No other lines of C I or N I were observed. This suggests that this lowest excited level is populated sufficiently to give rise to a P Cygni profile. Similar remarks apply to O I λ8446 and λ7774, although the latter arises from a metastable level and is presumably populated in a different manner. The O I λ8446 and λ7774 may therefore contain both fluorescence and P Cygni components in the early phases, although the fluorescence is clearly dominant in O I λ8446 after a few days.

As noted above, the well-established N I, C I, etc., lines in the early nova spectrum appear to arise from the lowest excited level with a permitted transition to the ground state: no doublet lines of N I or singlet C I transitions are observed. From the discussion in § III it appears that, for H and the O I triplet states, the population of the first excited level is due to trapped resonance-line photons the density of which may be determined by setting the supply rate equal to the rate of loss through Balmer-continuum ionizations. With the exception of O I, where the Lβ fluorescence mechanism provides a very high supply rate of λ1302 photons, the creation mechanism for resonance-line photons is presumably recombination. Since the Lα photon-creation rate is given by the hydrogen recombination rate and the loss mechanism is identical for all species, it follows that the number density of, for example, trapped N I λ1200 photons n_{1200} is given by

$$\frac{n_{1200}}{n_\alpha} \approx \frac{n(\text{N II})}{n(\text{H II})} , \tag{25}$$

and that the ratio of population of the first excited state to the ground state of N I is

$$\frac{n_N(2p^2 3s\ ^4P)}{n_N(2p^3\ ^4S^o)} \approx \frac{n(\text{N II})}{n(\text{H II})}\frac{n_2^H}{n_1^H} . \tag{26}$$

The optical depth in the lines arising from the $2p^3 3s\ ^4P$ level, namely, λ7452, λ8211, and λ8691, is therefore given approximated by

$$\tau(7452, 8211, 8691) \approx k\left[\frac{n(\text{N I})}{n(\text{H I})}\right]\left[\frac{n(\text{N II})}{n(\text{H II})}\right]\tau_{H\alpha} \tag{27}$$

[6] There is some possibility of confusion between O I λ9265 and H I (P9). A comparison of the observed feature with Pδ and P10 leads us to conclude that, between September 2 and September 6, O I λ9265 was the dominant contribution.

where k is a factor of order unity. From equation (18) it follows that

$$\tau(7452, 8211, 8691) \lesssim \left[\frac{n(\mathrm{N})}{n(\mathrm{H})}\right]^2 \tau_{\mathrm{H}\alpha}$$

$$\approx 0.8 \times 10^5 \left[\frac{n(\mathrm{N})}{n(\mathrm{H})}\right]^2 \frac{[P\Delta m_4 L_4 F(T)]^{1/2}}{[v_3{}^2 t_1{}^2(\Delta\nu_2)^{3/2}]} . \tag{28}$$

For $t_1 \approx 0.1$, and for normal composition $[n(\mathrm{N})/n(\mathrm{H}) \approx 2 \times 10^{-4}]$, it then follows that $\tau(7452, 8211, 8691) \approx 0.3$. Within the uncertainties, therefore, the decline in strength of the P Cygni components of N I (and presumably C I) can be accounted for in terms of diminishing optical depth in the nova envelope. The contribution from the four basic clouds eventually dominates the emission, presumably because their density decreases less rapidly than that of the surrounding gas, and the relative abundance of neutral species remains correspondingly higher.

The case of O I is more complicated. It is clear from the λ11287 line strength that Lβ fluorescence accounts for most of the λ8446 emission, especially after the first few days. On the other hand, the optical depth in λ8446 is high in the clouds and was probably significant in the surrounding medium in the early phases, so that some P Cygni contribution is likely.[7] The O I λ7774 line is more puzzling, since it arises from a metastable lower level. The origin of λ9265, if real, is also perplexing. It is, in our view, unlikely (though not impossible) that direct Lβ fluorescence in the $2p\ ^3P$–$3d\ ^5D^o$ transition can be responsible for the λ9265 feature, despite the fairly close wavelength agreement. The expected ratio of quintet to triplet fluorescence is less than $\sim 10^{-4}$ and should remain constant as the nova evolves, unless the effective velocity dispersion decreases. We suggest, instead, that the λ9265 emission and the population of the $3s\ ^5S^o$ level occurs through Lβ fluorescence in the triplet transition and subsequent collisional mixing of the $3d\ ^3D^o$ and $3d\ ^5D^o$ states. At the densities predicted for the nova shell at $t \approx 0.1$, the population of the $3s\ ^5S^o$ level is determined by the collisional supply rate from the $3d\ ^3D^o$ to the $3d\ ^5D^o$ level (followed by rapid emission of λ9265 and λ7774) and collisional de-excitation from the $3s\ ^5S^o$ level. In these circumstances the quasi–steady-state population of this level is given by

$$\frac{n^{\mathrm{O\,I}}(2s\ ^5S^o)}{n^{\mathrm{O\,I}}(2p\ ^3P)} \approx 2 \times 10^{-8}[L_4 F(T)]Q , \tag{29}$$

where Q is a factor which reflects the efficiency of the spin change collisional cross section to that for classical collisional de-excitation. The optical depth in O I λ7774 is then

$$\tau(\lambda 7774) \approx 1.5 \times 10^{-2} PQ[\Delta m_4/v_3{}^2 t_1{}^2(\Delta\nu_2)^{1/2}] , \tag{30}$$

so that $\tau(\lambda 7774) \approx 1.5$ for $t_1 = 0.1$ and declines at a rate similar to the N I and C I lines. A P Cygni scattering explanation for the C I, N I lines and in part for O I λ7774 thus appears plausible.

The O I λ9265 and the remainder of O I λ7774 emission must, on this picture, be due to triplet fluorescence and subsequent level mixing ($3d\ ^3D^o$ to $3d\ ^5D^o$). The ratio of λ9265 to λ11286 line strength should therefore depend directly on the density and decline approximately as $t_1{}^{-3}$; this is not inconsistent with the data of Tomkin *et al.*

V. SUMMARY AND DISCUSSION

Observations of the red and near-infrared spectrum of Nova Cygni 1975 have been presented. Particular attention has been paid to the development of the O I spectrum, especially the persistent great strength of O I $\lambda\lambda$8446, 11287. These results are interpreted in terms of a model consisting of an expanding shell containing concentrations of material of increasing density contrast. On the basis of this model and the available observational data, it is shown that:

1. The persistent strength of O I $\lambda\lambda$8446, 11287 is due to Lβ fluorescence.
2. The optical depth in Hα is large ($\gtrsim 10^3$) and is significant in O I λ8446 after one month.
3. The nebula is still ionization-bounded one month after outburst but only barely so.
4. The population of the $n = 2$ level of hydrogen is determined by a balance between the creation of new Lα photons by recombination and photoionization by Lα in the Balmer continuum. The density of O I λ1302 photons is found to be similar to that in Lα, leading to significant population of the $3s\ ^3S^o$ ground level of λ8446.
5. The population of the $n = 3$ level of hydrogen by trapped Lβ implies that the Paschen continuum would become optically thin after a few days. This is consistent with observation.
6. Photons trapped in the lowest resonance lines of common ions are unlikely to escape directly during the early lifetime of the nova owing to the high optical depth in the lines and the high ambient density which permits effective redistribution in the emitted profile. Therefore no strong emission should be observed in these UV transitions.
7. The trapped photon density in such resonance lines (other than O I) is determined by Balmer-continuum

[7] The clouds must themselves produce some scattered radiation, but this will appear superposed on the dominant fluorescence contribution.

ionization and by recombination rates. The photon densities accordingly vary approximately with the first power of the composition.

8. The evolution of lines of certain other ions (N I, C I) may be understood in terms of P Cygni line formation from a first excited state which is populated by trapped resonance photons. The optical depth in such transitions varies approximately with the second power of the composition.

The quintet O I $\lambda\lambda$7774, 9265 lines show evidence of excitation via Lβ fluorescence and exchange mixing between the $3d\,^3D^o$ and $3d\,^5D^o$ states. The resultant population of the $3s\,^5D^o$ metastable level gives an optical depth in λ7774 comparable with that in N I and C I lines and may thus account for the early P Cygni profile observed in the line.

The decline in the O I fluorescence lines relative to Hα after the end of October also requires comment. As long as Lβ photons are effectively confined within a cloud, absorption by O I must take place. The effective confinement condition breaks down essentially when the Hα optical depth falls below $\tau(\text{H}\alpha) \approx 10^3$. In the Nova Cygni nebula this occurs, because (1) simple expansion reduces the column density of material; (2) the ionization reduces the column density of neutral material; (3) the nebula ceases to be ionization-bounded (at high photon energies), thereby reducing the supply of Lα photons and hence the population of the $n = 2$ level; and (4) the two photon losses (effectively of Lβ photons) become relatively more important as n_α declines. More detailed calculations are clearly required to verify this qualitative discussion.

Finally, we wish to point out that a self-consistent model of the nova shell can be constructed on the basis of normal element abundances, although we emphasize that some enhancement of the heavier elements (C, N, O) cannot be excluded on the basis of this analysis.

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