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HIGH-DISPERSION OBSERVATIONS OF EMISSION LINES IN THE POSTNOVA HR DELPHINI

J. S. GALLAGHER*†
School of Physics and Astronomy, University of Minnesota
AND
CHRISTOPHER M. ANDERSON*
Washburn Observatory, University of Wisconsin, Madison
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ABSTRACT

The Wisconsin echelle spectrograph has been used on the KPNO 4 m Mayall telescope to obtain high-resolution line profiles of Hα; [N II] λ6548, λ6583; and [O III] λ5007 in the postnova HR Del. The lines show considerable structure with individual subcomponents having velocity widths of 40–70 km s^{-1}, even though the general velocity flow from the nova is ~500 km s^{-1}. We are able to identify major line components as having been present in the early nebular stage (6 years before the present observations); thus it appears that novae can produce well-defined condensations, even though matter is initially ejected at very high velocities. All lines also contain two major velocity groupings which we designate as shells A (centered near $V = \pm 100$ km s^{-1}) and B ($V = \pm 400$ km s^{-1}). Physical conditions differ in the two shells with shell B being more highly ionized and probably having a higher electron temperature. In shell A we observe I([N II] λ6584)/I(Hα) ≈ 2. Possible mechanisms which could produce this ratio including an overabundance of nitrogen are reviewed, and we conclude that the present data are weakly suggestive of a nitrogen excess. The observations are briefly discussed in terms of predictions of theoretical models for novae, and some possible parallels are noted between novae and other objects containing dynamically moving gas.

Subject headings: nebulae: individual — stars: mass loss — stars: novae

I. INTRODUCTION

Nova HR Del 1967, unusual during its outburst, is an equally interesting postnova system. Following an extended halt near maximum light which lasted for almost a year, the nova began a slow decline in visual light during mid-1968 (see Sanyal 1974). By 1973 it had nearly returned to its prenova magnitude of $m_{pg} \approx 12$ (Stephenson 1967; Gallagher 1974). At this time the system had a blue continuum and characteristic nebular stage emission lines (Gallagher 1974). HR Del is apparently a typical postnova (cf. McLaughlin 1960); however, unlike most old novae which tend to be unpleasantly faint (e.g., Humason 1938; Payne-Gaposchkin 1957; Kraft 1964), HR Del remains relatively accessible for further study.

In this paper we report results from a preliminary survey of emission-line profiles. The data were obtained with an echelle spectrograph and have unusually good spectral resolution. Thus we have been able to resolve the broad emission lines into individual components, and we are therefore able to use radial velocities to identify and study several distinct features in the as yet unresolved nova shell.

II. OBSERVATIONS AND REDUCTIONS

The observational material of this study is composed of five high-dispersion spectra of HR Del obtained on the nights of 1974 October 4, November 30, and December 1 with the Wisconsin echelle spectrograph (Schroeder and Anderson 1971) and the Kitt Peak National Observatory, N. U. Mayall 4 m telescope. The detector used was the KPNO Carnegie image intensifier (Direct System 1) and Kodak IIIaJ plates which were baked for 4 hours at 65° C in dry nitrogen and developed in D-19 for 5 min at 20° C. In addition to the object plates, one spectrum of the late-type dwarf BY Dra (obtained in conjunction with another project) and two spectra of the A0 Ib standard star η Leo were obtained on these same observing runs with the same equipment and utilized for calibration purposes. Each spectrum was calibrated for intensity-to-density conversion by means of KPNO Spot Box Wedge 119. Three of the HR Del spectra are centered on Hα, and two are centered on [O III] λ5007. Exposure times ranged from 16 to 60 min. All of these spectra were obtained with entrance slits of 100 μ (0″.4) which project to velocity widths of 12 km s^{-1} at the spectrometer focal plane. The spectra are shown in Figure 1.

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† Guest Observer, Steward Observatory, University of Arizona.

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All of the plates were traced on the University of Wisconsin high-speed, logarithmic digital microphotometer, the data from which was reduced on the computer facility of the University of Wisconsin Space Astronomy Laboratory. The software system of the microphotometer makes possible the proper correction of variable plate fog, luminous background (intensifier dark current and spectrograph scattered light), and the variable instrument sensitivity which is due to the rapidly changing blaze efficiency of the echelle grating. This latter correction was accomplished by reference to the spectra of η Leo. The resulting tracings are shown in Figure 2. It should be noted that in this figure the large negative velocity end of [N II] λ6584 is the same as the large positive velocity end of Hα, since the velocities observed are so large that some components of these two lines overlap. The velocities of the various components were established by direct measurement of the plates and from microphotometer tracings. These were related to heliocentric velocities by the standard technique except that in the case of the Hα region the paucity of comparison lines made it necessary to establish deviations from dispersion linearity. This was done by reference to the numerous Fe I lines in spectrum of the late-type dwarf BY Dra obtained immediately prior to the HR Del exposure. Although less than optimum, this procedure has proven adequate to within formal probable errors of measurement amounting in this case to ± 7 km s^{-1}.

The relative intensities for Hα and [O III] were established by reference to the η Leo spectra and its fluxes as given by Johnson *et al.* (1967) and to the total counts accumulated on each exposure in the pulse counting exposure meter of the Wisconsin echelle. Corrections were applied for atmospheric differences via the standard Palomar extinction curve (Oke 1963), corrected for the altitude difference between Palomar and Kitt Peak according to the prescription of Hayes and Latham (1975). Bandpass and plate sensitivity corrections were also applied with the net result that the intensity scale for [O III] in Figure 2 is compressed by a factor of 2 relative to that of Hα and [N II], and the precision of the resultant intensity ratios between [O III] and [N II] is probably not better than 50 percent. The important thing to note is that [O III] λ5007 is stronger than [N II] λ6584 and very much stronger than Hα.

III. VELOCITY STRUCTURE

Heliocentric radial velocities for the emission-line components identified in Figure 2 are listed in Table 1. The velocity of the most pronounced component (near $V = -100$ km s^{-1} in Fig. 2) was measured directly from both the plates and intensity tracings. For the Hα and [N II] lines, these methods give, respectively, $V = -102 \pm 7$ km s^{-1} and $V = -108 \pm 4$ km s^{-1} where the uncertainties reflect only the formal errors. Both techniques give velocities of equivalent quality, but, since the line structure is more easily studied from the tracings, we have used these measurements in Table 1. Also given in Table 1 are approximate velocity widths for some of the stronger line components. Table 2 gives some approximate line intensity ratios for stronger line components.

The [O III] λ5007 emission complex consists of two major groups of lines. For convenience we refer to these velocity groupings as shells, even though the geometry may be far from spherically symmetric (Hutchings 1972). Shell A has a velocity width of

TABLE 1

VELOCITIES FOR MAJOR LINE COMPONENTS

Line	Component	V*	ΔV†
[O III] λ5007...	α	−504	...
	β	−467	...
	γ	−428	...
	δ	−363	70
	ε	−291	80
	ζ	−92	70
	η	+55	...
	θ	+103	...
	ι	+145	60
	κ	+322	40§
	λ	+386	...
	μ	+466	90
Hα..........	a	−168	60
	b	−109	60
	c	+89‡	...
	d	+141‡	...
[N II] λ6583...	1	−317	40
	2	−167	60
	3	−102	60
	4	−49	40
	5	−9	30
	6	+21	40
	7	+102	60
	8	+147	50
	9	+232	50
	10	+320	40
	11	+436	70
	12	+511	...

* Measured heliocentric velocity in km s^{-1}. The formal error is about ± 10 km s^{-1}.

† Estimated full velocity width of half maximum intensity in km s^{-1}.

‡ Blended feature.

§ Core of feature.

TABLE 2

NORMALIZED RELATIVE LINE INTENSITIES

Component Velocity*	I([O III] λ5007)	I(Hα)	I([N II] λ6583)	I([N II] λ6548)
−300 (ε, −, 1)...	>7	...	1	...
−170 (−, a, 2)...	...	0.5	1	0.3
−100 (ζ, b, 3)....	5†	0.4	1	0.3
+145 (ι, d, 8)....	3	0.6	1	...
+320 (κ, −, 10)..	>6	...	1	...
All shell A.......	2.7	0.5	1	0.3
All shell B.......	>6.5	...	1	...

* For individual components, ratios refer to the smallest ΔV given in Table 1, i.e., to the core of the feature. Letters in parenthesis refer to the [O III], Hα, and [N II] λ6583 component designations as given in Table 1.

† Line component very broad; intensity is not well defined.

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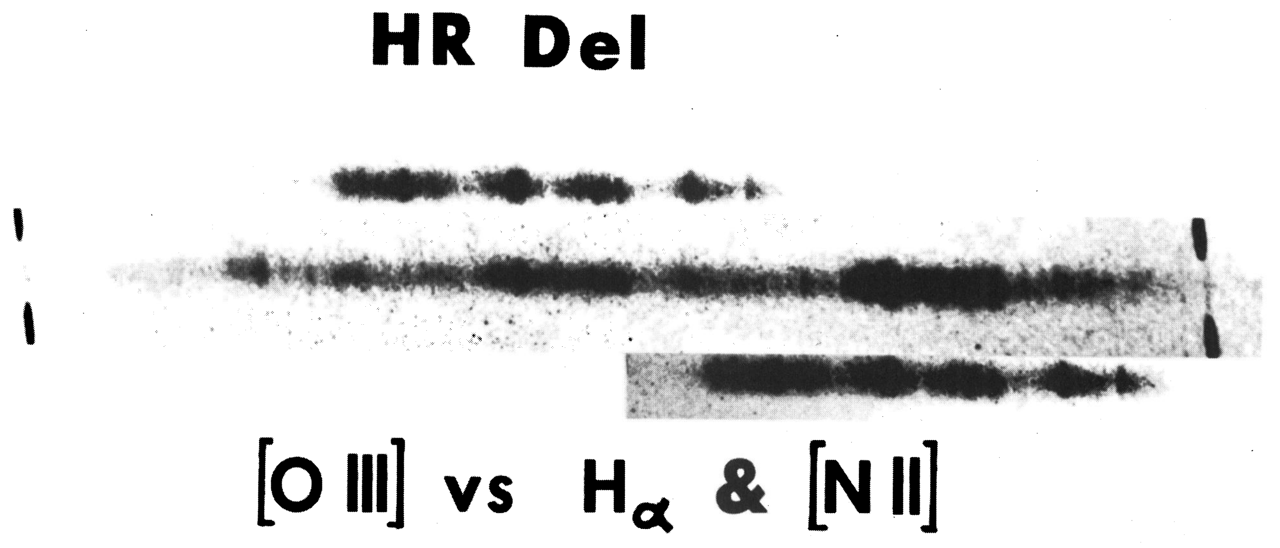

FIG. 1.—Spectra of [N II], Hα, and [O III] in HR Del obtained with the Wisconsin echelle spectrograph using a Carnegie image tube on the KPNO 4 m telescope are shown. The center strip contains (from left to right) [N II] λ6548, Hα, and [N II] λ6583. The upper strip compares [O III] λ5007 with Hα while in the lower strip the same [O III] λ5007 spectrum is reproduced with higher contrast to compare with [N II] λ6583. The [O III] spectra have been printed to match the velocity scale of the red lines. The complex structure of the emission lines and the presence of sharp components can easily be seen on the high contrast IIIaJ plates.

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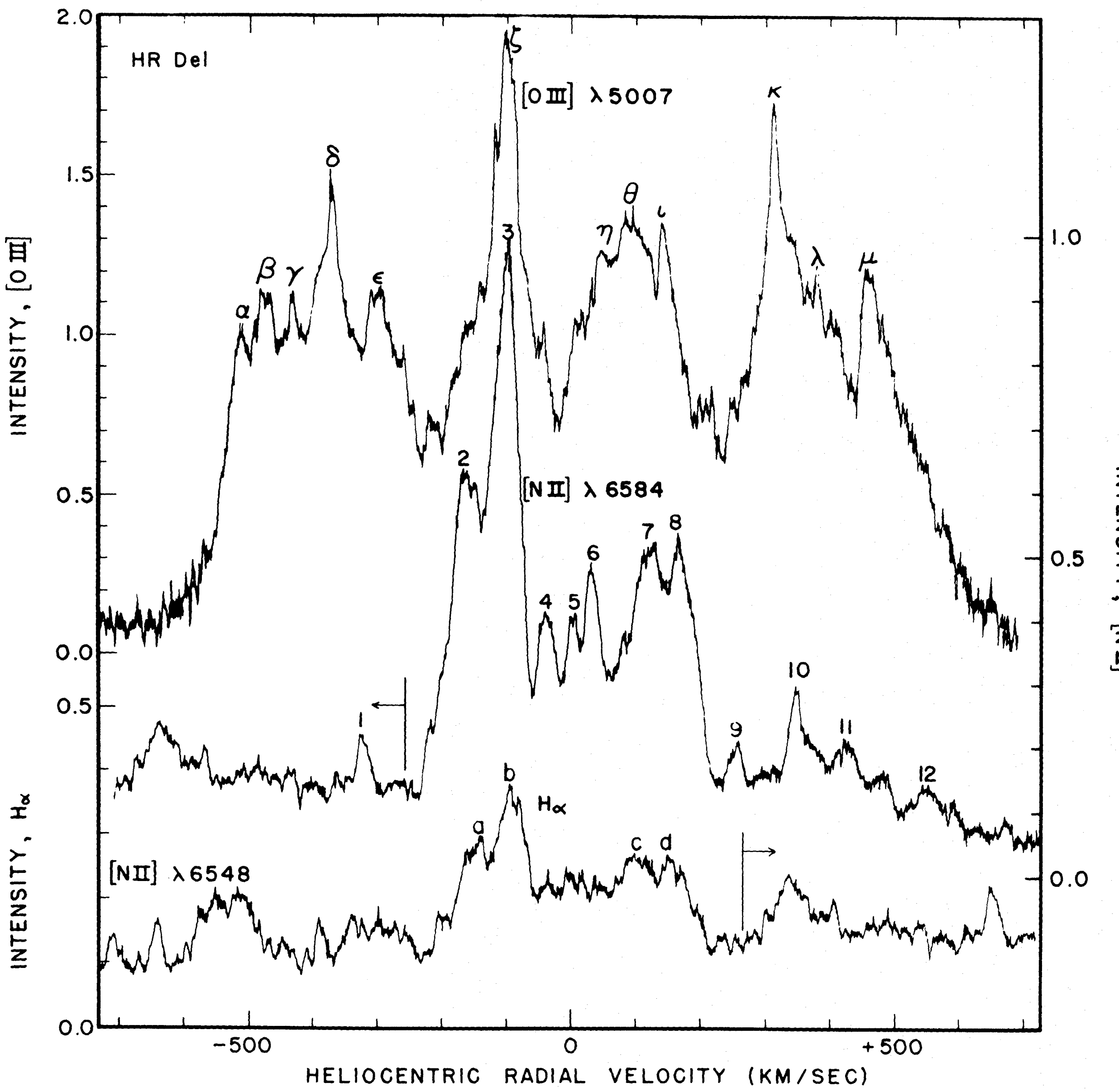

FIG. 2.—Intensity tracings of emission-line profiles corrected for instrumental response. Note that the high positive velocity end of the Hα profile overlaps with the large negative velocities of [N II] λ6583. We have estimated the flux ratios (to within about 50%) between the [O III] and Hα plates and have adjusted the intensity scale accordingly. Line components given in Table 1 are marked.

about 200 km s^{-1} and is centered near ± 100 km s^{-1}, while shell B has a similar velocity width but has $V \approx \pm 400$ km s^{-1}. The two shells are also distinguished by different internal physical conditions as is easily seen from a comparison of the [N II] and [O III] line profiles.

The complex structure which is present in both shells A and B of HR Del indicates the importance of inhomogeneities in the ejected material. Indeed, when photographs are obtained of nova shells (such as those associated with V603 Aql, DQ Her, or GK Per), blobs of material or filaments are usually clearly present (Wyse 1939; McLaughlin 1960; Mustel and Boyarchuk 1970). We therefore feel that it is reasonable to identify individual velocity components with as yet unresolved condensations in the nebula surrounding HR Del. This interpretation is further supported by the radio observations by Hjellming and Wade (1970) and Wade and Hjellming (1971) which show the time-dependent behavior of the free-free continuum to be indicative of a source with a nonuniform surface brightness.

What is surprising about the condensations in HR Del is, however, not that they exist, but that they have such small internal velocity dispersions. For an ionized

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gas with $T \approx 10^4$ K, the sound speed is $\sim$15 km s^{-1}. As can be seen from Table 1, many of the HR Del line components have estimated full widths of between 40 and 60 km s^{-1}, or only a few times the sound speed for $T \approx 10^4$ K. If an ionized gas is expanding into a vacuum, the expansion will occur at a speed near the sonic velocity. Thus, for many forbidden line components, a large fraction of the velocity dispersion can be attributed to the expected expansion of a condensation under the boundary conditions of zero external pressure. The extent of emission in the HR Del line profiles and the absence of sharp Hα emission in shell A indicates that some interblob material may be present, but there is no evidence that this material is hot enough now to exert significant pressure on the denser condensations. We therefore tentatively interpret the presence of sharp line components as an indication that the internal velocities of condensations have not been dramatically affected by the large radial velocities ($\sim$500 km s^{-1}) of matter in the nova shell. This in effect represents a "coherent" acceleration of matter; i.e., the end result of the accelerative process has been to produce high-velocity condensations whose internal conditions are primarily determined not by the acceleration process, but by the local gas temperature and pressure.

Clearly, it would be of some interest to isolate the mechanism which produces condensations in novae. Although our data have unusually good velocity resolution, the existence of similar "coherent" blobs may be seen in the spectra of V603 Aql, CP Pup, and GK Per which are shown by McLaughlin (1960), Sanford (1943), and Wyse (1939).[1] Some information might be obtained by trying to follow the development of individual line components during earlier stages in the nova's development. It is possible that the initial acceleration does, as predicted by the models of Starrfield *et al.* (1974*a*, *b*), impart a velocity dispersion of several hundred kilometers per second to the ejected matter. In this case, condensations must form later in the nova's development, perhaps as a result of thermal instabilities in the ejected material, or from interactions with either circumstellar matter (Fehrenbach and Petit 1969; Sanyal 1974) or the higher velocity "diffuse enhanced" ejecta.

We have therefore tried to follow individual components through the development of the nova. The basic two shell structure is clearly present from early in the nebular stage (Hutchings 1970*b*; Andrillat and Houziaux 1970*a*, *b*, 1971; Sanyal 1974). However, only some of the data by Sanyal (1974) have sufficiently high spectral resolution to allow a meaningful comparison with the individual component velocities in Table 1. In Figure 3 we schematically show the velocity structure of the lines in Figure 2 and compare these with some earlier observations. In 1969 August, Sanyal's spectra show that the small scale velocity structure of HR Del was virtually the same as that in 1974, even though relative intensities of the shell A and B components were quite different from those now measured. The lower dispersion observations of Hutchings (1970*a*) refer to a time early in the nebular stage, which began to appear in late 1968 July. The detailed correspondence between most features is now lost, although both major peaks in shell A seem to be present. For still earlier times we refer to the Ca II absorption velocities during the maximum plateau. Since an expanding shell is involved, the relationship between the absorption velocity and true material velocity is complex (e.g., Hutchings 1970*b*). However, there is some indication that the basic double peaked structure of shell B was already present. Also, there is weak evidence, in the form of a small absorption dip in the Hutchings data from 1967 September 8 to

[1] Nova CP Pup 1942, like HR Del, developed emission lines in which complex structure with velocity widths in the range of 40–100 km s^{-1} was clearly present (Sanford 1947). Furthermore, this structure remained constant in radial velocity as the nova declined during the nebular stage (Sanford and Greenstein 1957). Thus there is no reason to believe the nebular structure of HR Del represents an anomalous event.

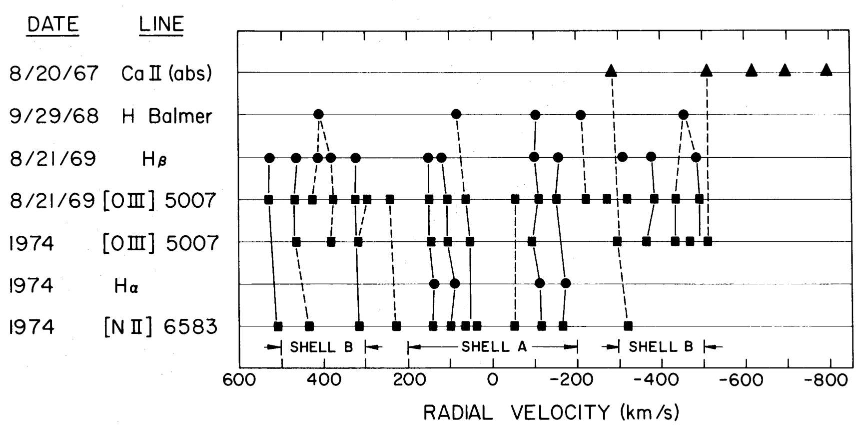

FIG. 3.—Velocity histories for sharp line components in HR Del. The diagram shows the velocities of line components in emission as taken from our data, Sanyal (1974), and Hutchings (1970*a*). The basic velocity structure seems to have been present at least as early as the beginning of the nebular stage. The Ca II absorption velocities from Hutchings do not correlate well with emission components, and prominent high-velocity absorption features are not present in nebular emission lines.

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September 15, that the prominent $-100\ \mathrm{km\ s^{-1}}$ feature had already formed.

The presently available observations therefore *suggest* that the small scale clumping of material in HR Del occurs soon after the initial outburst. However, we do not have sufficient information to allow a decision to be made between fragmentation during the ejection process versus later formation of condensations due to instabilities in the ejected matter. The observations are consistent with one attractive model for the production of condensations in which an instability is produced by the interaction between material ejected from the exploding star and the circumstellar accretion disk. This process might produce inhomogeneities immediately following the initial ejection of matter (Starrfield 1975).

Another aspect of the comparison between the maximum through transition absorption spectrum and the velocity structure of the nebular emission lines concerns the lack of high-velocity emission features. The diffuse enhanced spectrum of HR Del contained prominent absorption lines with radial velocities ranging from 700 to more than 1000 km s^{-1} (Fehrenbach and Petit 1969; Hutchings 1970*a*; Sanyal 1974). Some of these features, as was first noted by Fehrenbach and Petit, appeared very sharp and therefore seemed to be produced in matter with a very low internal velocity dispersion ($\sim 10\ \mathrm{km\ s^{-1}}$). One would not expect such clouds to disperse very rapidly, but they are not detected either in the present data or on 32 Å mm^{-1} Steward Observatory plates which are much more heavily exposed. The absence of sharp, high-velocity nebular emission could be due to several effects: (1) These clouds are too dense to have become ionized (but strong [O I] or [S II] is not presently found in HR Del [Andrillat and Houziaux 1970*a*, *b*; Gallagher 1975]). (2) The high-velocity flow may have contained too little mass to detect. Since diffuse enhanced absorptions are prominent only in very strong lines such as Ca II (McLaughlin 1960), the mass involved is probably small compared with that in the ejecta which produces the principal absorption spectrum (also see Hutchings 1972). (3) The high-velocity material may have been decelerated by an interaction with the principal ejection (e.g., Sanyal 1974). This is especially feasible if the mass involved is small.

Hutchings (1972) and Malakpur (1973) have used the velocity structure of the nebular emission lines to model the spatial distribution of the envelope. Both authors produce models in which the lower apparent velocity of shell A results from material ejected along the polar axis, while shell B originates from ejecta in the equatorial plane of the hypothesized binary. These identifications between polar and equatorial components must, of course, be considered as very tentative, since not even the binary nature, let alone the orientation of the system, has yet been established. The higher resolution measurements reported here add little further information to these geometrical descriptions, except to note that the material is not very uniformly distributed in either shell.

IV. SOME COMMENTS ON PHYSICAL CONDITIONS

With only three line profiles to work from, a complete analysis of the nebular spectrum is impossible. However, our data are sufficient to place some limits on the electron densities in condensations and to show that shells A and B probably have very different internal conditions. It is clear from Figure 2 that individual components of the nova envelope must be considered separately in any meaningful discussion of physical conditions. This important idea is also emphasized by Malakpur (1973) and by Sanyal and Robbins (1975).

In a high-density nebula, collisional de-excitation of forbidden lines becomes important, and the presence or absence of expected emission lines then allows an approximate estimate to be made for the density. Gallagher (1975) shows that the [O II] λ3727 doublet in HR Del is very weak compared to [N II] λ6583. Furthermore, this effect is probably not entirely due to internal reddening, as other ultraviolet region lines such as [Ne III] are relatively intense. Since N^+ has a lower ionization potential than O^+, any region containing N^+ should also contain O^+. The low intensity of the [O II] λ3727 emission is therefore a density effect, as the strong [O III] emission shows that oxygen is probably not severely underabundant (cf. Sanyal and Robbins 1975). When the critical densities for collisional de-excitation of [O II] $^2D_{3/2}$ and [N II] $^1D_2$ tabulated by Osterbrock (1974) are used, the density in shell A probably lies in the range $3 \times 10^3 < N_e \leqslant 8 \times 10^4$. From the extreme weakness of [O II], we finally choose $N_e \approx 5 \times 10^4$ for shell A.

With the present data, physical conditions in shell B can only be very crudely estimated. As can be seen from Figure 2 and Table 2, shell B differs from shell A in that both the $I(\mathrm{H}\alpha)/I(\mathrm{[O\ III]})$ and $I(\mathrm{[N\ II]})/I(\mathrm{[O\ III]})$ ratios are considerably smaller in shell B than in shell A. However, at the same time $I(\mathrm{[O\ III], A}) \approx I(\mathrm{[O\ III], B})$. This is suggestive of higher ionization in shell B, in which case the weakness of [N II] results from an increased ratio of N^{++} to N^+. Such an interpretation is unfortunately not unique, as collisional quenching of [N II] occurs at a density 10 times lower than that required to de-excite [O III] λ5007. It is therefore possible that shell B is simply very dense.

If the condensations in shell B are dense, we might expect to see some effects in the hydrogen recombination spectrum. The intensity of Hα emission from a condensation with volume V^* is

$$I(\mathrm{H}\alpha) \approx \langle N_e N_p \rangle G(T) V^* , \quad (1)$$

where $\langle N_e N_p \rangle$ is an appropriate mean across the condensation and $G(T)$ is the cross section for recombinations leading to the emission of an Hα photon. For temperatures near 10^4 K, $G(T)$ scales approximately as $1/T$. From equation (1) we see that large densities should lead to enhanced Hα emission unless V^* is small compared with the volumes of condensations in shell A or the electron temperature is exceptionally high.

Although the volumes of individual condensations

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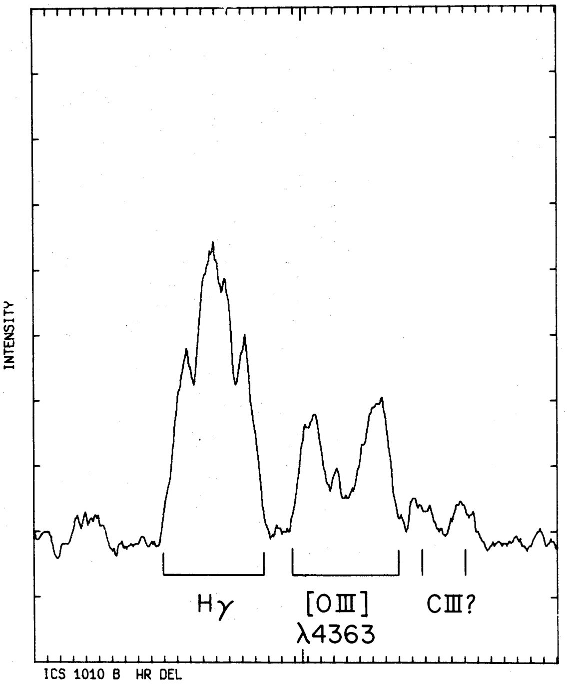

FIG. 4.—Intensity tracing of a 32 Å mm^{-1} spectrum of HR Del obtained with the Cassegrain spectrograph, image intensifier system on the Steward Observatory 90 inch (2.3 m) telescope in 1973 September. Shells A and B are clearly present in both Hγ and [O III]. Although the intensity calibration is only approximate, the flux from [O III] λ4363 increases, while Hγ decreases in shell B relative to shell A.

are not known, it is unlikely that *all* condensations in shell B would be smaller than their counterparts in shell A. The electron temperature is less certain. Figure 4 shows an intensity tracing from a Steward Observatory 32 Å mm^{-1} Cassegrain image tube spectrum of the Hγ region in HR Del. Because of calibration problems, the intensity scale is only approximate. Shells A and B can be clearly identified in both the Hγ and [O III] λ4363 profiles. This and all of the image tube spectra of HR Del obtained in 1973 show the λ4363 emission in shell B to be considerably stronger (~2–3 times) than in shell A (Gallagher 1975). Although we do not have a quantitative [O III] λ4363 to λ5007 intensity ratio, it would seem that the electron temperature of the shell B material must be higher than that for shell A. If we assume shell A has $T_e \approx 10^4$ K (see § V), then, since the intensity of [O III] λ5007 is about comparable in both shells, the electron temperature in shell B could be as high as 15,000 K.

Obviously, this temperature difference alone is insufficient to dramatically reduce the intensity of Hα, especially if the density has been increased to produce collisional de-excitation of [N II] emission. Thus it is probable that shell B does not have high electron densities, in which case the weakness of [N II] is indicative of a higher degree of ionization in shell B than in shell A. This and the larger electron temperature are both consistent with a lower density in shell B which would impede both recombination and cooling. However, as the relative volumes of emitting regions in the two shells are not known, we really cannot directly determine the density ratio between different condensations in the nova envelope.

A serious difficulty in this and other interpretations of the nebular spectra of novae lies in the short time scale of the nova event. The actual duration of the stage of heightened luminosity and the bolometric postnova luminosity are poorly known (Gallagher and Code 1974; Gallagher and Holm 1974). It is therefore possible that the nebula is not in a steady state. Emission lines from various ions may then undergo complex, time-dependent behavior which depends on the history of the nova's development (cf. Bahcall *et al.* 1972). An especially likely effect is "frozen" ionization. Since the nebula is expanding, high stages of ionization which are often prominent during the transition can persist after the nebula has cooled and photoionization ceased. An upper limit to the cooling time t_{cool} can be found by ignoring cooling due to expansion and considering only the radiative loss rate L_R. Let n be the total density, then

$$t_{cool} \leq \frac{(3/2)nkT}{N_e N_p L_R} = \frac{4.2 \times 10^4}{N_e} \text{ yr} , \qquad (2)$$

where the numerical value is based on L_R given by Osterbrock (1974, Fig. 3.2) for a gas with normal abundances and $T_e = 10^4$ K. The recombination time for a fully ionized hydrogen nebula is approximately

$$t_{rec} = \frac{N_p}{N_e N_p \alpha_B(T)} = \frac{1.2 \times 10^5}{N_e} \text{ yr} ,$$

where the numerical values are again for a normal nebula with $T = 10^4$ K. Thus at $T = 10^4$ K we find $t_{cool}/t_{rec} < 0.35$. As N_e drops, L_R becomes larger and thus t_{cool} remains less than t_{rec}. It is also interesting to note that for the adopted shell A density of $N_e = 5 \times 10^4$, $t_{cool} < t_{rec} < 2.4$ yr; the remnant of nova HR Del may still be supplying ionizing radiation to the nebula.

Mustel and Boyarchuk (1971) suggest that frozen ionization is an important cause of the observed differences between polar and equatorial ejecta in DQ Her. The present differences between emission from material in shells A and B in HR Del may also largely result from this or some other non–steady-state process. This viewpoint also receives support from observations made early in the nebular stage by Hutchings (1970*a*) and by Sanyal (1974) which show little difference between the intensity of emission from shells A and B. A more complete set of quantitative measurements is required before it will be possible to distinguish between the hot, high-ionization and non–steady-state models for shell B of HR Del.

V. THE [N II] PROBLEM

Like the nuclei of some galaxies, line components in shell A show an unusual ratio, I([N II] λ6583)/I(Hα) > 1. We have checked to ensure that this is not a result of

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calibration errors. The ratio I([N II] λ6548)/I([N II] λ6583) is fixed by the Einstein A values for the two transitions and must therefore be equal to 0.33 (Osterbrock 1974). As can be seen from Table 2, our data give the correct ratio to within 20 percent for the stronger peaks. We therefore believe the reduction process has yielded reliable results.

Mechanisms which might produce strong [N II] λ6583 emission have been extensively discussed in attempts to understand emission-line ratios in the nuclei of galaxies (for example, see Warner 1973, and references therein). Physically, the I([N II])/I(Hα) ratio depends on at least four factors: (1) the abundance ratio of ionized nitrogen to ionized hydrogen $N(N^+)/N(H^+)$, (2) the electron temperature which controls the population of the $^1D_2$ level of [N II] and therefore the intensity of λ6583 emission, (3) the relative volumes of the N^+ and H^+ Strömgren spheres, and (4) the electron density through the possibility of collisional quenching of the [N II] $^1D_2$ level. From the available observations of HR Del it is not yet possible to make any positive conclusions about the cause of the strong [N II] emission. However, since the data might be indicative of a nitrogen overabundance, further discussion is warranted.

We first consider why factors (2) through (4) may not be important in HR Del. Strong [N II] emission can result from an unusually high electron temperature. However, from Figure 4 we see that for shell A $I(\lambda 4363) \approx 1/5\, I(H\gamma)$, where the intensity ratio is rather poorly determined because of uncertainties in the calibration of the plate. This is near the λ4363/Hγ ratios observed for planetary nebulae which have excitations and densities similar to the envelope of HR Del (Peimbert and Torres-Peimbert 1971*a*; Gallagher 1975). Therefore, it is likely that shell A has rather normal physical conditions with an electron temperature $T_e \approx 10^4$ K. Both Malakpur (1973) and Sanyal and Robbins (1975) also find $T_e \approx 10^4$ K for the mean properties of HR Del early in the nebular stage, although it is not impossible that T_e has inincreased as the nova evolved. To obtain the observed intensity ratio in a uniform nebula with normal abundances we would require $T_e \gtrsim 13{,}000$ K if all nitrogen were in the N^+ ionization stage. However, we must also note that if the temperature of shell A is increased to 13,000 K then the strong λ4363 emission in shell B would require $T_e(B) \approx 18{,}000$ K. This seems unreasonably high, and it is therefore unlikely that the strength of [N II] is entirely due to a high electron temperature.

If the ionization mechanism were such that large amounts of N^+ are produced relative to the hydrogen ionization fraction, then I([N II])/I(Hα) > 1 can occur. This process seems most probable in the vicinity of neutral condensations in the nebula (e.g., Capriotti 1973). Although the nebular spectrum of HR Del is in general characteristic of rather high excitation with pronounced emission from He II λ4686 and the N III λ4640 blend, weak lines of [S II] λ4069, λ4076, and [O I] λ5577 might be present (Gallagher 1975). Thus there is only moderate evidence for ionization stratification. The existence of extensive regions with anomalously large $N(N^+)/N(H^+)$ ratios due to incomplete ionization of H or an unusual ratio of N^+ to N^{++} therefore seems improbable.

A further indication that the strong [N II] emission does not result from unusual local conditions may be found in the constancy of the [N II] to Hα line strength in shell A. From Table 2 we find I([N II])/I(Hα) = 0.5 ± 0.1 both for all measured individual line components and for an integration over all of shell A. If the nitrogen emission is enhanced as a result of the presence of condensations or ionization inhomogeneities, it would seem very fortuitous that the [N II] to Hα line ratios are the same for all of shell A.

The strong [N II] emission might therefore result from a high abundance of nitrogen in the material ejected by HR Del. Obviously, until measurements become available which more definitely show that other effects such as those discussed above are not important, a nitrogen overabundance cannot be rigorously established. The intensity ratio of λ6583 to Hα can be written in terms of a uniform volume emissivity as

$$\frac{I(\lambda 6583)}{I(H\alpha)} = \frac{j(\lambda 6583)}{j(H\alpha)} \approx \frac{N(N^+)}{N(H^+)} AF(T), \qquad (3)$$

where A is a constant containing atomic parameters and $F(T)$ defines the temperature dependence of the ratio. Equation (3) assumes the emitting volumes of H^+ and N^+ are the same for a given line component. If anything, the volume containing H^+ is larger than for N^+, which will tend to further increase the discrepancy of the line ratio.

We now assume $N(N)/N(H) = N(N^+)/N(H^+)$ which gives a lower limit for the nitrogen abundance. Following Peimbert and Torres-Peimbert (1971*b*), we have

$$\frac{N(N^+)}{N(H^+)} = 1.19 \times 10^{-4}(1 + 0.14x) \times T_e^{-0.34} \frac{I(\lambda 6583)}{I(H\alpha)} \exp\left(\frac{22000}{T_e}\right), \qquad (4)$$

where $x = 10^{-2} N_e T_e^{-0.5}$, T_e is assumed to be constant (thus the fractional variation is $t = 0$), and a Balmer decrement $I(H\alpha)/I(H\beta) = 2.87$ (Osterbrock 1974) has been taken. For $T_e = 10^4$ K and $N_e = 5 \times 10^4$, equation (4) yields $N(N^+)/N(H^+) \approx 1.6 \times 10^{-4}$. The cosmic abundance of nitrogen is $N(N)/N(H) = 9.1 \times 10^{-5}$ (Allen 1973). Under the assumption that the strength of [N II] λ6583 in HR Del is *entirely* due to an abundance effect, the minimum nitrogen overabundance would be a factor of 1.7. However, as compared with abundances determined from emission lines in H II regions, the discrepancy increases to about a factor of 3 (Osterbrock 1974). Conversely, total nitrogen abundances for planetary nebulae are, with considerable uncertainty, similar to the lower limit found here (Aller and Czyzak 1968).

Under our present assumptions, only a small change

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in electron temperature is required to bring the nitrogen abundance back to normal. However, the ionization correction factor, which we have ignored, may be quite large. In planetary nebulae with I([O III] λ5007)/I(Hβ) ratios similar to that found in HR Del, the correction for ionization is $N(N^+)/N(N) \approx 0.1$–0.2 (Peimbert and Torres-Peimbert 1971*b*; Gallagher 1975). A nitrogen excess in the shell A ejecta therefore remains as one reasonable explanation of the observed line ratios.

This is not the first indication of a nitrogen overabundance in novae. Antipova (1974) has summarized curve of growth and nebular abundance studies of Nova DQ Her 1934 and Nova V533 Her 1963. In both cases, carbon, nitrogen, and oxygen are enhanced up to 10 times the cosmic abundance. However, nova atmospheres may not be in equilibrium during the early decline and the nebula might not be in a steady state. The basic assumptions behind these methods for finding abundances may therefore not be applicable. Abundances in novae remain at best poorly determined. HR Del, however, offers a good opportunity for resolving the abundance problem for at least N and O. More high spectral resolution observations are therefore planned which will enable a complete study to be made of the strongest line components.

The determination of accurate abundances may also provide an observational test for the theoretical nova models of Starrfield *et al.* (e.g., 1974*a*, *b*). These models attribute the nova outburst to a CNO runaway on the degenerate component in a close binary system. The explosion is triggered by the buildup of hydrogen-rich matter which has been accreted from the other component of the binary. However, the models do not reproduce the observed features of galactic novae unless at least C and O are considerably more abundant than usual, and the resultant ejecta is predicted to have enhanced amounts of C, O, and N. Thus a careful measurement of abundances in the HR Del nebula may provide at least one experimental test for the CNO runaway theory for novae as well as identifying a possible important source for C, N, and O in the galaxy.

VI. SUMMARY AND CONCLUSION

We have made high spectral resolution observations of the Hα, [N II] λ6548, λ6583, and [O III] λ5007 emission lines in HR Del. These lines have considerable structure which probably arises from condensations in the expanding nebula. However, although matter has been accelerated to terminal velocities up to about 500 km s^{-1}, the velocity widths of some components are less than 50 km s^{-1}. It therefore seems likely that the internal velocities of the condensations are largely due to local conditions and have not been strongly affected by the acceleration process. The mechanism(s) which produces such coherently moving condensations has not yet been identified. Further study of this aspect of novae is certainly warranted (and may be relevant to the difficult astrophysical problems posed by the presence of sharp, high-velocity absorption lines in the spectra of quasi-stellar objects, e.g., Morton and Morton 1972*a*, *b*).

The ejecta surrounding HR Del is divided into two velocity groups which we have referred to as shells A and B. It is possible that these groups represent the equatorial and polar ejecta, although the orientation of the nova is still unknown and thus a definite identification cannot be made. The high-resolution spectra clearly show the two shells to have different physical properties. This is somewhat puzzling as such a pronounced difference was not observed in the early nebular stage. Non–steady-state effects may thus be important in the nebula. These in turn introduce additional uncertainties into attempts to derive physical conditions from the observations. Similar effects might be present in other objects having complex emission profiles (e.g., Seyfert galaxies). High spectral resolution measurements of ratios of components in emission lines might therefore yield some interesting results.

If we assume that the nebula is not very far from a steady state, then some preliminary estimates can be made for densities and electron temperatures in the nova shell. Assuming normal oxygen abundances, we have shown that for shell A $N_e \approx 10^{4-5}$, and we argue that T_e is probably rather near 10^4 K. However, the shell B material is more highly ionized and also appears to be hotter and perhaps less dense than shell A. If shell B is indeed the equatorial ejecta, then our observations conflict with the higher equatorial densities predicted by the Sparks and Starrfield (1973) model for nonspherical ejection of matter by novae. Since HR Del has been so well observed, a major effort should be made to determine if it is a close binary and what the orientation of the system is.

Another similarity between HR Del and other interesting objects is the large ratio I([N II] λ6583)/I(Hα) ≈ 2 in shell A. This could be a result of several processes, but since the structure of nova shells is complex and poorly understood, an unambiguous interpretation is not yet possible. However, the data are at least consistent with a nitrogen overabundance by a factor of 2 or more.

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J. S. GALLAGHER: School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455
CHRISTOPHER M. ANDERSON: Washburn Observatory, 475 North Charter Street, Madison, WI 53706

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