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SIMULTANEOUS SPECTROSCOPIC AND PHOTOMETRIC OBSERVATIONS OF THE VARIABLE CENTRAL STAR OF THE PLANETARY NEBULA IC 418

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RESUMEN

Presentamos los resultados de un estudio espectroscópico y fotométrico simultáneo de la estrella central variable de la nebulosa planetaria IC 418. Confirmamos que la escala de tiempo de las variaciones fotosféricas de velocidad radial es de pocas horas. No encontramos evidencias convincentes de movimiento orbital en un sistema binario. No encontramos ninguna evidencia de cambios significativos en la temperatura superficial; por consiguiente, las variaciones de brillo son causadas principalmente por variaciones en el tamaño de la estrella. Atribuimos estos cambios de radio a variaciones en el espesor óptico de una atmósfera extendida, producidas por fluctuaciones en la densidad que son la consecuencia de fluctuaciones rápidas en la tasa de pérdida de masa a niveles fotosféricos. La inestabilidad propuesta, originada en o bajo la fotosfera, no estaría asociada con pulsaciones.

ABSTRACT

We present the results of a simultaneous spectroscopic and photometric study of the variable central star of the planetary nebula IC 418. We confirm that the time scale of the photospheric velocity fluctuations is a few hours. We find no convincing evidence of orbital motion in a binary system. We find no evidence of significant changes in the surface temperature; therefore, the brightness variations are caused mainly by size variations. We ascribe these size changes to variations in the optical thickness of an extended atmosphere, produced by density fluctuations which are the consequence of short time scale fluctuations in the mass outflow rate at photospheric levels. The proposed instability, arising at or below the photosphere, would not be associated with pulsations.

Key words: PLANETARY NEBULAE – CENTRAL STARS – VARIABLE STARS-INDIVIDUAL

I. INTRODUCTION

Up to now, if we leave aside the special case of FG Sge, it has been possible to explain the brightness and/or radial velocity variations exhibited by central stars of planetary nebulae in one or the other of two different ways: binary systems and pulsations. Several examples of binary systems are listed by Méndez, Verga, and Kriner (1983, Paper I). An example of pulsations is K1-16 (Grauer and Bond 1984).

HD 35914, the central star of IC 418, shows photometric and radial velocity variations with a time scale of a few hours (see Paper I). The purpose of the present paper is to investigate if any of the two alternatives mentioned above plays a role in the case of HD 35914. In what follows we report the results of a simultaneous photometric and spectroscopic study of this star.

II. PHOTOELECTRIC PHOTOMETRY

Strömgren (*uvby*) photometry of HD 35914 was made by JCF with the 91-cm telescope of the Cerro Tololo Inter-American Observatory (CTIO) in 1984 November 7-10. Only the last part of the first night could be used,

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because of clouds. The 2nd and 3rd nights were of good photometric quality.

The measurements of HD 35914 were made relative to the 9th magnitude star HD 35734, using CTIO *uvby* filter set No. 3, and a dry-ice-refrigerated cold box with an ITT FW130 (S 20) photomultiplier. The sky measurements were always made 30 arc seconds south of each star. The selected diaphragm had a diameter of 24 arc seconds on the sky, as in Paper I, in order to include the whole nebula and minimize the influence of seeing and guiding. Several suitable standards were measured at the beginning of the 2nd and 3rd nights, in order to correct for the atmospheric extinction and to express the results in the Strömgren system.

The data acquisition was computer-controlled via "People's Photometry II" (see details in the CTIO facilities manual). The integration times were as long as necessary (normally less than 30 seconds) to ensure a theoretical precision of 0.5%. Unfortunately, several failures in the telescope and dome control systems produced unwanted interruptions in the data acquisition. The reductions were performed at the IAFE and at La Plata Observatory, using standard procedures.

TABLE 1

uvby PHOTOMETRY: ATMOSPHERIC EXTINCTION AND COMPARISON STAR

Filter	Atmospheric Extinction Coefficient	Comparison Star, HD 35734
u	0.61	10.27
v	0.31	9.16
b	0.20	9.02
y	0.14	9.05

Table 1 lists the adopted atmospheric extinction coefficients and the average *uvby* magnitudes of the comparison star, HD 35734. Figure 1 shows the four magnitude differences, HD 35914 (star + nebula) – HD 35734, as a function of time. The variations are similar (in time scale and amplitude) to those described in Paper I. Notice that from November 8/9 to 9/10 the mean brightness has increased.

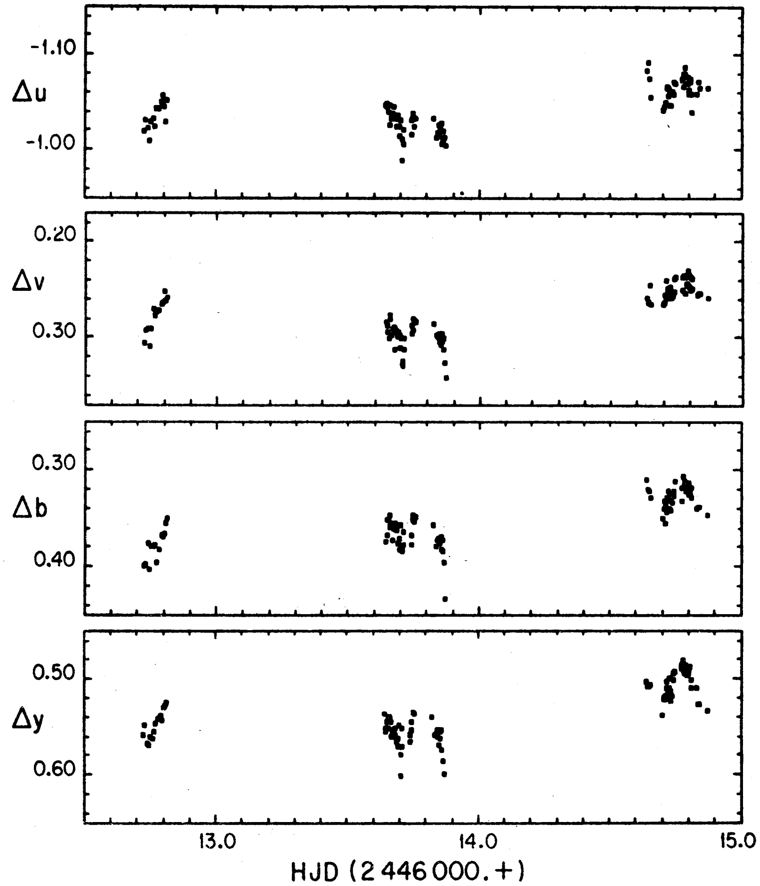

Fig. 1. The four magnitude differences, HD 35914 (star + nebula) – HD 35734, plotted as a function of time.

III. SPECTROGRAMS

On the same 3 nights (1984 November 7-10) 57 spectrograms of HD 35914 were obtained by RHM with the CTIO 1.5 m telescope, using the Cassegrain spectrograph with a 160 mm focal length camera. The slit width was always 2 arc seconds on the sky. The detector was a GEC CCD (epitaxial chip # 1). Preflash time was 300 microseconds. On the first night, grating 36 (1200 lines mm^{-1}) was used in the first order, giving a spectral resolution of approximately 2 A and a spectral coverage from 5325 to 5975 A. The exposure times for HD 35914 were 5 minutes. However, since the resulting signal-to-noise ratio was not good, for the 2nd and 3rd nights we decided to use grating 56 (600 lines mm^{-1}) in the second order, giving almost identical spectral resolution and coverage. With exposure times of 10 minutes, a reasonable signal-to-noise ratio was obtained. Longer exposure times were not attempted, because they would have produced an unacceptable decrease in time resolution. On all nights, order suppression was accomplished with a filter GG 495.

Since the main purpose was to obtain radial velocities, spectra of the He-Ar comparison lamp were taken before and after each stellar spectrum. Bias frames were taken every 2 hours. Several flat field exposures were made at the beginning and end of each night. At the beginnings of the 2nd and 3rd nights, several 15-minute exposures of the flux standard star LTT 1020 (Stone and Baldwin 1983; Baldwin and Stone 1984) were taken.

The reductions were made at La Serena, following standard procedures: the raw images were flat-field corrected, the spectra extracted and the sky subtracted, and the wavelength scales were calibrated using the He-Ar exposures. Flux calibrations were made, although they were not essential for our purposes.

All the final spectra of HD 35914 from each night were added together. Figure 2 shows the additions corresponding to the 2nd and 3rd nights. For a description of the spectrum see Paper I; no new stellar or nebular lines have been found. The stellar absorptions at 5411 and 5592 A turned out to be affected by bad pixels, and we decided to reject them and to concentrate our analysis on the stellar C IV absorption 5801 and 5811, the stellar C III emission 5695, and the nebular [N II] emission 5755.

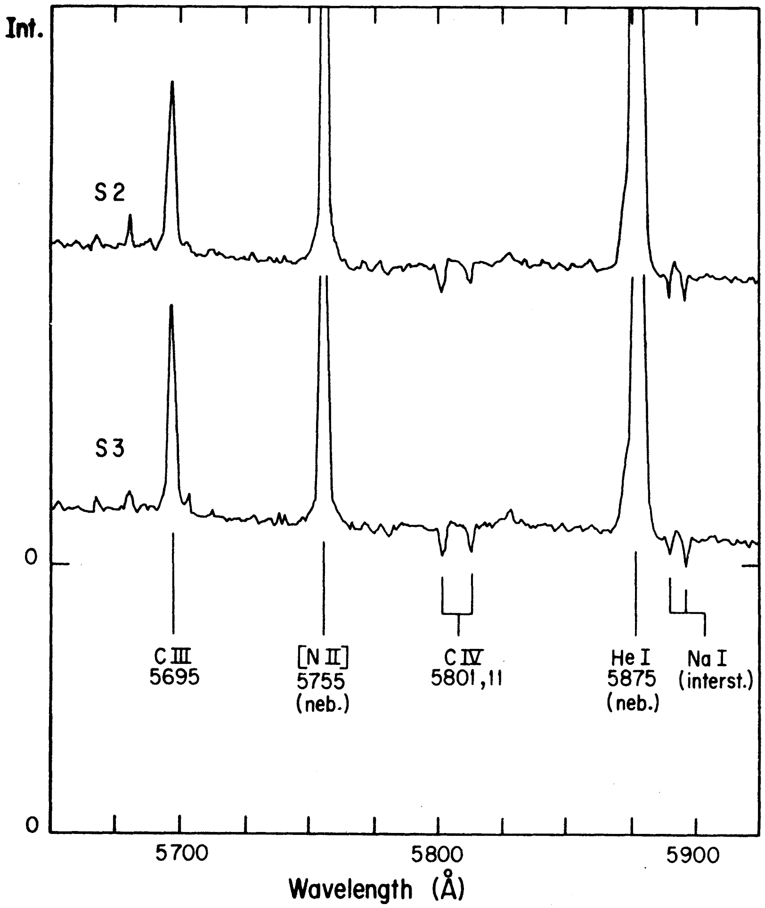

Fig. 2. Additions of spectra corresponding to the 2nd and 3rd nights. The levels of zero intensity are indicated for each addition.

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Also at La Serena, the equivalent widths of the stellar C IV absorption doublet were measured on all the individual spectrograms corresponding to the 2nd and 3rd nights. The equivalent widths are listed in Table 4, together with the heliocentric radial velocities (see below).

IV. RADIAL VELOCITIES

The derivation of radial velocities from the 57 reduced CCD spectra of HD 35914 was made at the IAFE, using the cross-correlation technique described by Tonry and Davis (1979). For any two discretely sampled similar spectra, binned linearly with ln λ, it is easy to construct a cross-correlation function (CCF), defined as a function of the logarithmic wavelength shift, in such a way that the CCF will have a maximum for the shift needed to produce the best possible superposition of the two spectra. From the position of this maximum, the relative radial velocity is obtained.

TABLE 2

CROSS-CORRELATION ANALYSIS
RADIAL VELOCITIES (KM/S) RELATIVE
TO ADDITIONS OF SPECTRA

Spectrum number	Heliocentric Julian date (2446000 +)	St. em. C III 5695	Neb. em. [N II] 5755	St. abs. C IV 5801, 5811	Relative to addition
102	12.8045	-6.2	-2.8	-9.9	S1
104	12.8122	-2.1	-1.7	+11.1	S1
106	12.8191	+2.2	-0.8	+6.1	S1
108	12.8268	+0.3	-0.2	+11.3	S1
111	12.8358	-0.3	+0.6	+4.5	S1
113	12.8427	+2.6	+0.4	+2.0	S1
115	12.8497	+3.2	+1.5	-1.6	S1
117	12.8573	+4.5	+0.4	-4.6	S1
119	12.8643	-6.2	+2.5	-13.7	S1
302	13.6289	-4.2	-1.8	-14.1	S2
304	13.6393	-5.7	-2.7	-14.5	S2
307	13.6511	-5.8	-2.5	-9.6	S2
309	13.6615	-3.3	-1.0	-6.0	S2
311	13.6740	-6.6	-1.8	-5.4	S2
313	13.6844	-3.9	-2.7	-12.8	S2
315	13.6942	-5.0	-2.5	-3.5	S2
317	13.7046	-5.3	-2.4	-9.4	S2
319	13.7150	-1.9	-1.5	-9.2	S2
322	13.7261	-2.8	-0.7	-0.8	S2
324	13.7372	-7.2	-0.1	-6.6	S2
326	13.7476	+1.1	+0.2	+14.3	S2
328	13.7581	+1.4	+0.3	+20.6	S2
330	13.7685	+4.1	+1.3	+14.8	S2
332	13.7782	+4.9	+0.3	+18.0	S2
334	13.7886	+4.5	+0.8	+11.8	S2
336	13.7990	+8.8	+1.7	+11.4	S2
339	13.8108	+3.3	+2.1	+1.0	S2
343	13.8324	+4.1	+2.0	+2.6	S2
345	13.8428	+0.2	+2.3	-2.1	S2
347	13.8525	+5.0	+3.5	+4.2	S2
349	13.8636	+5.9	+2.8	+9.5	S2
351	13.8740	+5.3	+3.4	-3.9	S2
428	14.6150	-0.3	-1.4	+18.7	S3
430	14.6255	+0.6	-1.0	+17.5	S3
432	14.6359	+0.4	-1.1	+21.2	S3
435	14.6470	-2.6	-0.6	-0.1	S3
437	14.6588	+0.5	-0.7	+3.1	S3
439	14.6692	+0.5	-0.4	+3.9	S3
441	14.6789	+2.0	-0.4	+1.1	S3
443	14.6893	-0.7	-0.5	+5.8	S3
445	14.7005	+2.9	-0.0	-0.8	S3
447	14.7109	-4.3	-0.5	-6.3	S3
449	14.7206	+0.5	-0.1	-0.7	S3
451	14.7310	-1.7	-0.1	+4.2	S3
454	14.7428	-0.2	-0.0	-4.9	S3
502	14.7581	-1.1	+0.5	+2.6	S3
504	14.7685	-0.8	+0.8	-2.0	S3
506	14.7789	+1.9	+1.1	+6.2	S3
508	14.7887	-3.1	+0.2	-4.3	S3
510	14.7991	-2.8	+0.1	-0.8	S3
512	14.8095	+1.0	+0.1	-11.8	S3
514	14.8199	+2.0	+0.1	+1.4	S3
517	14.8317	+0.4	+0.6	-2.7	S3
519	14.8414	+4.0	+1.1	-12.3	S3
521	14.8519	-0.1	+1.2	-15.6	S3
523	14.8616	+0.8	+0.8	-7.5	S3
525	14.8720	-0.3	+0.8	-4.7	S3
S1		+6.4	+5.9	+14.1	S2
S1		+2.4	-1.2	+6.7	S3
S2		-3.8	-7.7	-10.3	S3

We have followed the procedure suggested by Kilkenny, Hill and Penfold (1981): each individual spectrum of HD 35914 was correlated against the corresponding all-night spectrum addition. More precisely, since different spectral features give different velocities, we have applied the cross-correlation analysis separately to three different spectral regions: (*a*) from 5675 to 5715 A, isolating the stellar C III emission at 5695 A; (*b*) from 5735 to 5775 A, isolating the nebular [N II] emission at 5755 A; (*c*) from 5792 to 5822 A, isolating the stellar C IV absorptions at 5801 and 5811 A. Table 2 shows the three radial velocities obtained from each individual spectrum, relative to the corresponding all-night addition (we have labeled the additions S1, S2 and S3 for the 1st, 2nd and 3rd night, respectively). We also list the radial velocities of each addition relative to the other two.

An inspection of the relative [N II] nebular velocities in Table 2 shows that the behavior of the spectrograph is quite systematic: on all three nights the instrumental velocity increases with time. The heliocentric correction accounts for only a small part of this increase; the rest is probably attributable to mechanical flexures. However, for our purposes the important thing to remark is that the individual departures from this behavior are small, and therefore it is possible to obtain reliable heliocentric radial velocities adopting the nebular [N II] emission at 5755 A as our standard. From Table 2 in Paper I we adopt for this nebular line a heliocentric radial velocity of + 64 km s^{-1}.

In Table 3 we list the instrumental velocities on S1, S2 and S3, determined using the rest wavelengths given in Table 3 of Paper I and the observed wavelengths of symmetrical fits to the line profiles. In the case of C IV, we have assigned double weight to the line at 5801 A, because it is somewhat stronger than 5811. The reader can check that all the velocity differences between additions agree within 4 km s^{-1} with those listed at the bottom of Table 2.

TABLE 3

INSTRUMENTAL VELOCITIES DETERMINED ON SPECTRAL ADDITIONS[a]

Addition	C III	[N II]	C IV
S1	76	74	44
S2	73	69	27
S3	73	76	35

a. In km s^{-1}.

Let us call Sn the addition of all the spectra of HD 35914 corresponding to the nth night. The heliocentric radial velocity of the stellar C IV absorption doublet for any individual spectrum taken on that night is obtained as follows:

C IV velocity relative to Sn (Table 2)
– [N II] velocity relative to Sn (Table 2)
+ instrumental C IV velocity on Sn (Table 3)
– instrumental [N II] velocity on Sn (Table 3)
+ adopted heliocentric velocity of [N II] (+ 64 km s^{-1}).

A similar calculation yields the heliocentric velocity of the stellar C III emission at 5695 A. All the heliocentric radial velocities are listed in Table 4. We estimate that the uncertainties in these velocities are not larger than 5 km s^{-1}. Figure 3 shows the CIV heliocentric velocities compared with the *y* magnitude differences.

V. PRELIMINARY DISCUSSION: THE RADIAL VELOCITY BEHAVIOR

Putting together all the information we have accumulated on the C IV absorption radial velocity variations (see Section 4 and Paper I), it is now possible to discern some regularity. It would seem that the central star of IC 418 suffers rather frequent "high velocity episodes", during which the radial velocity increases abruptly and decreases almost immediately to approximately the same value it had before increasing. We have two nights (JD 2446012 and 13) in which the whole process took place in about 0.1 day. In several other nights (see also Paper I) we have descending branches that suggest a similar time scale. The amplitude of the velocity peaks is about 30 km s^{-1} in Paper I, and 20-25 km s^{-1} in the present paper. The starting velocity is normally some 50 km s^{-1} more negative than the nebular velocity, although on JD 2445042 it was only 15 km s^{-1} more negative, and the velocity peak reached more positive velocities than the nebula (see Paper I).

In Paper I it was possible to conclude that we are certainly dealing with a variable photospheric velocity field, but a question could not be answered: what is the real time scale of the photospheric velocity fluctuations, one day or a few hours?

If the answer is of the order of one day, then the high velocity episodes must be attributed to orbital motion in a very close binary system, and we expect them to show evidence of a period. That was the idea tentatively favored in Paper I.

If the time scale is a few hours, then a binary system becomes unnecessary (although not necessarily excluded), and the high velocity episodes can be attributed to non-periodic or multi-periodic phenomena, or to a combination of one or both of these with periodic phenomena (including orbital motion in a binary system).

Having stated the problem in this way, we now consider if the new data can help us to eliminate at least some of the possibilities.

VI. ON PERIODS AND CORRELATIONS

Are the high velocity episodes periodic? Figures 12, 13 and 14 of Paper I show three "descending branches" observed on consecutive nights. All three have happened at almost the same UT. Therefore, in order to decide if the high velocity episodes are periodic, we only need to investigate periods which are almost exactly 1, 1/2, 1/3, 1/4, . . . days. Three such periods were the most promising in Paper I: 0.165, 0.198 and 0. 248 days. None of them are supported by Figure 3 of the present paper: we notice that on JD 2446014 a high velocity episode happened at the beginning of the night and was not repeated later. From this we must conclude that a lower limit for

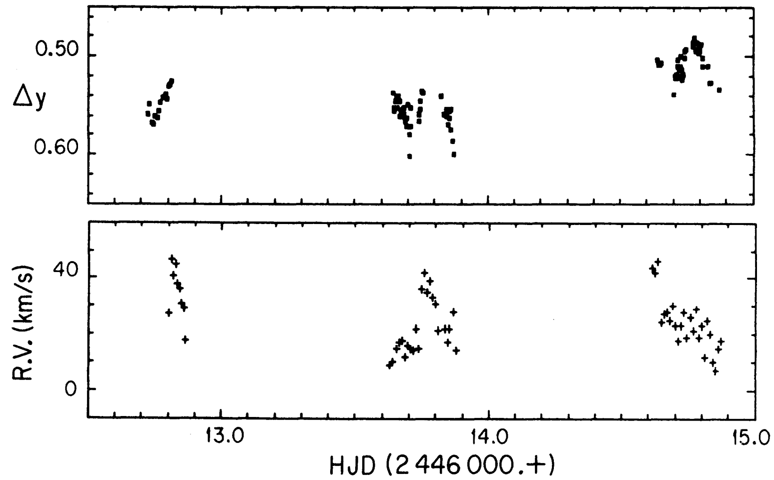

Fig. 3. The heliocentric radial velocities of the stellar C IV absorptions, plotted as a function of time, and compared with the y magnitude differences taken from Figure 1.

TABLE 4

HELIOCENTRIC RADIAL VELOCITIES AND EQUIVALENT WIDTHS

		Radial velocities (km/S)		Equivalent widths (A)
Spectrum number	Heliocentric Julian date (2446000 +)	St. em. C III 5695	St. abs. C IV 5801, 5811	St. abs. C IV 5801, 5811
102	12. 8045	62	27	
104	12. 8122	65	47	
106	12. 8191	69	41	
108	12. 8268	66	45	
111	12. 8358	65	38	
113	12. 8427	68	36	
115	12. 8497	68	31	
117	12. 8573	70	29	
119	12. 8643	57	18	
302	13. 6289	65	9	0. 31
304	13. 6393	65	10	0. 32
307	13. 6511	65	15	0. 32
309	13. 6615	66	17	0. 31
311	13. 6740	63	18	0. 46
313	13. 6844	67	12	0. 40
315	13. 6942	65	16	0. 53
317	13. 7046	65	15	0. 33
319	13. 7150	67	14	0. 24
322	13. 7261	66	22	0. 26
324	13. 7372	61	15	0. 46
326	13. 7476	69	36	0. 55
328	13. 7581	69	42	0. 48
330	13. 7685	71	35	0. 47
332	13. 7782	72	39	0. 43
334	13. 7886	72	33	0. 33
336	13. 7990	75	31	0. 35
339	13. 8108	69	21	0. 40
343	13. 8324	70	22	0. 30
345	13. 8428	66	17	0. 38
347	13. 8525	69	22	0. 41
349	13. 8636	71	28	0. 48
351	13. 8740	70	14	0. 51
428	14. 6150	62	44	0. 55
430	14. 6255	63	42	0. 64
432	14. 6359	63	46	0. 43
435	14. 6470	59	24	0. 55
437	14. 6588	62	27	0. 46
439	14. 6692	62	28	0. 37
441	14. 6789	64	25	0. 36
443	14. 6893	61	30	0. 37
445	14 7005	64	23	0. 45
447	14 7109	57	18	0. 35
449	14 7206	62	23	0 59
451	14. 7310	60	28	0. 48
454	14. 7428	61	19	0. 65
502	14. 7581	60	26	0. 43
504	14. 7685	60	21	0. 55
506	14. 7789	62	29	0. 55
508	14. 7887	58	19	0. 69
510	14. 7991	58	23	0. 61
512	14. 8095	62	12	0. 47
514	14. 8199	63	25	0. 44
517	14. 8317	61	20	0. 48
519	14. 8414	64	10	0. 38
521	14. 8519	60	7	0. 54
523	14. 8616	61	15	0. 55
525	14. 8720	60	18	0. 60

the period is 0.257 days (see Table 4). In addition, the three maxima in Figure 3 happened at significantly different UT's: the fractional julian dates are 0.82, 0.76, 0.62. This fact permits to eliminate periods near 1, 1/2, 1/3 days. Therefore, the new information permits to conclude that the interval between velocity peaks is of variable duration. This interval appears to be usually longer than the duration of the peaks, in one case at least 0.2 day (JD 2446014).

Since the high velocity episodes cannot be periodic, we infer that the time scale of the photospheric velocity fluctuations is a few hours.

It now seems unlikely that the central star of IC 418 is a binary system. After a careful period search using methods of Marraco and Muzzio (1980) and of Deeming (1975), the C IV absorption radial velocities do not offer any convincing evidence of periodicity. To this we may add the lack of significant radial velocity variations of the C III stellar emission line at 5695 A (see Table 4 and Paper I). Concerning the photometry, again we have not been able to find any convincing period. The data on JD 2446013 and 14 might suggest a cyclical variation with a period of about 0.17 days. However, the mean brightness has changed, as already mentioned at the end of Section 2. Besides, the data in Paper I show, on JD 2445340 two maxima separated by more than 0.2 daps. The variations on JD 2445341 are also incompatible with that interpretation. Of course, we cannot rule out the possible existence of different periods at different times; but again this would not be compatible with orbital motion.

On the other hand, we are careful to remark that we have not shown that HD 35914 cannot be a binary system. As stated in Section 5, radial velocity variations produced by orbital motion could well be masked by additional variations produced by non-periodic or multiperiodic phenomena. The same comment applies to the photometry.

The picture might become clearer if it were possible to obtain simultaneous photometry and spectroscopy over a longer interval than what is possible from a single observatory; this would require a coordinated effort by at least two southern observatories in different continents.

Now, let us consider correlations. In Figures 3 and 4 we do not find any convincing relation between stellar

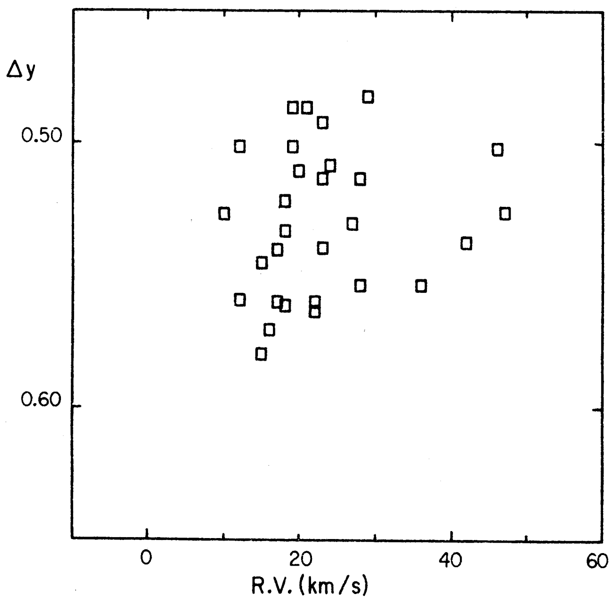

Fig. 4. The y magnitude differences plotted as a function of the C IV radial velocities.

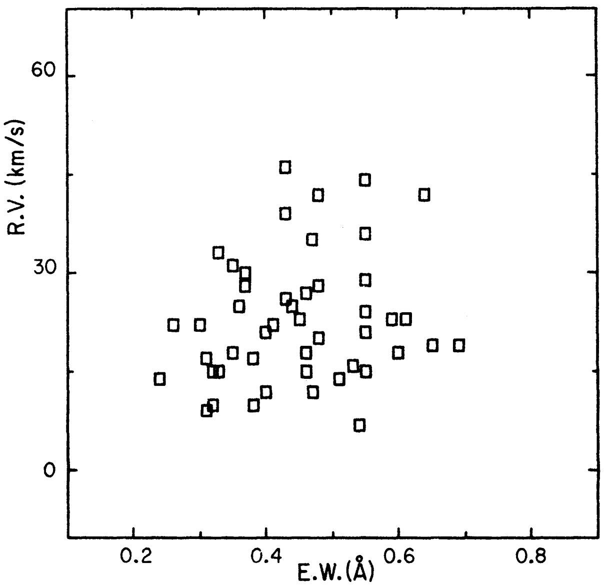

Fig. 5. The C IV radial velocities plotted as a function of the C IV equivalent widths.

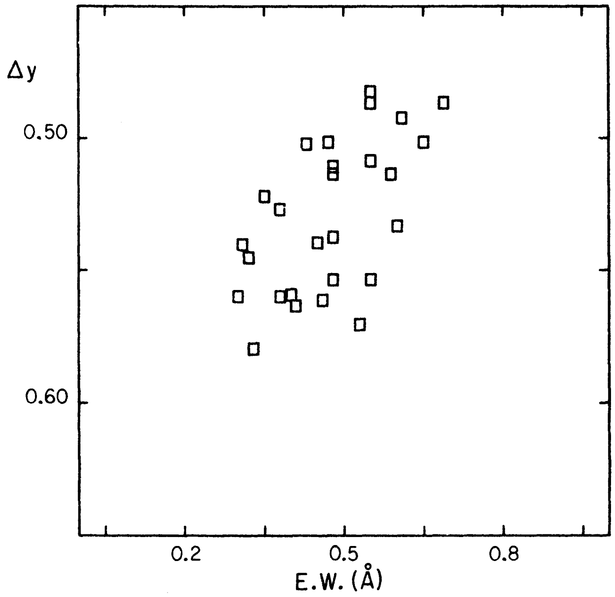

Fig. 6. The y magnitude differences plotted as a function of the C IV equivalent widths.

brightness and C IV absorption radial velocities. In particular, notice in Figure 3 that the behavior on JD 2446013 and 14 is not compatible with a common period for brightness and velocity variations. Figure 5 shows no correlation between radial velocities and equivalent widths of the stellar C IV absorptions. However, in Figure 6 we do find some correlation between stellar brightness and C IV equivalent widths. The meaning of all this information will be discussed in Section 9.

VII. A LIMIT FOR SURFACE TEMPERATURE VARIATIONS: SUBTRACTION OF THE NEBULAR CONTRIBUTION TO THE MEASURED FLUXES

Since some kind of pulsation might be at least partly responsible for the observed photometric and radial velocity variations, it is important to find out if there have been significant variations in the surface temperature of HD 35914. In order to use the *uvby* photometry for that purpose, it is necessary to subtract the nebular

TABLE 5

DATA USED TO CONVERT (STAR + NEBULA) *uvby* MAGNITUDES INTO (DEREDDENED) STELLAR FLUXES

Filter Wavelength (A)	*u* 3500	*v* 4110	*b* 4670	*y* 5470
uvby mags of α Lyrae	1.45	0.20	0.039	0.035
Absolute Fluxes of α Lyrae^a	3.12×10^{-9}	8.09×10^{-9}	5.66×10^{-9}	3.56×10^{-9}
Extinction Function, f (λ)	1.32	1.17	1.046	0.87
$\int_0^\infty t_\lambda \, d\lambda$ (A)	145	110	97	134
$\Sigma f_L t_\lambda (H\beta = 100)^b$	11	19	5.5	0.8
Dereddened Contr. from Neb. Lines^a	4.81×10^{-13}	9.83×10^{-13}	2.94×10^{-13}	2.71×10^{-14}
Computed Nebular Continuum Fluxes^a	2.47×10^{-12}	2.74×10^{-13}	2.52×10^{-13}	2.45×10^{-13}

a. In erg cm^{-2} s^{-1} A^{-1}.
b. See text.

contribution to the measured fluxes. Let us describe the procedure we have followed (see Tables 5 and 6).

The first step was to convert the *uvby* (star + nebula) measurements into absolute fluxes, using the *uvby* magnitudes of α Lyrae (Crawford and Barnes 1970; Oke and Schild 1970), and interpolating in the absolute energy distribution of α Lyrae (Hayes and Latham 1975) for the corresponding wavelengths. The fluxes thus obtained were corrected for the effects of interstellar extinction, using

$$\log I = \log F + c\, f(\lambda) \tag{1}$$

where F is the observed flux, I is the corrected flux, c is the logarithmic extinction at Hβ and f(λ) gives the extinction relative to that at Hβ, as a function of wavelength. We have derived our f(λ) from Seaton (1979) and have adopted for IC 418 c = 0.32, from Aller and Czyzak (1983).

The next step was to compute the dereddened nebular line contributions and theoretical nebular continuum contributions to be subtracted to the dereddened (star + nebula) fluxes.

We first describe the computation of the nebular line contributions. If we call f_L the flux from a given nebular line (erg cm^{-2} s^{-1}) and t_λ the filter transmission at that wavelength ($0 < t_\lambda < 1$), then the contribution of this line to the measured (star + nebula) flux can be expressed by

$$F_L = f_L\, t_\lambda \left[\int_0^\infty t_\lambda\, d\lambda\right]^{-1} \quad (\mathrm{erg\ cm^{-2}\ s^{-1}\ A^{-1}}) \tag{2}$$

We have adopted the filter transmissions given by Crawford and Barnes (1970), and have added, for each *uvby* filter, the contributions from all the nebular emission lines of IC 418 listed by Kaler (1976*a*). To convert the relative fluxes into absolute fluxes, we have used a nebular Hβ flux of 2.40×10^{-10} erg cm^{-2} s^{-1} (log F(Hβ) = – 9.62, Carrasco, Serrano, and Costero 1983). The resulting fluxes were finally corrected for the effects of interstellar extinction, using formula (1).

The nebular continuum flux was computed for each filter wavelength using the dereddend Hβ flux, I(Hβ) = 5.01×10^{-10} erg cm^{-2} s^{-1}, the tables of Brown and Mathews (1970) and the following nebular parameters from Aller and Czyzak (1983): electron temperature 8300 K, electron density 10000 cm^{-3}, N(He^{+})/N(H^{+}) = 0.093 and N(He^{++})/N(H^{+}) = 0. The Hβ recombination coefficient was taken from Brocklehurst (1971).

TABLE 6

HD 35914: *uvby* MEASUREMENTS AND DERIVED DEREDDENED STELLAR FLUXES AT MAXIMUM AND MINIMUM BRIGHTNESS

	u 3500 A	*v* 4110 A	*b* 4670 A	*y* 5470 A
		Maximum		
uvby Magnitudes (Star + Nebula)	9.20	9.39	9.33	9.53
Dereddened (Star + Nebula) Fluxes^a	6.55×10^{-12}	4.04×10^{-12}	2.35×10^{-12}	1.08×10^{-12}
Dereddened Stellar Fluxes^a	3.60×10^{-12}	2.78×10^{-12}	1.81×10^{-12}	8.03×10^{-13}
Dereddened Stellar Magnitudes	8.79	8.86	8.78	9.15
		Minimum		
uvby Magnitudes (Star + Nebula)	9.28	9.49	9.44	9.65
Dereddened (Star + Nebula) Fluxes^a	6.09×10^{-12}	3.68×10^{-12}	2.12×10^{-12}	9.62×10^{-13}
Dereddened Stellar Fluxes^a	3.14×10^{-12}	2.43×10^{-12}	1.58×10^{-12}	6.90×10^{-13}
Dereddened Stellar Magnitudes	8.94	9.01	8.92	9.32

a. In erg cm^{-2} s^{-1} A^{-1}.

After the subtraction of the nebular contributions, the dereddened stellar fluxes were converted back to dereddened *uvby* magnitudes (see Table 6). As a by-product, we have also computed the "undereddened" visual magnitude that would be measured for HD 35914 if there were no nebula: V = 9.85 and 10.01 at maximum and minimum brightness respectively.

In Table 6 we find that, at minimum brightness, $(u-b)$ has become more positive by 0.01 mag, and $(u-y)$ more negative by 0.02 mag. These differences are small and comparable to the combined uncertainty expected from the measurements and the nebular subtraction procedure. Therefore, the observations speak against a significant variation of the surface temperature, as already suggested (tentatively) in Paper I.

In the literature there are several determinations of the surface temperature of the central star of IC 418, mostly using the Stoy (or energy-balance) method; see e.g., Kaler (1976*b*) and Preite-Martinez and Pottasch (1983). There is a satisfactory agreement between different authors. We adopt a surface temperature of 32000 K, which is not likely to be in error by more than 3000 K. Now we can estimate, from model atmosphere calculations, what temperature variation could be masked by the uncertainties in our colors. Working on the continuous energy distributions of the non-LTE models of Mihalas (1972) we infer an upper limit of about 1000 K for surface temperature variations.

VIII. INTERPRETATION OF THE BRIGHTNESS VARIATIONS

The low upper limit for surface temperature variations that we have found in Section 7 implies that the brightness variations are caused mainly by variations in the stellar radius. Notice that the observed colors would imply, at most, a small increase in temperature when the star is fainter, which would only strengthen our conclusion.

It is well known and easy to show, from elementary definitions and the flux calibration of the scale of apparent visual magnitudes, that

$$5 \log \varphi = 42.21 - V_0 - 10 \log T_{eff} - BC \quad , \qquad (3)$$

where φ is the stellar angular diameter in milliarcseconds, and V_0 is a dereddened apparent visual magnitude. Using the information about the surface temperature derived in Section 7, bolometric corrections from Code *et al.* (1976) and the V_0's from Table 6, we find that the angular diameter of HD 35914 has varied 9 ± 1% around a mean value of 0.016 milliarcseconds.

IX. DISCUSSION

We need a plausible explanation for the radial velocity variations (see Sections 5 and 6) and for the size variations (see Section 8). Radial pulsations can be clearly ruled out, owing to the absence of temperature variations.

Non-radial pulsations deserve a more careful analysis. Consider for example the well known non-radial pulsator 53 Per (Smith 1977; Smith and McCall 1978; Buta and Smith 1979). Are we observing a similar phenomenon in HD 35914? On the positive side, we can mention the combination of significant size fluctuations with little or no color changes. The amplitudes of the brightness and radial velocity variations are larger in our case, by a factor of about two; but perhaps this is not a fundamental objection.

On the other hand, we can mention two arguments against this interpretation: first, the absence of a common period for our brightness and radial velocity variations, as mentioned in Section 6. Second, the shape of our radial velocity curves: they do not show the typical smooth, more or less sinusoidal variations associated with traveling waves. However, one could still argue that these arguments are not conclusive, because there might be additional variations, produced for example by binary motion, superposed on the pulsational variations.

A definitive test is the absence or presence of absorption-line profile variations. Unfortunately, this requires spectrograms with high spectral and time resolutions. At this point we must mention that in January 1986 Méndez and Kudritzki have obtained 5 high-resolution spectrograms of HD 35914 on 4 different nights using the CASPEC, an echelle spectrograph at the Cassegrain focus of the 3.6 m telescope of the European Southern Observatory, La Silla, Chile. With a CCD as detector, exposure times of 15 minutes permitted to obtain spectrograms with a signal-to-noise ratio of about 50 and a spectral resolution of 0.2 A, extending from 4000 to 5000 A. On these spectrograms, which will be adequately described in a separate paper, the He II absorptions at 4200 and 4541 A show significant radial velocity variations (30-40 km s^{-1}) without any accompanying profile variations. Clearly, the observations are few, and of lower quality than what can be obtained for brighter stars, and it would be preferable to analyze the C IV absorptions at 5801 and 5811 A; but we think that this combination of large radial velocity variations and no significant profile variations can be taken as additional evidence that non-radial pulsations are not the main reason for the observed variations.

Knowing from Paper I that orbital motion alone (if present) is not enough to explain the observed radial velocity variations, having excluded radial pulsations, and having found non-radial pulsations to be unlikely, we now discuss what appears to be the only remaining alternative: that the observed radial velocity variations are, at least partly, a consequence of short time scale fluctuations in the mass outflow rate at photospheric levels, and that the size changes are produced by variations of the optical thickness in an extended atmosphere. There is a close connection between these two ideas. In order to explain the size changes, in the absence of temperature variations, the suggested optical thickness fluctuations must be attributed to density fluctuations; these density fluctuations would be a natural consequence of the variations in the mass outflow rate.

The picture we have in mind can be caricatured in the following way: imagine the outward accelerating atmosphere of HD 35914 at a certain time when the brightness is maximum. Now, by some convenient mechanism, we switch off the mass outflow at the bottom. Since the mass loss continues above, the density begins to decrease; this produces a decrease in the optical thickness and a consequent decrease in the observed radius of the star. By switching on and off at suitable times we try to reproduce the observed behavior.

Let us now discuss if the proposed picture is consistent with Figures 4 to 6.

In Figure 6 we find some correlation between stellar brightness and the equivalent widths of the C IV absorptions. Perhaps this correlation should be expected; since we have attributed the decrease in brightness to a decrease in stellar radius, which implies a slight increase in surface gravity, one might expect a decrease in the mass per unit area above the continuum, and thereby a decrease in the equivalent widths of absorption lines formed near the continuum.

On the other hand, it is somewhat disappointing to find no correlations in Figures 4 and 5. But the reason may be that, in a situation as highly dynamical as we are proposing, the influence of the fluctuations in the mass outflow rate could, given different initial conditions, require different times to produce the observed changes in the radial velocities of the photospheric absorption lines, on the one hand, and in optical thickness and equivalent widths, on the other. Besides, we expect some complicating influence of the optical thickness changes on the observed radial velocities. A very detailed hydrodynamical model of the atmosphere would be necessary to make definite predictions. In addition, it would also be possible to invoke a complicating influence of orbital motion on the observed radial velocities, as we did in the discussion about non-radial pulsations.

For the moment, we tentatively conclude that fluctuations in the mass outflow rate at photospheric levels, not produced by a pulsational instability, provide the most likely (perhaps we should say the less unlikely) explanation of the observed behavior of HD 35914.

Since we are not postulating anything special about HD 35914, we might expect other stars with similar T_{eff} and log g to show similar variations. The important factor to produce relatively large brightness variations would be the existence of a sufficiently extended atmosphere. Concerning central stars of planetary nebulae, studies as detailed as performed on HD 35914 are not available in the literature. A good choice for further investigations would be HD 138403 (He 2-131, see Méndez and Niemela 1979; Surdej, Surdej, and Swings 1982), which has shown variable P Cygni profiles on a time scale of a few days. Another relatively cool, presumably low-gravity, bright central star that can be studied in detail is HD 141969 (He 2-138).

Turning our attention to more massive stars with similar T_{eff} and log g, it is interesting to note that low-amplitude irregular or semi-regular brightness variations, as well as variable atmospheric velocity fields, not obviously attributable to non-radial pulsations, are known to occur among late O giants and supergiants (Baade 1986). Unfortunately the time scales are not well known, and simultaneous photometric and radial velocity studies are lacking. But more detailed observations could well lead to find other cases like that of HD 35914.

X. SUMMARY OF CONCLUSIONS

In Paper I it was possible to show that orbital motion alone (if present) is not enough to explain the observed radial velocity variations: the velocity field near the photosphere must be variable. In Section 5 of the present paper we give a more detailed description of the observed radial velocity variations. In Section 6 we show that the interval between the "high velocity episodes" is of variable duration, and infer that the time scale of the photospheric velocity fluctuations is a few hours. In Section 7 we obtain a low upper limit for surface temperature variations, and in Section 8 we show that the brightness variations must be attributed mainly to variations in the stellar radius. In Section 9 we state our reasons to think that radial pulsations can be excluded and non-radial pulsations are unlikely. As an alternative, we suggest that the variable velocity field can be a consequence of short time scale fluctuations in the mass outflow rate at photospheric levels. The proposed instability, arising at or below the photosphere, would not be associated with pulsations. We ascribe the brightness variations to changes in the optical thickness of an extended atmosphere, producing changes in the size of the star which are only indirectly related to physical motion of the material. We suggest that this kind of brightness and radial velocity variations might be detectable (and may have been detected) in other stars with similar T_{eff} and log g.

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