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EMISSION LINE VARIATIONS OF NOVA V1500 CYGNI AND THE STRUCTURE OF THE CENTRAL OBJECT

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ABSTRACT

Simultaneous observations of continuum and emission-line variations in Nova V1500 Cygni have been used in the past to measure the light travel time between the central object and the portion of the nebula where the emission lines are formed. These investigations have shown that the phase lags do not increase linearly with time and inferred that the central object is an anisotropic radiator. This paper discusses the conditions affecting the emission lines during early portions of the outburst, and shows that it is not possible to uniquely determine the geometry of the continuum-emitting region from time lag measurements alone. Balmer-line time lag measurements actually determine the distance to the H^+ ionization front, which expands and contracts to maintain ionization equilibrium, rather than to an "average" position in the nebula. The phase lag measurements are further complicated by a large positive velocity gradient across the nebula, as evidenced by differences in the breadths of Balmer and Fe II lines. These two facts can account for the amplitude-wavelength correlation discovered by Hutchings and McCall. Line trapping may also affect phase lags, since the emission lines were optically thick during the early outburst. Within these uncertainties, the phase lag measurements can be reconciled with either the isotropic radiator or the sweeping searchlight model of the central object.

Subject headings: stars: emission-line — stars: individual — stars: novae

I. INTRODUCTION

Nova V1500 Cygni's 3 hour photometric variation is one of the most peculiar phenomena associated with this fast nova's outburst. The 3.3 hour period is typical of orbital periods of close binaries, but it is difficult to understand either the period changes ($P/\delta P \approx 10^2$) or the ill-defined waveform in terms of orbital motion and eclipses alone.

Three models have been proposed to account for the period changes. The first, by analogy with AM Herculis, proposes that the white dwarf was initially in synchronous rotation with the secondary, but that the system left synchronism as a result of the outburst (Semenink *et al.* 1977; Hutchings 1979). A combination of strong magnetic fields and luminous spots brings the system back to corotation and produces the nearby sinusoidal light-curve. One problem with this model is that a significant fraction of the total energy released in a nova outburst must originate from accretion for this model to work. A second model takes advantage of the fact that Nova Cygni's luminosity exceeded the Eddington limit for several months after the outburst (Fabian and Pringle 1977). If the surface of last scattering in the outflowing wind is larger than the binary separation, then a hollow tunnel is swept out by the orbiting secondary, producing a sinusoidal modulation. The apparent period depends only on the expansion or contraction velocity of the surface of last scattering. The third class of models, in which the variation is an intrinsic instability in the luminous member of the system (i.e., pulsation), has generally fallen out of favor since much larger period changes should be produced as the system evolved.

The emission-line profile variations, discovered by Campbell (1976) within a week of the outburst, could constrain models of the origin of the 3 hour variation. The delay time between continuum maximum and maximum at a particular frequency in an emission line is set by the light travel time between the central object and the material producing emission at that frequency, and also by anisotropies in the radiation field of the central object. The phase lag between continuum maximum and maximum at the rest frequency of the emission line is particularly simple, since the line-emitting material is presumably moving at right angles to the line of sight. In this case the phase lag is simply the light travel time between the central object and the nebula. Campbell (1976) obtained good phase coverage on 1975 September 5.2, and showed that his data could be interpreted in terms of an isotropically radiating central object and either an expansion velocity of 1700 km s^{-1} with the expansion beginning several weeks before the observed outburst, or with an outburst time coincident with the optical observations and an expansion velocity of 3000 km s^{-1} (Campbell 1976). Hutchings and McCall (1977) and Hutchings, Bernard, and Margetish (1978) have reinterpreted Campbell's data in terms of a central object radiating as a sweeping searchlight; this model is required if the deduced radius of the ejecta is to increase linearly with time. Patterson (1978) extended the ephemeris for the continuum variation to include the time of the phase lag measurements. This made it possible to directly compare the emission-line and continuum variation (the previous studies had employed only the waveform of the emission-line variation). Patterson concluded that the single beam sweeping searchlight is the preferred model, although models employing an isotropic radiator work nearly as well.

The purpose of this paper is to examine the constraints which photoionization theory imposes upon the interpretation of the emission-line variations. We argue that the Balmer-line phase lag measurements actually determine the distance to the H^+ ionization front rather than to an average position in the ejecta. Since the velocity of this ionization front is only indirectly related to the expansion velocity of the shell, the observation that the phase lags do not increase linearly with elapsed time does not show that the central object is an anisotropic radiator.

Published McDonald Observatory data are used to show that significant differences between the breadths of Balmer and Fe II emission lines existed at the time of the line variations. This difference can be understood in terms of a velocity gradient through the ejecta. The combination of this velocity gradient and the localization of the Balmer-line variability at the H^+ ionization front accounts for the modulation amplitude–wavelength correlation discovered by Hutchings and McCall. A third complication is introduced by the fact that the lines for which we have the best measurements, the Balmer lines, were optically thick during the early outburst (Strittmatter *et al.* 1977). We show that additional phase lags could be introduced by line trapping. We conclude that the interpretation of Nova Cygni's emission-line variations is considerably more complicated than was originally believed, and that it is premature to endorse or reject any specific model on the basis of detailed agreement with the emission-line changes alone.

In § II the physical conditions in the nebula at the time of the phase lag measurements are considered. Specific models of the central object are considered in § III. A decisive test between the two models of the central object is proposed in § IV, and a summary of the new results is given.

II. GENERAL CONSIDERATIONS

In this section we estimate parameters which affect the line-forming region over the period when the phase lag measurements were made. Nova emission lines are generally believed to be formed in a large envelope surrounding the remnant (see Hutchings 1972). This nebula is heated and ionized by the radiation field of the central object. If the density estimated by Ennis *et al.* (1977; $N_e \approx 10^{10}$ cm^{-3}) is correct, then both the cooling time [$\tau_{\rm cool} \approx kT_e/N_e\Lambda(T_e) \approx 1$ s, where $\Lambda(T_e) \approx 10^{-22}$ ergs s^{-1} cm^{-3} is the cooling function taken from Dalgarno and McCray 1972] and the recombination time ($\tau_{\rm rec} \approx (N_e\alpha_B)^{-1} \approx 200$ s) are much shorter than the time scale for the periodic variation ($\tau_p \approx 10^4$ s), so the nebula should be in instantaneous equilibrium, and the ionization will change to compensate for the changing continuum flux.

a) *Luminosity*

Since roughly half of all hydrogen photoionizations produce an Hα photon under most conditions, the Hα flux emitted by the nebula can be used to set a lower limit to the ionizing flux from the remnant. Strittmatter *et al.* (1977) have shown that Balmer lines were optically thick during the early outburst. Netzer's (1975) study of the effects of self-absorption on the hydrogen emission spectrum has shown that, for conditions similar to those in this phase of the outburst ($N_e \approx 10^8$–10^{10} cm^{-3}, $T_e \approx 10^4$ K), the Hα flux will be affected by 20% at most. The absolute calibration of the McDonald data (Tomkin, Woodman, and Lambert 1976) gives an Hα flux of 5.9×10^{-8} ergs s^{-1} cm^{-2} on day 4.6 (following Ennis *et al.* 1977, time is reckoned from 1975 August 28.5), which corresponds to an intrinsic source luminosity of 8.9×10^{37} ergs s^{-1}. This assumes a distance of 1.8 kpc and $E_{B-V} = 0.53$ mag (Ferland 1977). The Hα flux corresponds to 6.4×10^{49} photoionizations s^{-1} or 10^{39} ergs s^{-1}. The actual luminosity is much larger, since we have assumed that each photoionization destroyed a 1.0 ryd photon, we have neglected the (considerable) power in the Balmer continuum of the central object, and the covering factor, which accounts for the fraction of the ionizing photons intercepted by matter, has been set to unity. These factors could easily raise the total luminosity by another order of magnitude. Nova Cygni's luminosity clearly exceeds the Eddington limit ($\sim 10^{38}$ ergs s^{-1}) for a 1 solar mass white dwarf and electron scattering opacity.

The consequences of super-Eddington luminosities have been considered in various models of the nova outburst (see Bath and Shaviv 1976; Bath 1978). Mass loss rates of order 10^{+22} g s^{-1} result (Bath 1978). Because of continued mass loss, the emission lines are likely to be formed in a large envelope (the material above the photosphere) extending to a radius $r_{\rm max} = V_{\rm max}(t - t_0)$, where $V_{\rm max} \gtrsim 3000$ km s^{-1} is the velocity of the most rapidly moving material (§ II*e*).

b) *Ionization Structure*

Balmer lines are formed by recombination in a highly ionized Strömgren sphere within the nebula. Several lines of evidence suggest that the nebula is radiation bounded, so that the outer edge of the ionized zone does not extent to $r_{\rm max}$. This follows since the flux in ionizing photons estimated above is capable of ionizing only 10^{28} grams (the total ejected mass was at least 10^{29} g and probably exceeded 10^{30} g [Patterson 1979]). Strong O I emission was also present during the early outburst (Tomkin, Woodman, and Lambert 1976). O I emission must originate mainly in the H^0 zone because the ionization of O^0 and H^0 are coupled by change exchange (see Williams 1973). A highly ionized Strömgren sphere extends from the remnant to this ionization front. At a typical point

[$r \approx 10^3$ km s^{-1} $(t - t_0)$], the ionizing photon flux is $\varphi_i \geq 3 \times 10^{21}$ s^{-1} cm^{-2} on day 4.6 when the infrared energy distribution suggested $N_e \approx 10^{10}$ cm^{-3}. The photoionization balance equation

$$\varphi_i a_v(\mathrm{H}) N_{\mathrm{H}^0} = N_e N_{\mathrm{H}^+} \alpha_B(T_e) , \quad (1)$$

[where a_v(H) and $\alpha_B(T_e)$ are the photoionization and recombination coefficients] predicts $N_{\mathrm{H}^0}/N_{\mathrm{H}^+} \approx 10^{-6}$. The gas is very highly ionized at a typical point in the Strömgren sphere.

Now consider the effect which a change in the ionizing continuum will have upon the ionization structure and the resulting line emission. Small changes in φ_i have little effect upon the emission ($\propto N_e^2$) from a typical point in the H^+ zone, since the electron density cannot increase. Instead, the Strömgren sphere expands and contracts to maintain the balance between photoionizations and recombinations. (Emission-line variations could not have occurred had the nebula been matter-bounded rather than radiation-bounded.) Because the variation is localized at the H^+ ionization front, the phase lag between continuum maximum and emission-line maximum actually measures the distance between the central object and the H^+ ionization front, rather than the distance to a typical point in the H^+ zone. This difference is important, because the nebula is thick compared with its radius (mass loss was continuing), and because the ionization front can move relative to the material.

The position of the ionization front is set by photoionization equilibrium. The balance equation between the total number of ionizing photons, Q(H), and the number of recombinations in a spherical homogeneous nebula of radius R, is

$$Q(\mathrm{H}) = \tfrac{4}{3}\pi R^3 N_e^2 \alpha_B(T_e) , \quad (2)$$

or

$$R \propto Q(\mathrm{H})^{1/3} N_e^{-2/3} \quad (3)$$

(see Gallagher 1977). Ferland and Shields (1978) found that $N_e(t) \propto (t - t_0)^{-2.3}$, during the nebular phase of the outburst. The ionizing flux Q(H) is likely to be nearly constant during early portions of the outburst, since the McDonald data show that the power in Hα was nearly constant over the first 10 days. The result is that the ionization front, whose position is measured by the phase lags, expands at a rate $dR/dt \propto t^{0.5}$, i.e., the front accelerates.

c) The Fe II *Lines*

In this section observations of Fe II and Balmer-line profiles will be used to infer the existence of a positive velocity gradient across the nebula. Because of this gradient, the variable part of an emission line, which is localized at the outer ionization front, will also be at the largest radial velocity, an effect discovered by Hutchings and McCall (1977).

All phase lag measurements were made during the η Carinae phase of Nova Cygni's outburst. During this phase of the outburst, nova spectra are characterized by strong emission lines of Fe II, Mg II, Na I, and Ca II in addition to the Balmer lines. Portions of scans obtained by Tomkin, Woodman, and Lambert (1976) are shown in Figure 1 and give an idea of the nova spectrum on the three nights when good phase coverage is available.

Ferland *et al.* (1979) have proposed the following scenario to explain nova spectra during the η Car phase. The radiation field of the central object can contain few photons with energies greater than 1.8 ryd, since recombination lines of He I and He II are absent (Tomkin, Woodman, and Lambert 1976). If the radiation field is sufficiently cool, then the bulk of the radiation emitted by the central object will lie longward of 912 Å, and an extensive Fe^+, C^+, H^0 zone will extend beyond the H^+ zone. This outer zone is a likely site for the formation of the optical Fe II lines. This model of the position and production of the H^+, Fe^+ lines is supported by Hutchings, Bernard, and Margetish's (1978) observation that the Fe II and Balmer lines display different phase lags. This is a natural consequence of the fact that the Fe II lines are formed in an outer region of the nebula, beyond the H^+ zone.

If the Balmer and Fe II lines are formed in distinct zones in the nebula, then these lines will have different widths if the expansion velocity is not constant. Figure 2 shows profiles of Hβ and Fe II RMT 42 λ5018 on a common radial velocity scale. The red half of Hβ is blended with Fe II RMT 42 λ4923, but λ5018 is unblended. (Neither He I 5015 nor [O III] 5007, 4959 was present at this time.) The greater breadth of the Fe II line must be entirely intrinsic, since the resolving power of the spectrometer is $\sim 3\%$ greater at λ5018 than at λ4861 ($\delta\lambda = 4$ Å = constant). Evidently the expansion velocity in the Fe^+ region is $\sim 30\%$ larger than that in the H^+ zone.

The origin of the velocity gradient is beyond the scope of this paper, but several possibilities exist. It can be shown that pressure due to the trapped Lα radiation within the cloud greatly exceeded the gas pressure if the estimates of the ionizing flux made above are correct and Lα is broadened by thermal motions (Ferland and Netzer 1979). This pressure would act to produce an internal expansion in addition to the outward acceleration caused by the super-Eddington radiation field of the central object. Alternatively, the material could have been ejected with a spread of velocities.

The modulation amplitude–radial velocity correlation discovered by Hutchings, Bernard, and Margetish (1978) is a direct result of the ionization structure and velocity gradient discussed here. Hutchings *et al.* found that the amplitude of the 3 hour variation was largest in the line wings. This occurs because the H^+ ionization front, the location of the 3 hour line variation, occurs at the largest radial velocity in the H^+ zone. The amplitude-velocity correlation is a direct consequence of our model of the wind, and is an important indication that this sort of picture must be correct.

Two more points must be made. Ferland and

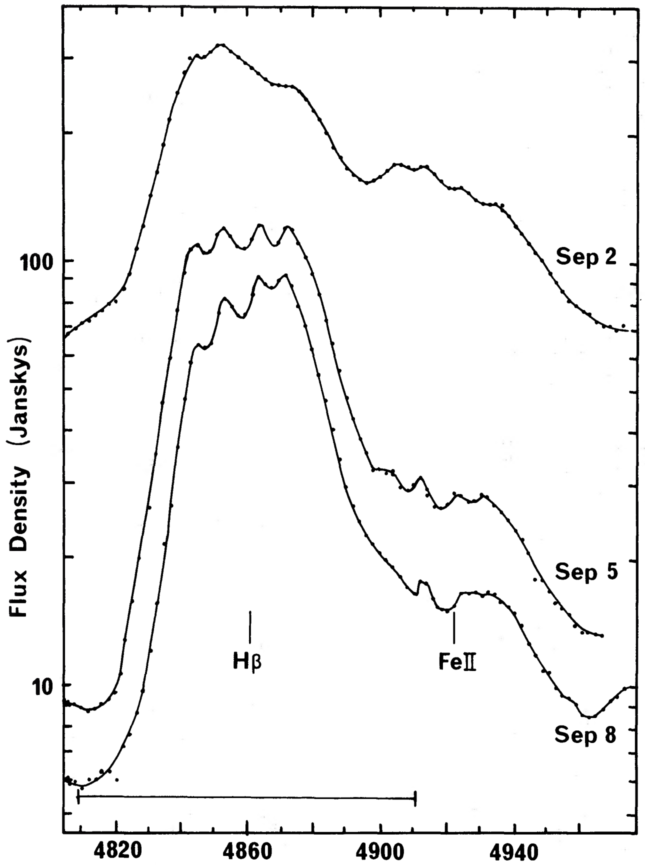

FIG. 1.—The region near Hβ at the times of the emission line modulation studies. The V/R ratio of Hβ varies with time because of Balmer self-absorption (line photons preferentially scatter back toward the central object because of the large opacity in the outward direction). The horizontal bar indicates the wavelength region used by Hutchings *et al.* (1978) to derive the blue-red wing phase shift. The Fe II line at λ4925 is included within this interval.

Shields (1978) found that He II, H I, and O I lines had similar profiles during the nebular phase ($t \gtrsim 40$ days). This shows that the ionized zone extended across only a small fraction of the nebula at that time, and that the total ejected mass must have been much larger than Ferland and Shields measured. Second, although λ5018 is broader than Hβ, the extreme blue wing of each line reaches the continuum at the same velocity, $V_{\max} \approx 3000$ km s^{-1}. This suggests that the high velocity wings of the Balmer lines originate in outer regions of the nebula rather than in a wind near the central object as suggested by Patterson (1979). If the high velocity material is at a greater distance from the central object than the low velocity material, then the absence of a shock-heated region caused by the encounter between the two regions (Shields and Ferland 1978) is easily understood.

d) *Line Transfer*

The best phase lag measurements are of the Balmer lines, which Strittmatter *et al.* (1977) have shown to be optically thick during the early outburst. Line trapping will have several consequences, i.e., a steep Balmer decrement, intense O I 8446 emission (by the Bowen [1947] fluorescence mechanism) and asymmetric line profiles (see Fig. 1). An optical depth in Hα of $\sim 10^2$ is necessary to simultaneously reconcile the 8446/Hα intensity ratio and the Balmer decrement (Ferland and Netzer 1979).

Repeated scattering of Balmer lines will simultaneously smear out the amplitude of the variation and introduce a second phase lag if the distance a photon travels before escaping increases significantly. A comparison between the amplitudes of the line and continuum variations can provide a good indication of the importance of line trapping if the continuum variation is gray (the same amplitude at all frequencies). If the continuum variation is primarily a geometrical effect (as is generally believed), the gray assumption should be valid.

The amplitude of the Hα modulation on day 7 was 5–10% (Campbell 1976). The observed continuum varied by 10–15% at this time (Patterson 1978), but the intrinsic amplitude must be larger, since the optical continuum is a combination of emission from both the central object and the ejecta (Gallagher and Starrfield 1976; Ferland and Wootten 1977). The second continuum should be constant from light travel time arguments. The infrared-optical energy distribu-

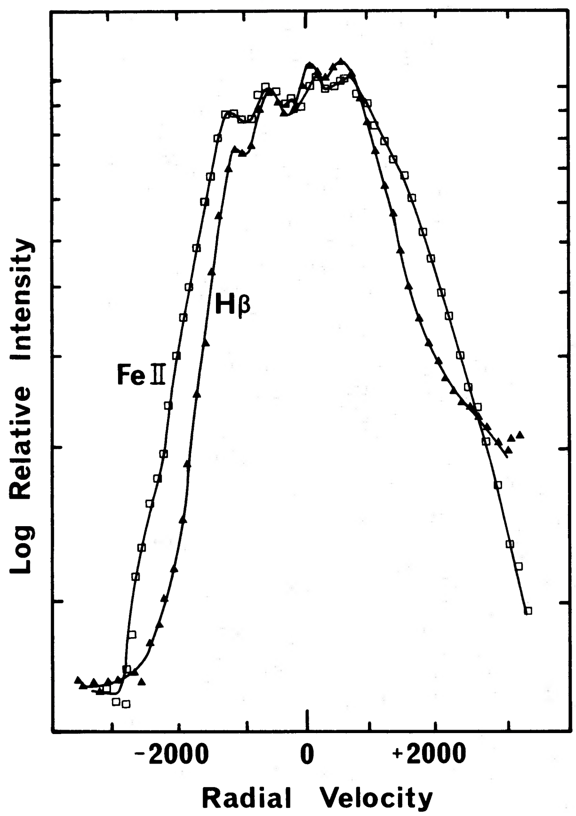

FIG. 2.—Comparison of the profiles of Hβ and Fe II RMT 42 λ5018 on Sept. 8. Although the peaks of the lines lie at the same velocities, the wings of the Fe II line are much stronger than those of Hβ at similar velocities. This is produced by a velocity gradient through the nebula.

tion (Ferland and Wootten 1977) indicates that most of the optical continuum originated in the nebula [I(Nebula)/I(remnant) > 5], so that the intrinsic amplitude of the continuum modulation was 50–100% on day 7, much larger than the line variation.

This argument suggests that line trapping may have smeared out the line variation to some extent. The phase delays introduced by scattering could be significant, since the H^+ zone is thick relative to its radius. Precise estimates of the importance of this effect are not possible without a detailed model of the wind.

e) *Expansion Velocity*

The largest acceptable phase lag is set by the expansion rate, the elapsed time from the onset of expansion, and the geometry of the central source. For instance, Campbell's original model for the system on day 7 requires either an onset of expansion several weeks before the optical outburst and a velocity of 1700 km s^{-1}, or an onset coincident with the optical outburst and a high velocity ($\sim$3000 km s^{-1}). The optical spectrum tells us surprisingly little about the expansion velocity of the ejecta. The absorption lines observed near maximum light are averages over the visible hemisphere of the photosphere, but correspond to $V_{\rm exp}$ = 2300 km s^{-1} when a reasonable correction is made (Barnes 1976). Tomkin, Woodman, and Lambert found that the Na D lines remained in absorption long after Balmer absorption lines had disappeared, and indicated a similar velocity ($\sim$2400 km s^{-1}). These values refer to the principal absorption system. A second velocity system was present at $\sim$4000 km s^{-1} (Duerbeck and Wolf 1977) and Barnes's correction increases this velocity to over 5000 km s^{-1}.

The correction for projection effects on the emission-line velocities is even more uncertain. The half-widths at half-maximum of Hβ and Fe II λ5018 set lower limits of 1750 km s^{-1} and 2400 km s^{-1}, respectively, and the wings of both lines extend to 3000 km s^{-1}. Clearly we must be prepared to accept expansion velocities considerably greater than the canonical value for fast novae ($V_{\rm exp}$ = 1300 km s^{-1}).

It is impossible to determine an expansion velocity accurately, and the question is moot since a unique velocity cannot describe the expansion. This problem is an especially vexing one, since the two fundamental distance indicators for novae, the blackbody and nebular expansion parallaxes, both require accurate expansion velocities. Velocities in the range 2000 km s^{-1} $\lesssim V_{\rm exp} \lesssim$ 5000 km s^{-1} are certainly present in ejecta from Nova Cygni, and the "principal" velocity may be of order 2500 km s^{-1}.

III. MODELS

The phase lag observations can be characterized by two parameters, the blue wing–red wing phase lag and the line center–continuum lag (Patterson 1978). Since a continuum ephemeris is available after day 4 (Semenink *et al.* 1978; Patterson 1978), times of maximum line and continuum emission can be compared directly. The phase lag between the continuum and the rest frequency of an emission line is the simplest to interpret, since matter emitting at the null radial velocity is likely to be moving at right angles to the line of sight. The time lag for Balmer lines is simply the light travel time to the hydrogen ionization front if transfer effects are unimportant.

The second type of measurement determines the time of maximum intensity as a function of wavelength. This time lag depends on both the separation between the approaching and receding ionization fronts and the inclination of these fronts to the line of sight if a ring geometry is assumed. This phase lag–wavelength relationship seems less reliable since it gives greatest weight to the line wings. Emission at extreme radial velocities is more likely to be affected by velocity stratification in the wind and by clumpiness in the ejecta. As an example of the uncertainties, the phase lag–wavelength relationship on 1975 September 5 (Campbell 1976) would have a different slope if only the four peaks of the line were considered (the region between 6540 Å and 6580 Å). Further, the red wing of Hβ includes a strong contribution from Fe II 4923 (see Fig. 1), so timings which rely upon this line are suspect.

Patterson (1978) considered both isotropic and anisotropic continuum modulations (his Table 4)

TABLE 1

LINE CENTER-CONTINUUM PHASE LAGS

Date	$(t - t_0)/P$	φ_{lc}	V_{exp} (km s^{-1})
Sept 2.4...	34.7	1.05	9×10^3
		0.05	4.3×10^2
Sept 5.2...	54.5	1.59	6×10^4
		0.59	3.2×10^3
Sept 8.4...	77.2	2.55	1×10^4
		1.55	6.0×10^3
		0.55	2.1×10^3

TABLE 2

BLUE-RED WING PHASE LAGS

Date	$(t - t_0)/P$	φ_{BR}	sin i
Sept 2.4.....	34.7	0.2 ± 0.2	any
Sept 2.4.....	34.7	0.8	none
Sept 5.2.....	54.5	1.20 ± 0.06	1.03 ± 0.05
Sept 8.4.....	77.9	0.8 ± 0.3[a]	0.7 ± 0.3

[a] Set to twice the blue-wing line-center phase lag.

and found mixed agreement between predictions and observations for all the models, but concluded that a single beam searchlight model was the favored geometry.

Table 1 explores the consequences of interpreting the line center–continuum phase lags in terms of an isotropic radiator. Our purpose is not to demonstrate that an isotropic radiator is the preferred model, but rather to investigate the conditions necessary for this model to work. The line center–continuum phase lag, φ_{lc}, in units of the period P, is

$$\varphi_{lc} = (V/c)[(t - t_0)/P] , \quad (4)$$

where V is the expansion velocity and $(t - t_0)$ the elapsed time from outburst. Table 1 gives the phase lag and elapsed time (Patterson 1978). Various phases (uncertain by integral cycle counts) are assumed, and the expansion velocity found by inverting equation (4). Note that systematic errors in the velocity are introduced when the continuum and line observations do not refer to the same cycle ($\varphi_{lc} > 1$) because the waveform does not repeat well from cycle to cycle (Young *et al.* 1977).

The velocities in Table 1 would be meaningful only if all the material were ejected instantaneously, with a large spread in velocity. It is more likely that mass loss continued long after maximum light, since the system's luminosity was clearly super-Eddington for at least a week. In this case the velocities in the table are lower limits, because the H^+ ionization front lies within recently ejected material. The earliest observations (when the ionization front was closest to the central object) should be most affected by continued mass loss, and the September 2 measurements do give the smallest velocity.

In light of the uncertainties in the physical conditions, it does not seem reasonable to argue that the results in Table 1 rule out an isotropically radiating central object. The sweeping searchlight model completely fails to reproduce the line center variation, since this model predicts either no modulation at the rest frequency (if the duty cycle of the searchlight is sinusoidal) or modulation at twice the period (if the duty cycle is sharply pulsed).

The phase lag between blue and red wing maxima determines a second set of equations. The phase lag between the maxima is given by

$$\varphi_{BR} = 2(V/c)[(t - t_0)/P] \sin i . \quad (5)$$

The inclination i enters if the material lies in a ring (see Hutchings 1972). Table 2 presents the blue-red phase lags and is taken from Hutchings *et al.*, Patterson (1978), and Campbell (1976).

Only the Hα observations (September 5; Campbell 1976) are entirely unambiguous. Both the September 2 and September 8 observations of Hβ are badly blended with Fe II RMT 42 λ4923 (see Fig. 1). The data on September 2 (Hutchings, Bernard, and Margetish 1978) are too sparse to allow a unique phasing, but the $\varphi_{BR} = 0.85$ solution would require a sweeping searchlight, while the $\varphi_{BR} = 0.05$ solution is consistent with an isotropic radiator. The September 8 observations of Hβ have a well determined phase, but the phase lag–wavelength correlation shows a pronounced curvature, probably because of the contribution from the Fe II line.

Campbell's (1976) Hα observations on September 5.2 show that the phase lag between the blue and red wing maxima was twice the blue wing–line center phase lag. The phase lag deduced on September 8.4 ($\varphi_{BR} = 0.8 \pm 0.2$) by doubling the unblended blue wing–line center measurements is significantly different from the observed blue-red phase lag ($\varphi_{BR} = 1.45 \pm 0.08$). This difference is probably caused by the Fe II blend.

Table 2 gives the inclinations derived by inverting equation (5) and taking the velocities given in Table 1. The results are consistent with an inclination near 90° and suggest that the material in the extreme wings is moving nearly directly toward the observer, if the central object is an isotropic radiator.

IV. SUMMARY AND CONCLUSIONS

The aim of this paper has been to examine the conditions under which the Balmer and Fe II lines were formed in the envelope of V1500 Cygni when the rapid line variability was observed. The observations are largely unable to discriminate between the two models for the origin of the variation (an intrinsic, isotropic variation or a geometrical, anisotropic variation). The greatest uncertainty in interpreting the time delay between continuum and emission-line maximum is introduced by the ionization structure of the nebula; the phase lags actually measure the distance to the H^+ ionization front rather than to an "average" position determined by the expansion velocity. The position of this front is set by photoionization equilibrium and is not constrained to move with the matter or to expand at constant velocity. A positive velocity gradient existed across the nebula because Fe II lines are broader than Balmer lines. This gradient accounts for the amplitude-wavelength correlation discovered by Hutchings and McCall (1977). Mass loss is likely to have continued for at least a week after maximum, since the luminosity was clearly super-Eddington during this time. This mass loss will further affect the position of the H^+ ionization front. Additional uncertainties enter because the waveform of the photometric variation did not repeat well from cycle to cycle (the line and continuum measurements usually referred to adjacent cycles) and because of possible phase lags introduced by line trapping.

A decisive test of the two models for the variation is possible in principle. The total power in a recombination line such as Hα should not change if the continuum modulation arises from a geometric effect rather than some intrinsic instability. (This test must be performed before the light travel time across the nebula becomes a significant fraction of the period, of course.) Since Hα emission dominates the Johnson *R* filter (Gallagher and Ney 1976), a comparison of the amplitudes of *R* band and continuum variations would decide the issue. This type of observation should receive high priority should another nova be observed to undergo rapid periodic variations. A second test has already been mentioned. If the nebula is fairly symmetric, then the searchlight model predicts that no variation should be observed at line center. This argument favors the isotropic radiator, but would be invalidated if material perpendicular to the line of sight were anisotropic. In view of these considerable uncertainties, it seems premature to eliminate any class of models on the basis of the emission-line profile observations alone.

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REFERENCES

Barnes, T. G. 1976, *M.N.R.A.S.*, **177**, 53P.
Bath, G. 1978, *M.N.R.A.S.*, **182**, 35.
Bath, G., and Shaviv, G. 1976, *M.N.R.A.S.*, **175**, 305.
Bowen, I. A. 1947, *Pub. A.S.P.*, **59**, 196.
Campbell, B. 1976, *Ap. J.* (*Letters*), **207**, L41.
Dalgarno, A., and McCray, R. 1972, *Ann. Rev. Astr. Ap.*, **10**, 375.
Duerbeck, H., and Wolf, B. 1977, *Astr. Ap. Suppl.*, **29**, 297.
Ennis, D., Becklin, E., Beckwith, S., Elias, J., Gatley, I., Matthews, K., Neugebauer, G., and Willner, S. 1977, *Ap. J.*, **214**, 478.
Fabian, A. C., and Pringle, J. 1977, *M.N.R.A.S.*, **180**, 749.
Ferland, G. J. 1977, *Ap. J.*, **215**, 873.
Ferland, G. J., Lambert, D. L., Netzer, H., Hall, D., and Ridgway, S. 1979, *Ap. J.*, **227**, 489.
Ferland, G. J., and Netzer, H. 1979, *Ap. J.*, **229**, 274.
Ferland, G. J., and Shields, G. A. 1978, *Ap. J.*, **226**, 172.
Ferland, G. J., and Wootten, A. 1977, *Ap. J.* (*Letters*), **214**, L27.
Gallagher, J. S. 1977, *A.J.*, **82**, 609.
Gallagher, J. S., and Ney, E. P. 1976, *Ap. J.* (*Letters*), **204**, L35.
Gallagher, J. S., and Starrfield, S. G. 1976, *M.N.R.A.S.*, **176**, 53.
Hutchings, J. B. 1972, *M.N.R.A.S.*, **158**, 177.
Hutchings, J. B. 1979, *Ap. J.*, **230**, 162.
Hutchings, J. B., and McCall, M. 1977, *Ap. J.*, **217**, 775.
Hutchings, J. B., Bernard, J., and Margetish, L. 1978, *Ap. J.*, **224**, 899.
Netzer, H. 1975, *M.N.R.A.S.*, **171**, 395.
Patterson, J. 1978, *Ap. J.*, **225**, 954.
———. 1979, *Ap. J.*, **231**, 789.
Semenink, I., Kruszewski, A., Schwarzenberg-Czerny, A., Chlebowski, T., Mikolajewski, M., and Wolczyk, J. 1977, *Acta Astr.*, **27**, 301.
Shields, G. A., and Ferland, G. J. 1978, *Ap. J.*, **225**, 950.
Strittmatter, P., *et al.* 1977, *Ap. J.*, **216**, 23.
Tomkin, J., Woodman, J., and Lambert, D. L. 1976, *Astr. Ap.*, **48**, 319.
Williams, R. E. 1973, *M.N.R.A.S.*, **164**, 111.
Young, P., Robinson, E., Africano, J., Ferland, G., and Woodman, J. 1977, *Pub. A.S.P.*, **89**, 37.

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