7. This line, which on 1965 (Paper I) was outstanding in the infrared (est. int. 30) has been steadily fading. Already weak on 1967, further declined and in the last 1971 spectra is barely visible. The weakening of this line, excited by a resonance effect due to Ly_β indicates that, with the increasing degree of ionization, most of the OI atoms have been ionized.
8. The strength of this line has been increasing from 1969 to 1971. The same strengthening has been noticed in the [SIII] line λ 9532, in the 2F line 6310 and in the 3F lines 3721—3796.
9. The shortest wave-length line of the blend ([SIII]) appears to be the main contributor. The two infrared [SIII] lines 9069 and 9532 are outstanding in the spectra of planetary nebulae, like NGC 7027.
10. Very strong on planetary nebulae of high excitation.
11. A slight fading has been noticed from 1969 to 1971.
12. It is the strongest line in the extreme infrared spectrum.

V 1016 Cygni, Spectral Observations 1968—1971

M. PIM FITZGERALD (Waterloo, Ontario)

Abstract

Identification of approximately 230 emission lines between 3120 Å and 5045 Å have been made on twelve plates taken between 1968 and 1971. The line intensities and ratios fail to give a consistent detailed picture of the nebula, but indicate that on average the electron pressure and density have changed little. The Balmer decrement has become less steep since 1968, indicating higher optical depth. However, the permitted iron lines have completely gone, indicating lower density. Excitation is increasing in some parts of the nebula, as indicated by the increased strength of the [Fe V] lines, and the recent appearance of strong lines of [Ne V]. The continuum remains weak, though it is easily seen on plates taken on April 8, 1969, and on those taken in June 1971. The radial velocity of the object fluctuates between −50 and −70 km/sec, and the line widths remain about 120 km/sec. The wing to the violet of the emission lines is still present. The continued brightness of this object, and the relative lack of change in the spectrum over several years, indicate even more strongly that V 1016 Cygni is likely to be a planetary nebula in the stages of formation.

I. Introduction

The peculiar emission object V 1016 Cygni, discovered by McCUSKEY (1965), has continued to be of interest to several people (BOYARCHUK, 1967; FITZGERALD et al., 1966, 1969, 1970), MAMMANO and ROSINO (1966, 1968); and O'DELL (1967, 1968). It is not the purpose of this paper to present a massive list of figures on the more than 230 emission lines now identified on plates taken at the Warner and Swasey Observatory (130 Å/mm, and objective prism) and the David Dunlap Observatory (12 Å/mm and 40 Å/mm), but rather to touch on a few of the more interesting results found for this object. A more detailed paper will be prepared at the end of this observing season.

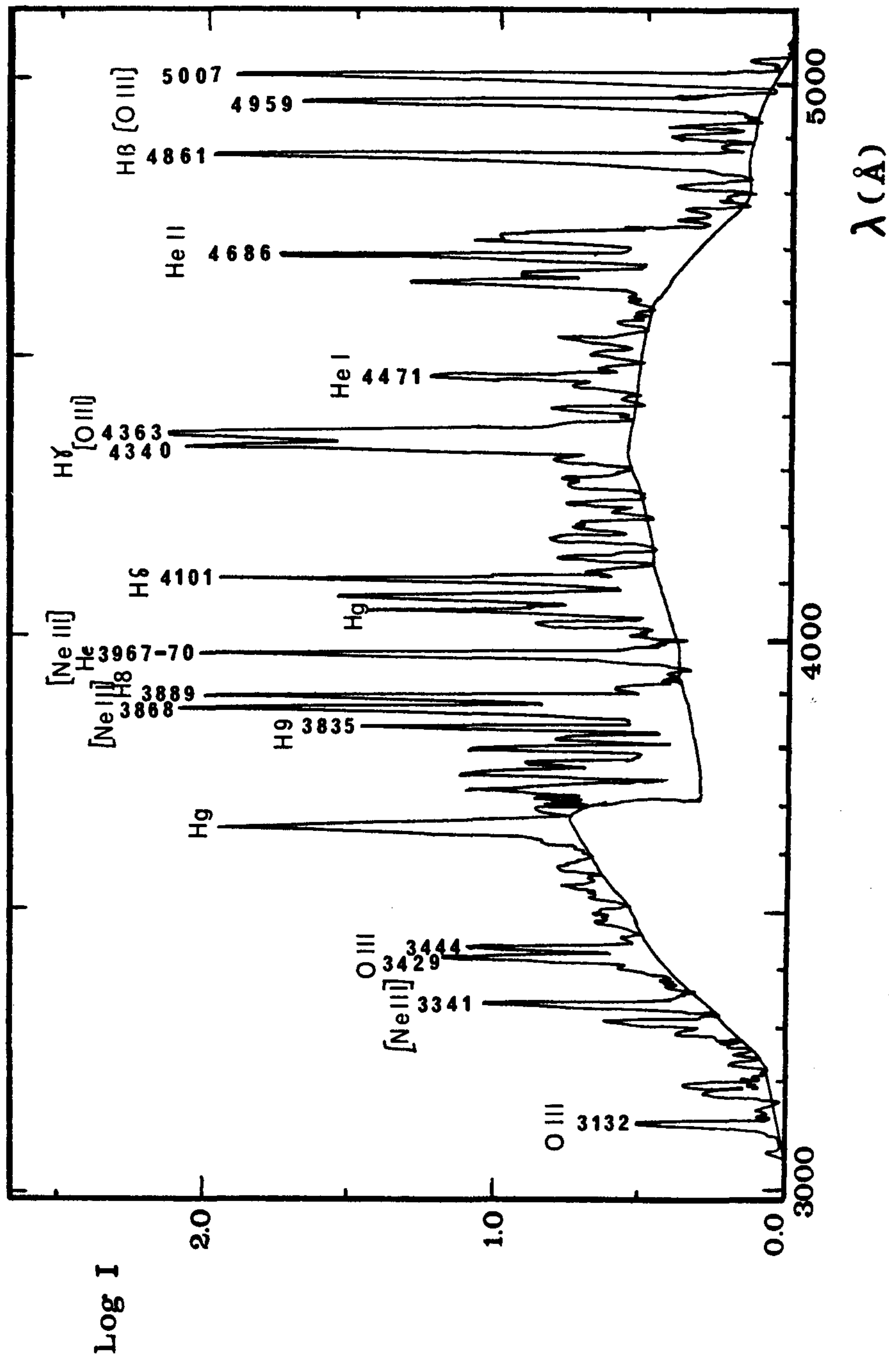

Fig. 1: V 1016 Cygni (1969, Apr. 8). This tracing was made using a very wide slit on the microdensitometer in order to enhance the continuum with respect to the emission lines.

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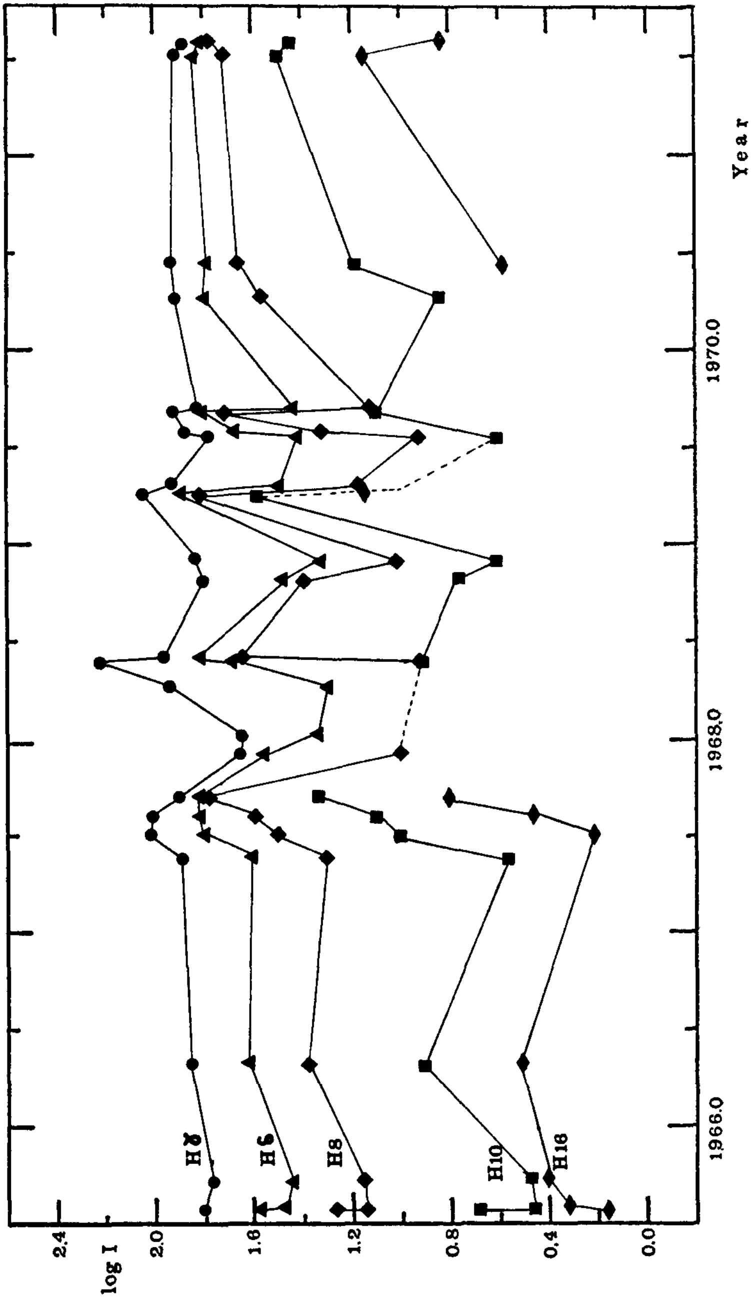

Fig. 2: Variation in log I for H_γ, H_δ, H_8, H_{10}, H_{16}. log I ($H\beta$) = 2.00.

When first discovered by McCUSKEY (1965) the object was thought to be a rather extreme example of a symbiotic star. Its pre-outburst spectra showed it to be a late M star with Hα emission of about $m_{pg} = 15^m$ or fainter. In 1964 its brightness increased to $m_{pg} = 12\overset{m}{.}8$, and it had reached $V = 11\overset{m}{.}7$ by 1966. Since then it has continued to brighten slightly. BAKOS (1971) gave magnitudes and colours of $V = 10\overset{m}{.}47$, $B-V = 0\overset{m}{.}05$, and $U-B = -0\overset{m}{.}13$ for April, 1971. While such results cannot strictly be intercompared for different observers (PHILIP, 1968); BAKOS' measurement definitely indicates a further increase in magnitude.

Since 1965 the spectrum of V 1016 Cygni has undergone some changes. Most noticeable was the change of the band seen around 4680 Å to the lines of He II λ 4686 and other elements, occuring by 1967. No indication has been seen on our plate material for a return to an M-type spectrum however. The persistence of the emission spectrum over so long a period has led both MAMMANO and ROSINO (1968), and FITZGERALD and HOUK (1970) to conclude the object is likely to be a planetary nebula in the making. The lack of large changes in the spectrum between 1968 and 1971 tends to strengthen this hypothesis.

II. Spectral Observations

Since 1968 we have taken twelve plates of V 1016 Cygni. Of these, the deepest have been those taken on April 8, 1969 (WARNER and SWASEY, 130 A/mm) and on June 16 and 30, 1971 (David Dunlap Observatory, 40 A/mm). The continuum is visible on all three plates, being particularly strong between 4300 and 4700 Å, and in the Balmer continuum. A log intensity tracing of the plate of April 8, 1969 (uncorrected for spectral sensitivity or interstellar absorption) is shown in Figure 1. The tracing was made using a very wide slit, so that only the strongest lines appear. The ratio $D = \log \frac{I(\lambda < 3650)}{I(\lambda > 3650)}$ (ALLER and LILLER, 1968) is less than 0.55 implying $T_e < 25{,}000$.

Line identifications of some of the stronger or more interesting lines are given in Table I. Plots of the variation of line intensity with respect to Hβ (Log I (Hβ) = 2.00) are shown in Figure 2 to 5 for several lines of H, He, [OII], [OIII], [NeIII], [NeV], [SII], and [FeV]. Apart for the numbers given in brackets in Table I (at right hand side) all intensities are uncorrected for spectral sensitivity and interstellar reddening. The intensities in brackets are corrected for spectral sensitivity and based on the plates of July 31 and Aug. 7, 1969. The correction procedure was described by FITZGERALD and HOUK (1969).

Elements of particular interest are discussed below, in order of atomic number. All emission lines were identified with the use of MOORE's (1945) Multiplet Tables and the Catalog of Emission lines of MEINEL et al. (1969).

Hydrogen. — Since November 1968 Hγ has remained relatively constant, but all other hydrogen lines have increased in strength by 0.4 to 0.7 in log I. This increase has been relatively steady with some noticeable fluctuation. The plate of April 8, 1969, for example, showed the lines of Hγ to H 20 to be particularly strong, having intensities comparable to those found for the lines in 1971. This effect could be due to the emulsion (the Kodak Ia O plate was uncalibrated and a standard sensitivity curve for IIa O plates used) but more likely represents a real change in the object at about that time. The change in the hydrogen line strengths between Nov. 1968 and June 1971 is in the sense that the Balmer decrement flattened (as in the change for April 1969). A decrease in the Balmer decrement is consistent with increased optical depth and hence increasing density in the emitting region. The nebula is still fairly optically thick to hydrogen radiation, as found by O'DELL (1967).

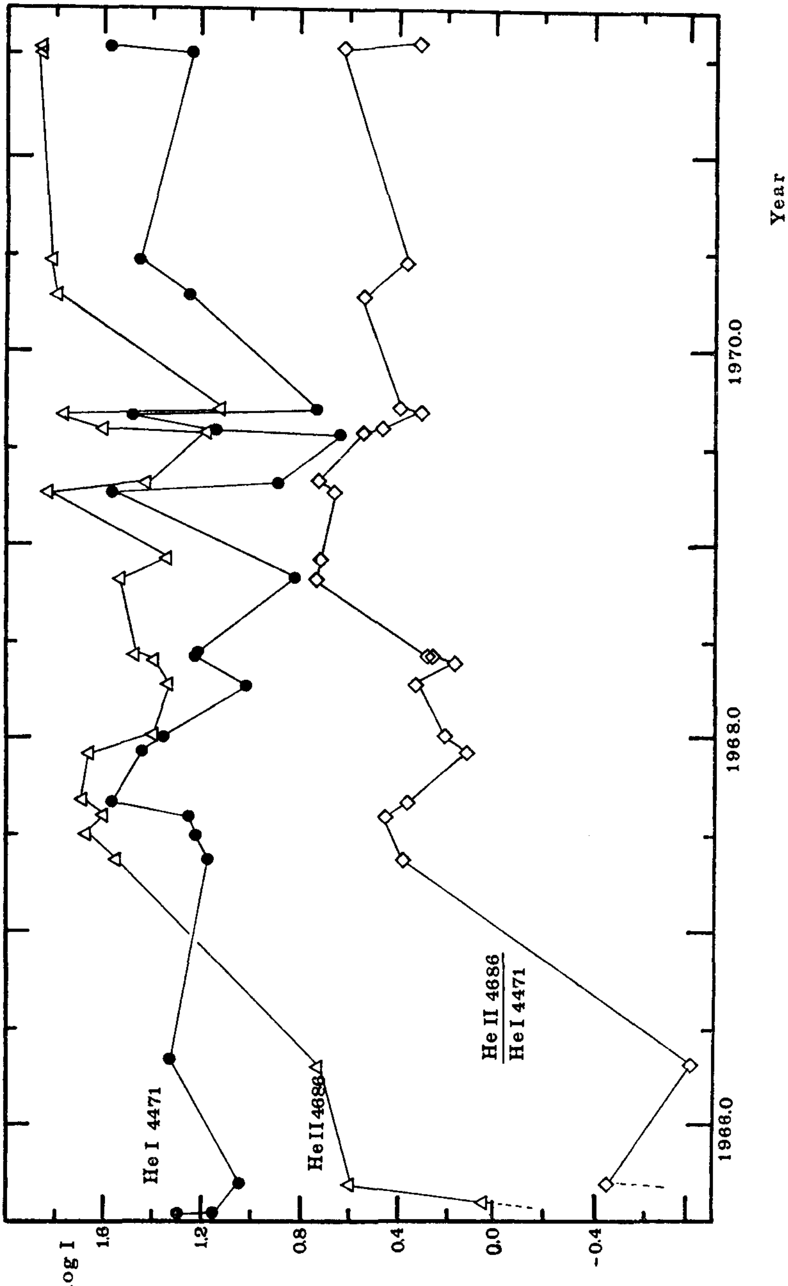

Fig. 3: Log I for Helium, log I (Hβ) = 2.00.

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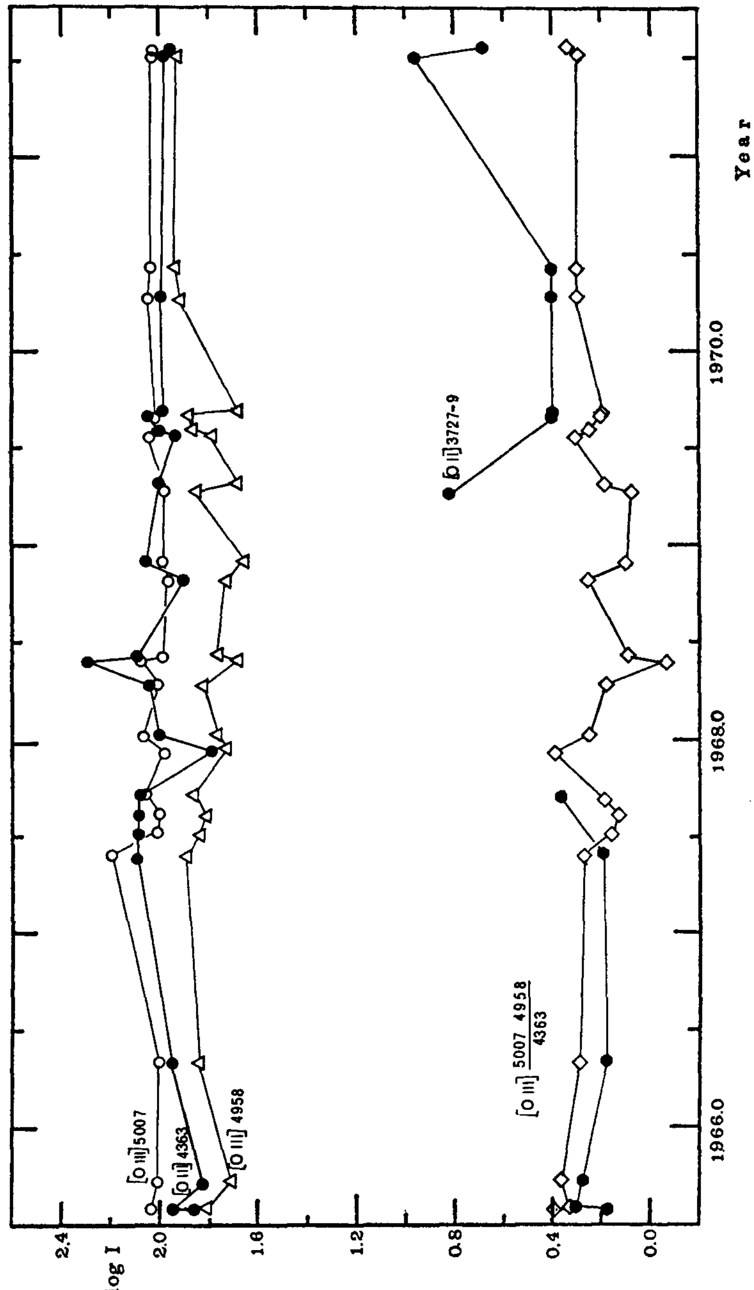

Fig. 4: Variation in log I for Oxygen, log I (Hβ) = 2.00.

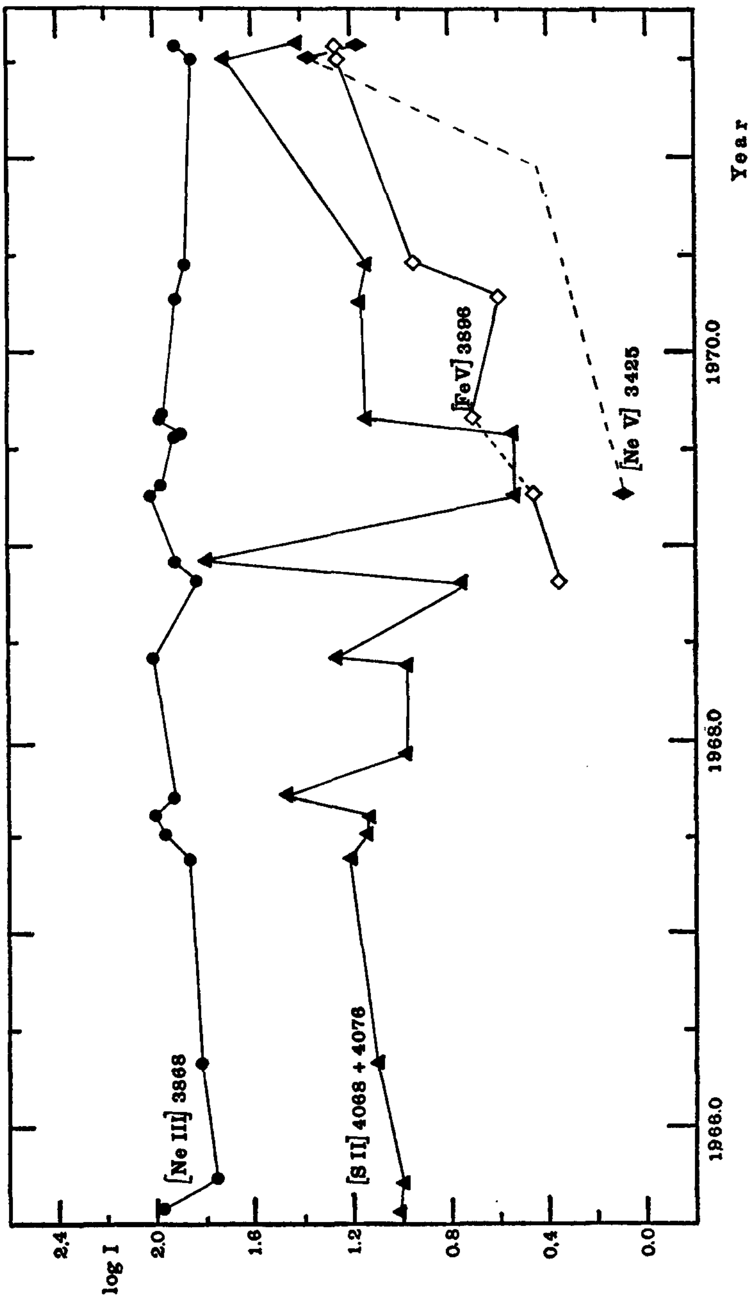

Fig. 5: Variation in log I for [NeIII], [NeV], [SII] and [FeV]. log I (Hβ) = 2.00.

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Table I: Log I, uncorrected for spectral intensity, for some lines of interest. Estimates shown in brackets at the end of the table have been corrected for spectral sensitivity and are based on two plates taken in July and August, 1969. Most of the log intensities given are average values from several plates for the period noted. Those from single plates are denoted by *.

Measured Line (Å)		1965	1966	May-July 1967	Aug.-Sept. 1967	1968	* Apr. 1969	May-July 1969	Aug.-Nov. 1969	* Apr. 1970	* June 1970	June 1971	July-Aug. 1969
	Dispersion (Å/mm)	130	130	130	130	130 / 12	130	12	12 / 40	40	40	40	12
	Identification												
3132.8	O III-2				0.55		1.20						
3342.1	Ne III-2F			0.60	0.74		1.30						
3345.5	Ne V-1F						0.79						
3425.72	Ne V-1F						v wk					1.29	
3444.18	O III-15			0.94	1.02	0.79	1.48		0.70			1.36	
3686.72	H 19			0.45	0.46	vwk	0.88		vwk			0.50	
3703.70	H 16	0.29	0.50	0.32	0.62	vwk	1.16		vwk		0.58	0.99	
3725.72 / 3729.09	O II-1F	0.25	0.18	vwk	0.47		0.83		vwk / vwk	vwk / vwk	vwk / vwk	0.70 / 0.25	
3734.52	H 13	0.24	0.50	0.30	0.80	wk	1.19	vwk	0.46	0.54	0.66	1.11	
3750.11	H 12	0.36	0.53	0.50	0.86	0.49	1.25	wk	0.54	0.60	0.98	1.10	
3759.65	O III-2	0.18	0.34	0.48	0.62	0.28	1.32		wk	0.36	1.02	1.20	
3797.89	H 10	0.54	0.90	0.78	1.22	0.84	1.58	0.60	1.10	0.84	1.18	1.48	(0.64)
3819.95 / 3820.11	He I-22 / Fe V-3F	0.26	0.43	0.36	0.75	0.46	1.16		0.54	0.36	0.92	1.15	
3833.72	H 9	0.75	1.06	0.91	1.33	0.96	1.62	0.79	1.20	1.04	1.38	1.48	(0.77)
3839.98	Fe V-3F				vwk	vwk	0.98	0.33	0.37	0.54	0.96	1.30	(0.30)
3868.79	Ne III-1F	1.79	1.83	1.93	1.98	1.94	2.04	1.95	2.00	1.94	1.90	1.90	(1.91)
3888.86	H 8	1.19	1.38	1.41	1.69	1.35	1.83	1.30	1.41	1.57	1.66	1.76	(1.26)
3895.90	Fe V-1F			0.30	wk	0.36	0.46	wk	0.72	0.60	0.95	1.28	
3967.33 / 3970.24	Ne III-1F / Hε	1.42	1.62	1.82	1.52 / 1.24	1.48 / 0.99	1.98	1.63 / 1.15	1.76 / 1.28	1.75 / 1.36	1.87 / 1.30	1.89 / 1.44	(1.70)
4068.49	S II-1F	0.70	0.78	0.98	1.02	0.80	1.67	0.4	1.07	1.10	0.94	1.40	(0.25)
4101.65	Hδ	1.50	1.62	1.70	1.83	1.58	1.90	1.52	1.61	1.80	1.79	1.84	(1.50)
4340.36	Hγ	1.80	1.86	1.96	1.96	1.91	2.06	1.88	1.88	1.92	1.94	1.90	(1.71)
4363.19	O III-2F	1.88	1.96	2.11	2.10	2.09	2.21	2.00	2.03	2.01	2.00	1.98	(1.83)
4471.68	He I-14	1.16	1.33	1.20	1.41	1.07	1.58	0.92	1.11	1.25	1.46	1.82	(0.76)
4685.65	He II-1	vwk	0.74	1.62	1.65	1.43	1.84	1.41	1.45	1.79	1.82	1.86	(1.24)
4861.28	Hβ	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	(2.00)
4958.80	O III-1F	1.80	1.85	1.88	1.86	1.76	1.87	1.79	1.80	1.93	1.95	1.95	(2.01)
5006.83	O III-1F	2.05	2.02	2.12	2.05	2.03	2.00	2.05	2.02	2.07	2.05	2.04	(2.51)

Helium. — The general tendency for the lines of He I to decrease in intensity, which started in 1967, has continued. A few lines of He I (notably λ 4143 and λ 4026) have increased in intensity however. The lines of He II have increased in intensity on the whole, indicating an increasing excitation in the nebula between 1968 and 1971. The two strongest Helium lines, He II λ 4686 and He I λ 4471 have both tended to increase relative to Hβ since August 1969, after a decline in intensity which had been fairly steady since 1967.

The intensity ratio (He II λ 4686)/He I λ 4471) reached a maximum in late 1968, and declined to a minimum by August 1969. It is now rising again. This indicates that the ex-

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citation has been variable over the last few years. On average, however, it has increased since 1968, though not as markedly as it did between 1966 and 1967.

Oxygen. — The lines of O II are only faintly visible and continue to fade. The forbidden lines of [O II] $\lambda\lambda$ 3727 and 3729 were definitely present on the better exposed plates. However the intensity ratio λ 3729/λ 3727 was about 0.4, close to the limiting value (ALLER and LILLER, 1968) indicating very high density Ne $\sim 10^6$ to 10^7 elect./cm^3 as found by MAMMANO and ROSINO (1966). The strengths of these lines relative to [O III] are apparently increasing, indicating decreasing density. The lines of O III, while mainly visible only on the better exposed plates, must be extremely strong. For instance λ 3133 had log I = 1.20 in 1968. Other O III lines (such as λ 3429, 3431, 3444 and 3759) are also very strong and getting stronger. The forbidden line [O III] λ 4363 has remained approximately constant since 1968, whereas the lines $\lambda\lambda$ 4958 and 5007 have increased slightly since 1968, implying decreasing electron temperature. This reverses the trend present until late 1968. The ratio $\frac{I(\lambda\,4958) + I\,(5007)}{I\,(\lambda\,4363)}$, equal to 4.6 in 1968, implies electron densities between 10^6 and 10^7 elect./cm^2 (O'DELL, 1967).

Neon. — The [Ne III] line λ 3868 has remained approximately constant, though the blended line λ 3967 has possibly increased in intensity since 1968. The lines of [Ne IV] $\lambda\lambda$ 4714 and 4724 have strengthened noticeably. They were especially strong on the plate of April 8, 1969, but otherwise increased uniformly since 1968 by about 1.0 in log I. The lines of [Ne V], in particular λ 3425, which were not seen prior to 1968, are now very strong, indicating a rather large change in excitation.

Sulphur. — Sulphur is represented by the [S II] lines $\lambda\lambda$ 4068 and 4076. In 1970 these lines reversed their decline in intensity started after reaching a maximum in late 1967. By 1971 they had returned to their 1967 levels, implying an increased density.

Iron. — The decline in strength of the permitted iron lines has continued. Few, if any, are visible in 1971. Of the forbidden lines those of [Fe II] have changed little since 1968, possibly decreasing slightly. Those of [Fe III] have increased noticeably, and those of [Fe V], first seen in 1967, are not quite as strong. The lines of [Fe IV] (BLOCH and SWINGS, 1969) have decreased slightly. [Fe VI] is represented by the 2F multiplet. The general intensity increase in the forbidden lines of higher ionization of iron and the fading of the permitted lines, is indicative of a decrease in density and/or an increase in electron temperature.

Other elements. — Among the other elements present are C, N, Mg, Si, Ar, Sc, Ti, Cr and Ni.

Molecular lines. — On the plates of April 8, 1969 and June 1971 faint air-glow lines of O_2 are definitely present. Somewhat surprising are nine faint lines appearing on the plate of June 30, 1971, which are coincident with the lines of Al H commonly found in emission stars. These lines are otherwise unidentificable. Most of the brighter lines of Al H appear, or are blended, in the spectrum. Since most lines this faint are either identified with other multiplets or with unidentified lines previously seen in planetary nebula or symbiotic stars, it is believed that Al H is probably present even though the identification is from only one plate.

III. Line Structure and Radial Velocity

The general appearance of the lines, which was characterized by a noticeable wing to the violet side in 1968, has changed little. A close inspection of plates obtained at 12 A/mm indicates that the violet wing was possibly separated from the main part of the line by a very narrow absorption-like feature. This is not interpreted as absorption, probably results from structure in the nebula. Analysis of a plate taken on July 29, 1971, at 12 A/mm, indicates that the violet wing is still present (several lines are shown in Figure 6). If any change has taken place in the wings, it has been to strengthen them slightly. The line widths remain about 40 km/sec to the red side, and 80 km/sec to the blue side of the densest part of the line, or very slightly larger.

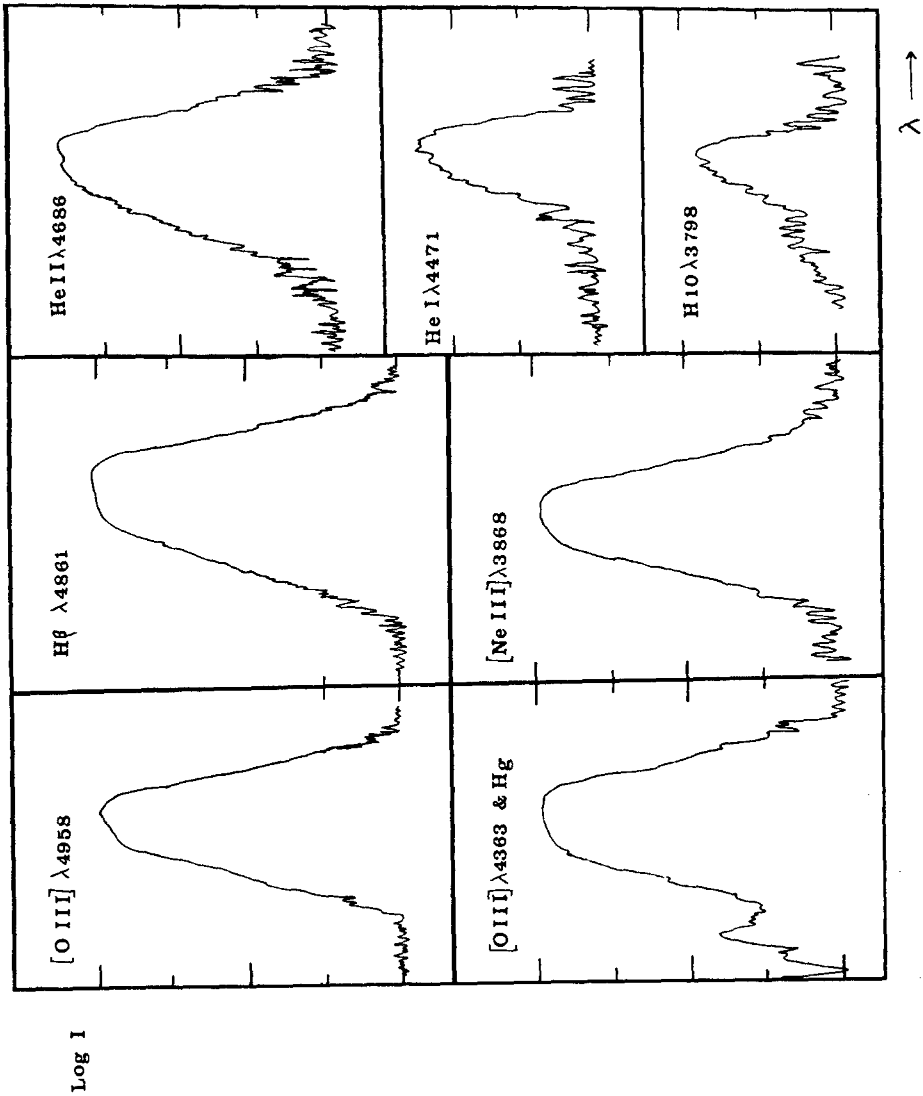

Fig. 6: Log I tracings for July 30, 1971.

Further evidence that the nebula is becoming rather complex comes from the radial velocities found from the David Dunlap Observatory plates. Velocities have been measured from the lines of hydrogen, helium, [O III] and [Ne III] lines. No systematic difference from the mean velocity was found for any multiplet. In Figure 7 are shown the resulting radial velocity measures since 1966. In this figure the point indicated by an open circle was from the 130 A/mm plates, using the Mercury night sky lines as reference lines. The points designated by triangles are from MAMMANO et al. (1966, 1968). The apparent variability of the radial velocity is not easy to explain. It is not possible to correlate it successfully with observations of changes in the line intensities, but it is probably related to changes in emission rate in different parts of the nebula, having different velocities.

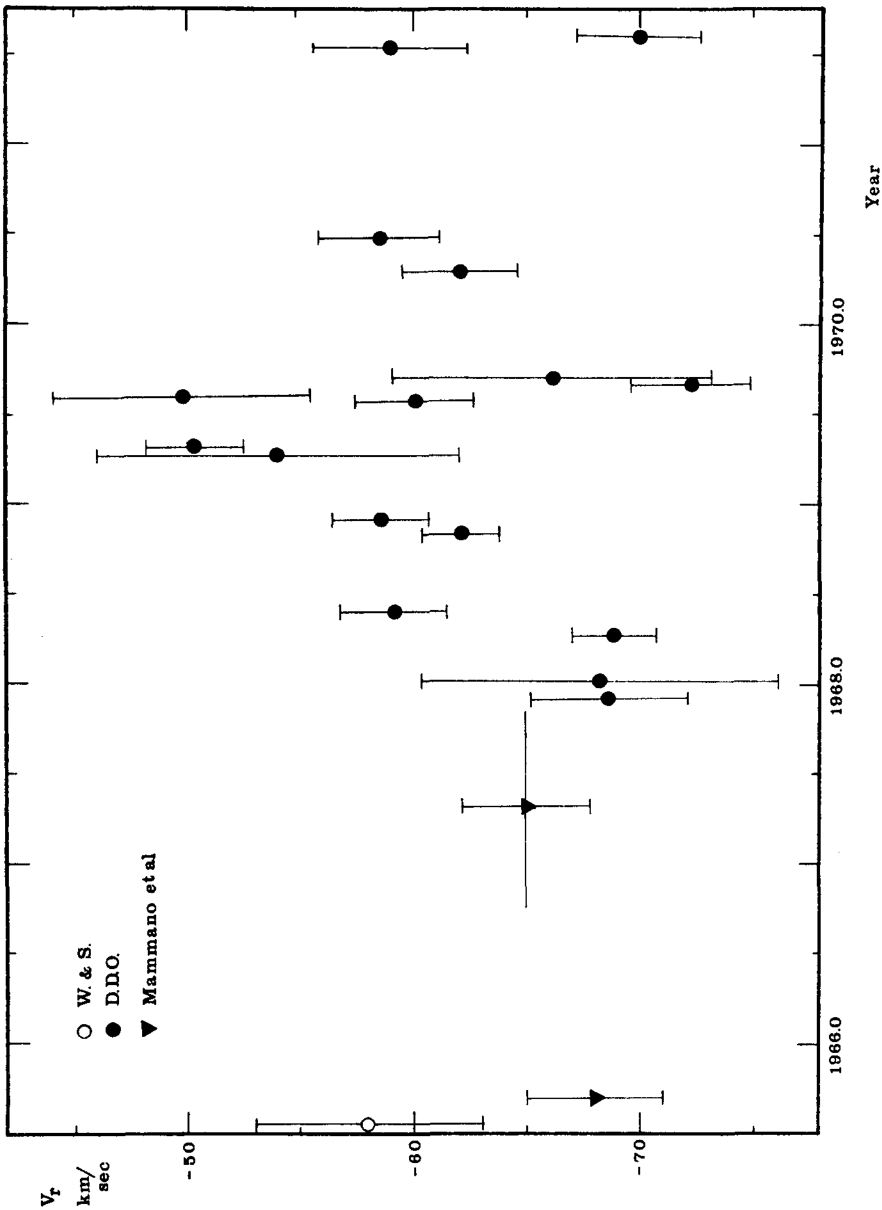

Fig. 7: Radial velocities of V 1016 Cygni. The bars represent standard errors of the mean.

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IV. *Discussion and Conclusions*

The spectral-intensity changes observed in V 1016 Cygni since 1968 do not give a consistent picture of the physical conditions present. The changes in hydrogen line intensities indicate an increase in optical depth, interpretable as a density increase (CAPRIOTTI, 1964) and this is partially supported by the increase in the intensity of the [S II] lines. On the other hand, the increased excitation evidenced by the He II/He I ratio, the increased strength of [Ne V], [Fe V], [O II], all support a higher ionization temperature or lower density. The slight increase in the ratio $[I(4958) + I(4959)] / I(4363)$ also supports a lower temperature.

After correcting the ratio of the observed intensities of the [O III] lines for the effects of interstellar absorption (assuming after O'DELL (1967) that the reddening correction in log I is 0.15) we find for the observations corrected for spectral sensitivity an effective temperature $\sim 8100\,°K$ in 1969, assuming electron densities $\gtrsim 10^6$ elect./cm^3. A possible interpretation of the overall results is that continued expansion of the object is resulting in a decreased density, but that matter is still being thrown off by the parent star. An increase in the total amount of material in the object is consistent with the increasing optical depth for hydrogen, and an overall decrease in density satisfactorily explain most of the other spectral changes observed. In fact if we assume that the electron density of the object has remained about 10^6—10^7 elect./cm^3, and that the expansion velocity is about 60 km/sec., then we will probably require an influx of new material to maintain the mean density and hence the relative strength of the [O III] line λ 4363 over the 7 years of observation.

The possible presence of Al H is also rather intriguing. It is possible that if the object originating the nebula was indeed the M star observed prior to 1965, then we are seeing emission from the Al H molecules remaining from the original atmosphere. It seems possible that the molecules would not have had time to dissociate on the outer layers of the nebula, and could therefore be capable of producing emission lines.

While it is not possible to make any definite conclusions about the nature of V 1016 Cygni at present, the general stability of the spectrum, despite an apparent expansion velocity of about 40 to 80 km/sec over a period of 7 years, argues against the object being a symbiotic star or slow nova. It seems more likely, as suggested previously, that the object is a planetary nebula in the formation process. Observations of the spectral and light variability over the next several years might help to confirm or reject this hypothesis.

Acknowledgements

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References:

ALLER, L. H., and LILLER, W., 1968, in Nebulae and Interstellar Matter, ed. B. M. MIDDLEHURST and L. H. ALLER (Chicago: University of Chicago Press), chap. 9.
BAKOS, G. A., 1971, (private communication).
BLOCH, M., and SWINGS, J. P., 1969, Ap. Letters, 3, 141.
BOYARCHUK, A. A., 1969, Astrofizika, 4, 289.
CAPRIOTTI, E. R., 1964, Ap. J. 139, 225.
FITZGERALD, M. P., HOUK, N., McCUSKEY, S. W., and HOFFLEIT, D., 1966, Ap. J., 144, 1135.
FITZGERALD, M. P., and HOUK, N., 1969, Information Bull. on Var. Stars, N. 372.
———, 1970, Ap. J. 159, 963.
MAMMANO, A., and ROSINO, L., 1966, Mem. Soc. Astr. Italy, 37, 493.
———, 1968, ibid., 39, 471.
McCUSKEY, S. W., 1965, I. A. U. Circ., 1916.
MEINEL, A. B., AVENI, A. F., and STOCKTON, M. W., 1969, in Catalog of Emission Lines in Astrophysical Objects (Tuscon: Optical Sciences Centre and Steward Observatory, Univ. of Arizona.
MOORE, C. E., 1945, Contrib. Princeton Univ. Obs., No. 20.
O'DELL, C. R., 1967, Ap. J. 149, 373.
———, 1968, I.A.U. Symposium No. 34, p. 373.
PHILIP, A. G. D., 1968, Ap. J. (letters), 151, 169.