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Variable central stars of young planetary nebulae

I. Photometric multisite observations of IC 418

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Abstract. We report the results of a photometric multisite campaign devoted to HD 35914, the variable central star of the Planetary Nebula IC 418. From the analysis of 120 hours of data acquired with a variety of techniques, we find that HD 35914 exhibits two distinct kinds of variability: irregular light modulation with a time scale of days, as well as cyclic variations with a time scale of 6.5 hours. The short-term variations are not strictly periodic, and cannot be reasonably explained by multiperiodicity; they appear to be semiregular. The star is generally redder when it is brighter; this behavior appears to be connected with the long-term variability.

A re-analysis of most of the older data obtained for HD 35914 by various researchers suggests that the basic behavior of the star did not change during the last 15 years.

We carefully discuss all the possible causes for the light variations of the star. Rotational modulation of surface features cannot explain the observations, and binarity is unlikely. Pulsations may be excited, but wind variability (or a combination of both) can also not be ruled out.

Key words: stars: variables: other – stars: individual: HD 35914 – planetary nebulae: individual: IC 418 – stars: oscillations – stars: mass loss – techniques: photometric

1. Introduction

Variability of O-type stars is a common phenomenon; it is rather the rule than the exception. Extensive spectroscopic (e. g. Howarth et al. 1993, Kaper et al. 1996) as well as photometric investigations (Balona 1992) have already been undertaken for a number of massive O stars. In most cases, the variability is attributed to variations in the stellar wind, but also pulsation of some objects has been suggested as a possible explanation (e. g. Reid et al. 1995).

However, not only massive O stars exhibit variability; several "cool" central stars of Planetary Nebulae (CSPN) appear to show similar behavior. The observational material of these stars is, however, much sparser than that of massive objects. The best investigated representative of these "cool" CSPN is HD 35914, the central star of IC 418. Its variability was first reported by Gilra et al. (1978) on the basis of ultraviolet flux measurements by the Netherlands Astronomical Satellite. Subsequently, Méndez et al. (1983, 1986, hereafter MVK and MFL, respectively) undertook both photometric and spectroscopic studies of HD 35914. They discovered that the star shows light and radial velocity variations with a timescale of a few hours, and that it also changes its mean magnitude. MFL suggested that the variability of HD 35914 is caused by modulation in the mass outflow, supported by a relationship between the strength of stellar absorption lines and stellar brightness. On the other hand, Maene et al. (1994) investigated the possibility of wind variability by simultaneous IUE spectroscopy and optical photometry, without finding a correlation between the intensity of the stellar wind and the star's optical brightness.

Although MVK and MFL presented arguments against the idea that pulsations could be excited in HD 35914, model calculations were performed by Gautschy (1993) and Zalewski (1993) showing that pulsations may be excited in "cool" CSPN. This possibility was also invoked by recent observational studies

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(Kuczawska et al. 1996, hereafter KZW), which were, however, based on relatively small amounts of data. Further observations of HD 35914 were reported by Jasniewicz (1987) as well as by Bond & Ciardullo (1991).

Interestingly, the period analyses of the different authors did not agree: some concluded that no periodicity is present, while some claimed to have detected at least quasi-periodicities. Such findings from single-site data can be caused by several different kinds of behavior of the star. For instance, it could be multiperiodic and aliasing results in power spectra being too complicated to be correctly interpreted. Another possibility is that the light and radial velocity variations are periodic, but the changes in the mean light level produce spurious results. Of course, the star could indeed be an intrinsically irregular or semiregular variable.

In an attempt to resolve the question of whether HD 35914 shows periodic light variations or not, a photometric multisite campaign was organised in 1993 (December). In this paper we report the results of this campaign and we attempt to investigate comprehensively the behavior of HD 35914. In Sect. 2 we describe our observations, Sect. 3 is devoted to data reduction, and in Sect. 4 we analyse our data. Section 5 contains a re-analysis of the data by Jasniewicz (1987) as well as those by MVK and MFL. We discuss the results in Sect. 6 and summarize our findings in Sect. 7. Moreover, we have organized a simultaneous spectroscopic and photometric campaign for HD 35914 (Méndez et al., in progress), whose results we will publish as Paper 2 in this series.

2. Observations

Multisite photometric observations of HD 35914 were carried out in December, 1993. To explore the light variability of the star over a wide range of time scales and to compare the applicability of different methods, a variety of observing techniques was used in the campaign.

Conventional differential aperture photometry through Johnson B and V filters was acquired at South African Astronomical Observatory (SAAO) with the 0.5 m telescope (observers: R. Medupe and D. W. Kurtz), at Perth Observatory, Australia with the 0.6 m telescope (P. V. Birch) and at the San Pedro Mártir (SPM) Observatorio Astronómico Nacional, Mexico, with the 0.8 m telescope (observers: R. Costero and M. Alvarez). High-speed photometric measurements through a Johnson V filter at Mount John University Observatory (MJUO), New Zealand, were obtained by D. J. Sullivan with the 1.0 m telescope and a two-channel photometer.

Differential time-series photometric observations were acquired through apertures large enough to include the whole nebula. HD 35734 and BD-12 1174 were used as comparison stars; both objects were already measured by earlier observers and were not found to be variable. New $uvby\beta$ photometry of these stars (Handler 1995) shows that they are outside of the instability strip.

To be able to search for low frequencies in the high speed photometric data and to check nightly changes of the mean magnitude of HD 35914, the high speed measurements were interrupted at irregular intervals to monitor HD 35734 for about two minutes (for a further discussion of this technique we refer to Breger & Handler 1993).

CCD observations with a Johnson V filter were made with the 0.8 m telescope at Observatorio del Teide (OT), Tenerife by A. Herrero and M. A. Guerrero, using a Thomson 1024×1024 CCD; this detector/telescope combination produced images with 5.4 electron readoutnoise, and a scale on the CCD of $0\farcs44$ per pixel. Typically, each observation consisted of a series of 35 to 60 second exposures, roughly centered on IC 418. The seeing through most of these observations varied between $1\farcs5$ and $2\farcs0$, although periods of worse seeing (and substantial cirrus) also occurred.

An overview of the observations is given in Table 1.

3. Data reduction

3.1. Photoelectric measurements

The photoelectric measurements were corrected for coincidence losses, sky background and extinction. Differential magnitudes of the comparison stars were calculated and no evidence for variability of HD 35734 and BD-12 1174 with an upper limit of 1 mmag was found. Consequently, standard B and V magnitudes for all stars were calculated.

The next step in the reduction procedure was the removal of the nebular contribution to the measured program star magnitudes to be able to examine the data for color variations and to determine the intrinsic amplitude of the light modulations. Although Johnson B and V filters were used at all observatories, differences up to 0.2 mag in the (star + nebula) measurements were found between the different telescopes. These deviations are not intrinsic to the star, which can easily be confirmed by checking overlapping measurements from different observatories. This effect might be due to the nebular [O III] emission at 5007 Å. This wavelength is near the steepest slope of the V filter transmission curve, and small differences in the bandpasses can of course yield differences in the measured (star + nebula) magnitudes.

Since no tracings of the transmission curves of the filters used were available, the standard procedure to remove the nebular flux from the data (as described by MFL) could not be adopted. Therefore, we proceeded as follows: preliminary tests convinced us that the average visual magnitude of the star alone had not changed significantly from the value of V = 9.93 mag determined by MFL. We then calculated the average B magnitude for the star alone, by using $(B-V) = (B-V)_0 + 0.7\,c$, where c is the logarithmic extinction at Hβ (for IC 418: c = 0.30, Shaw & Kaler 1989). We adopted $(B-V)_0 = -0.29$ for a star with $T_{\rm eff}$ = 36000 K (Méndez et al. 1992, Napiwotzki et al. 1993). This gave a mean B of 9.85 mag for the central star. Consequently, the necessary flux was removed from the (star + nebula) data to yield the above mean stellar magnitudes for each observatory.

Table 1. Journal of the observations

Date (UT)	Start (UT)	Start (HJD 2449300 +)	Length (hrs)	Observatory	Observer(s)
5 Dec 93	7:52	26.832	4.1	SPM	MA
6 Dec 93	6:20	27.769	6.5	SPM	MA
7 Dec 93	20:16	29.349	5.7	SAAO	RM, DWK
8 Dec 93	19:20	30.310	5.2	SAAO	RM, DWK
9 Dec 93	10:53	30.958	1.1	SPM	MA
9 Dec 93	19:35	31.321	5.0	SAAO	RM, DWK
10 Dec 93	5:45	31.744	2.0	SPM	MA
10 Dec 93	13:26	32.064	4.0	Perth	PVB
10 Dec 93	19:04	32.299	6.8	SAAO	RM
11 Dec 93	10:06	32.926	2.5	MJUO	DJS
11 Dec 93	13:56	33.085	5.5	Perth	PVB
11 Dec 93	19:22	33.312	5.2	SAAO	RM
12 Dec 93	19:14	34.306	5.6	SAAO	RM
13 Dec 93	7:01	34.797	4.9	SPM	RC
13 Dec 93	13:28	35.066	5.6	Perth	PVB
14 Dec 93	5:05	35.716	6.5	SPM	RC
14 Dec 93	10:30	35.942	1.4	MJUO	DJS
14 Dec 93	13:04	36.049	6.0	Perth	PVB
14 Dec 93	13:20	36.060	1.6	MJUO	DJS
15 Dec 93	9:54	36.917	2.9	MJUO	DJS
15 Dec 93	23:21	37.478	3.6	OT	AH, MAG
16 Dec 93	5:33	37.736	5.6	SPM	RC
16 Dec 93	23:03	38.465	2.9	OT	AH, MAG
17 Dec 93	6:40	38.782	4.3	SPM	RC
17 Dec 93	19:14	39.306	1.3	SAAO	RM
17 Dec 93	23:19	39.476	3.4	OT	AH, MAG
19 Dec 93	19:14	41.306	5.5	SAAO	RM
20 Dec 93	19:17	42.308	6.6	SAAO	RM

Afterwards, overlaps of different sites were examined and corresponding magnitude shifts applied to align these overlaps. Fortunately, each observatory was involved in at least one overlap. These final magnitude shifts were smaller than 0.01 mag, suggesting that the variations of the mean magnitude of HD 35914 did not influence the reduction procedure significantly. While the rms scatter of the comparison star data is about 2 - 5 mmag depending on the observatory, we estimate that the reduced HD 35914 data have an accuracy of about 7 mmag per single measurement. This larger scatter is due to the nebular subtraction.

3.2. CCD observations

In total, our CCD observations consisted of 173 1024×1024 CCD frames. To reduce these data to a manageable format, we used a compaction algorithm prior to data analysis. After applying the overscan and flatfield correction to our CCD frames, we extracted 64×64 pixel regions surrounding IC 418 and 7 nearby field stars. These regions were then placed into a set of "packed" pictures, in which each image contained data from 16 individual frames.

Photometric reductions were then accomplished using a combination of IRAF and the point-spread-function fitting (PSF) routines of DAOPHOT (Stetson 1987). IC 418's comparison stars were first used to define each frame's PSF. The central $1\farcs6$ of this PSF was then used to measure the magnitude of HD 35914 relative to these stars. By restricting the PSF-fitting radius to a region of the order of the best seeing full-width-half-maximum, we ensured that the uncertainty introduced by HD 35914's nebula (whose contribution to an aperture magnitude changes with seeing), was minimized. This technique is capable of producing measurements with better than $\sim$ 0.01 mag accuracy, under both photometric and non-photometric conditions (cf. Howell & Jacoby 1986). We note, however, that since all of HD 35914's comparison stars are substantially ($\gtrsim 3$ mag) fainter than central star itself, the dominant error in the HD 35914 measurements does not originate from its nebula, but from the precision of the comparison star measurements.

The constancy of the comparison stars was checked; no evidence for variability for any of these objects was found. However, due to their different magnitudes, the residuals of the measurements of the individual stars showed different scatter. Thus, final synthetic comparison star magnitudes were computed by adopting a weighted mean of the measurements of the individual objects. These synthetic comparison star data were subtracted

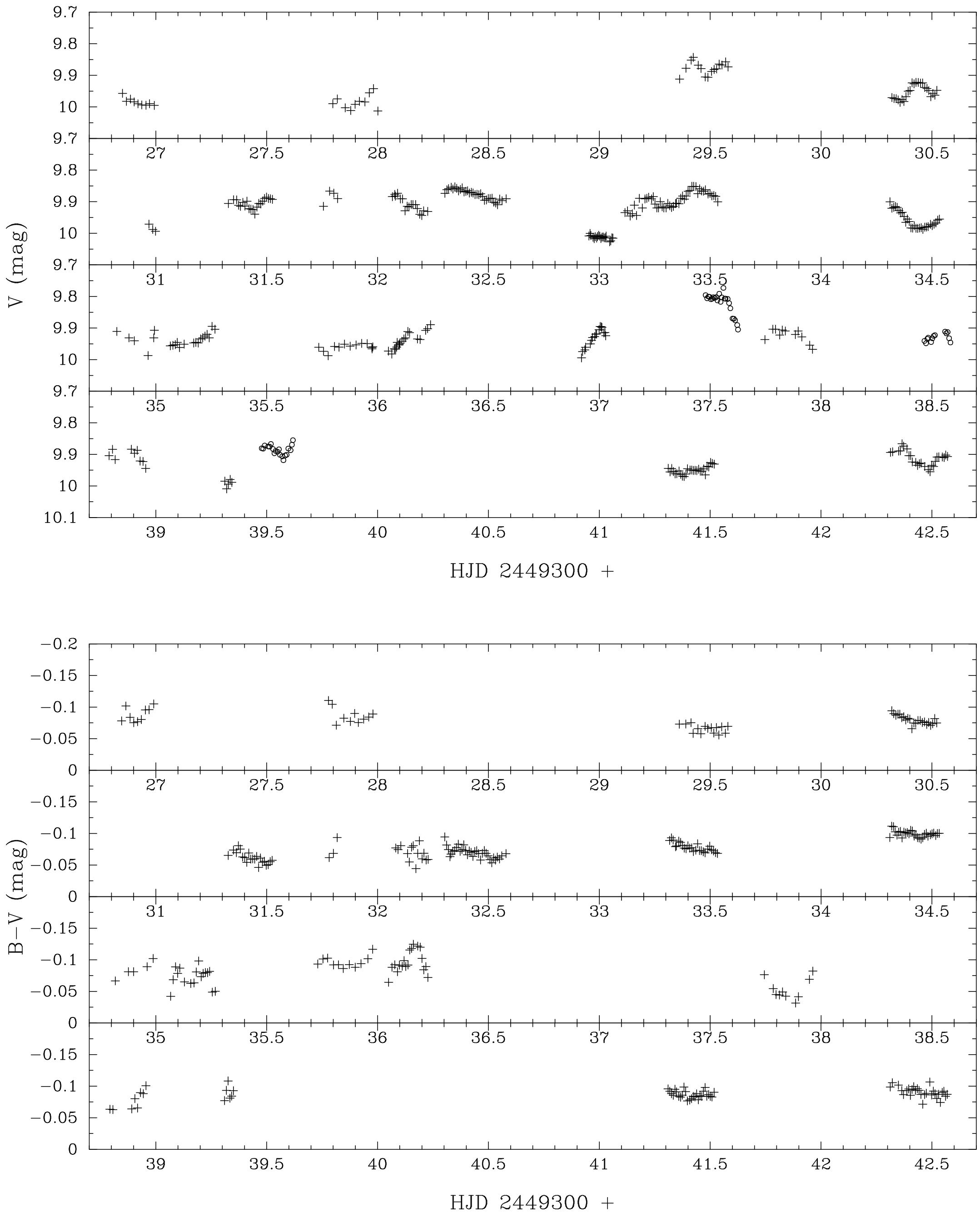

Fig. 1. Upper panel: Multisite V-filter light curves of HD 35914, high speed photometric as well as CCD data are binned (see text) Crosses: photoelectric measurements, open circles: CCD data. Lower panel: $(B - V)$ color variations of HD 35914

from the measurements of HD 35914 on a point-by-point basis. We estimate that the reduced CCD magnitudes of HD 35914 have an rms error of 8 mmag per single measurement, which is comparable to the scatter of the reduced photoelectric data.

Regrettably, the CCD observations did not overlap in time with any data set acquired at another observatory. Therefore, they could not be aligned with the other measurements, which has to be taken into account during data analysis. On the other hand, they are useful to check the adopted mean magnitude for the photoelectric data, since magnitudes of some comparison stars were already known. We find a mean V of 9.87 ± 0.05 mag for the CCD observations, which is in good agreement with the values adopted above. The check of the adopted average magnitude of HD 35914 is possible because the CCD reductions permit an adequate nebular subtraction. However, we did not use this value for our photoelectric data, since the mean V magnitude of HD 35914 determined by MFL is based on more measurements. Our error size for the mean magnitude of HD

35914 originates mainly from the uncertainties in the comparison star magnitudes and from the unknown transformation of the CCD magnitudes into the standard system; thus it is larger than the precision of a single HD 35914 measurement. Finally, all the times of measurement were converted into Heliocentric Julian Date (HJD). The reduced V and $(B-V)$ light curves are plotted in Fig. 1.

4. Analysis

4.1. Search for periodicities in the V light curves

Data analysis was mainly performed by using single-frequency Fourier and multiple-frequency least-squares techniques implemented in the program PERIOD (Breger 1990). First, the high-speed data were checked for possible high-frequency (50 cycles/day $< f < 8000$ c/d) signals. No such signal was found, even if the CCD data were added (for 50 c/d $<$ $f <$ 400 c/d). Consequently, the high-speed and CCD data were summed into 10 minute bins to give them similar weight to the differential photometric data in the subsequent analysis. An amplitude spectrum of all the data was calculated, showing that also no variability with frequencies between 10 and 50 c/d is exhibited by HD 35914. Therefore, we may restrict the analysis to frequencies lower than 10 c/d.

Similarly to the results of previous studies, slow variations of the mean magnitude of HD 35914 (with a time scale of a few days) can be seen in our data (Fig. 1). To search for periodicities in these mean magnitude variations, we can only consider the photoelectric data because the zeropoint of the CCD data could not be aligned with the other measurements (see Sect. 3.2). A power spectrum calculated for these data (Fig. 2) does not give any hint of periodicity. To allow for nonsinusoidal variations, the analysis was repeated by calculating residualgrams (see Martinez & Koen 1994) instead of power spectra, but again no convincing evidence for periodicity in the variations of the mean magnitude of HD 35914 could be found.

On the other hand, the light curve of Fig. 1 suggests that variability on shorter time scales (a few hours) is present in HD 35914. To examine these short-term modulations, the variations of the mean light level of the star need to be suppressed. Therefore, the zeropoints of single runs were adjusted, and straight lines were fitted to the two longer light curve segments near HJD 244 9333.3 and HJD 244 9336.0. Runs shorter than 2.5 hours were not included in the analysis, but the CCD data could of course be used. Numerical simulations indicate that our data treated in this way can be searched effectively for frequencies down to 2 c/d.

Consequently, power spectra and spectral windows were calculated for our data as well as for two subsets (HJD $<$ 244 9334.7 and HJD $>$ 244 9334.7). The subsets contained approximately the same amount of data and spanned a similar time interval. The results are shown in Fig. 3.

The broadening of peaks in Fig. 3b relative to Fig. 3c is due to the different distribution of the measurements in the data subsets. In Fig. 3a, many of the higher peaks are split. This

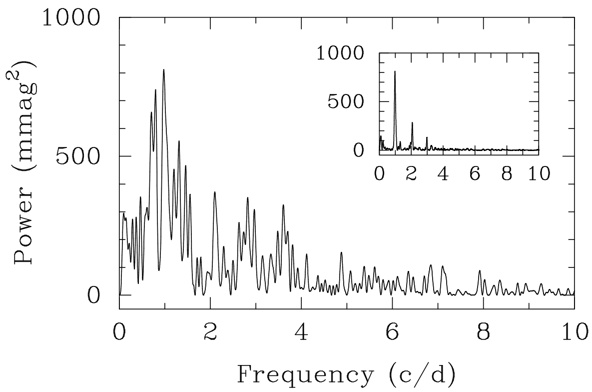

Fig. 2. Spectral window (inserted) and power spectrum of the data displayed in the upper panel of Fig. 1, but without the CCD data. We have calculated the spectral window by transforming a single sinusoid of frequency 0.976 c/d, corresponding to the highest peak in the lower panel, sampled exactly as the original data. This illustrates the effects of "reflection" of aliases at zero frequency, which are small for our data. Consequently, we will not further apply this method

can be caused by a changing frequency or by close multiple frequencies. To examine both hypotheses, we constructed an (O-C) diagram for the frequency corresponding to the highest peak in Fig. 3a near 3.7 c/d. That peak is also prominent in Figs. 3b and 3c, and is present in Fig. 2 as well. For the (O-C) diagram (Fig. 4) we have used both maxima and minima in the light curves, since they are generally sinusoidal. Epoch 0 was arbitrarily taken to be at HJD 2449300.000. The times of minimum were shifted by 0.5 cycles to be analysed together with the light maxima; a mean zeropoint of the combined data was subtracted.

Multiperiodicity with close frequencies, as can be suspected from Fig. 3a, would cause a smooth, sinusoidal trend in the (O-C) diagram; this is not the case in Fig. 4. Some scatter of the times of maxima and minima is present, but there is no evidence for a phase jump. An underlying regularity appears to exist, since the maxima/minima generally occur with phase shifts of less than 20% of a cycle. In case of irregular variability, the times of maxima/minima would be scattered over the whole diagram. Assuming multiperiodicity with several frequencies, we should be able to strongly decrease the residuals between light curve and fit by allowing a number of such signals. However, adopting this procedure never yielded satisfactory results; we would need to remove an unreasonably large number of frequencies.

To obtain more clues about the behavior of HD 35914, we also tried to subject our data to wavelet analysis (Szatmary et al. 1994). Regrettably, this attempt failed, since the duty cycle of our measurements was too low for wavelets to be applied. Thus, we are left with the results of our classical frequency analysis.

It is clear that HD 35914 cannot be a strictly periodic variable star. The variations with a time scale of a few hours can also not be reasonably explained in terms of (strict) multiperiodicity. On the other hand, since we found a signal near 3.7 c/d to be present throughout the whole data set (with some phase scatter),

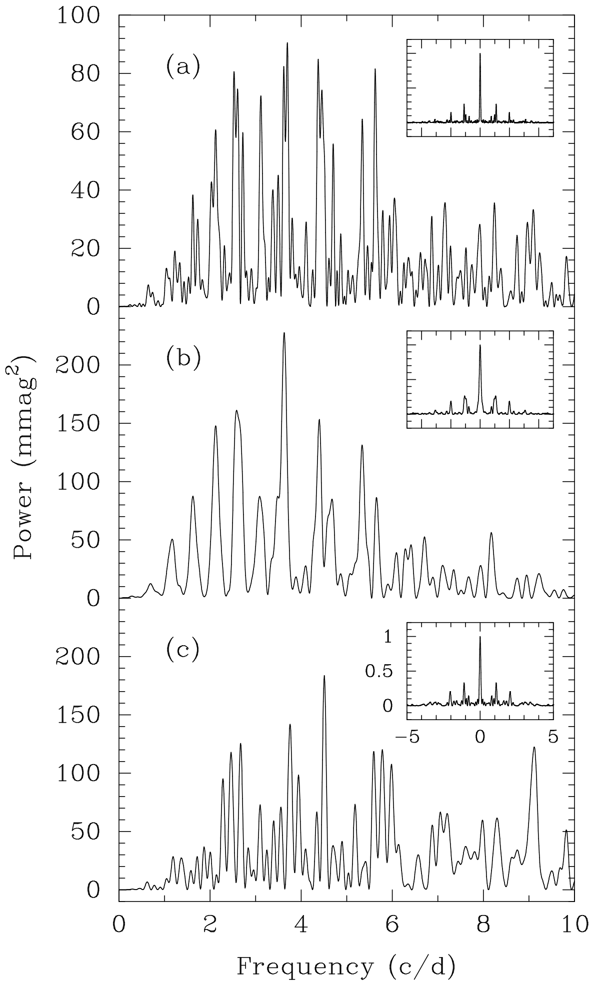

Fig. 3a–c. Amplitude spectra and spectral windows (insets) of the HD 35914 data corrected for variations of the mean light level. Panel **a** shows the transform of the full data set, **b** that of the first subset (see text) and **c** that of the second subset. Note the different ordinate scale of Panel **a**

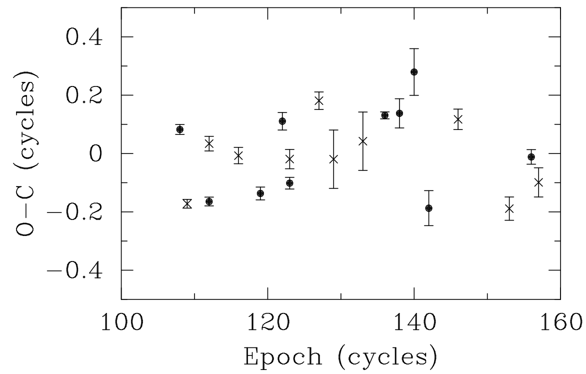

Fig. 4. (O-C) diagram for f = 3.7 c/d. Dots represent timings determined from light maxima, crosses those derived from minima (shifted by 0.5 cycles)

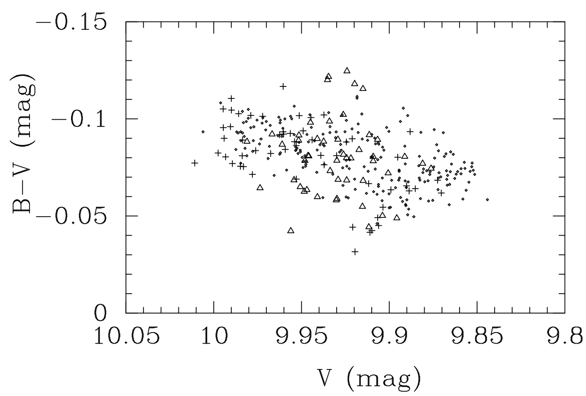

Fig. 5. The $(B - V)$ color of HD 35914 against its V magnitude. A general trend exists in the data, in the sense that HD 35914 is redder when it is brighter. Dots represent SAAO data, crosses are SPM data, triangles are Perth data. The trend occurs in the data of all three sites

we also do not want to designate the variability of HD 35914 to be irregular; we call it therefore semiregular.

4.2. Color variability

The $(B - V)$ color variations (Fig. 1) do not resemble the V filter data at all. On the other hand, as shown in Fig. 5, our measurements do suggest that the star is redder when it is brighter[1]. We first suspected that this could be caused by an inappropriate correction for the nebular contribution to the data. Let us explore this possibility:

We assumed the mean V magnitude of HD 35914 to be 9.93 mag (Sect. 3.2), and showed the difference to the value of 9.87 mag from our CCD observations is explained by the observational uncertainties. The only remaining possibility of error is that our assumed $(B - V)$ color is wrong. Therefore, we removed enough flux from the B data to achieve a minimum of color variability. We found insignificant color variability to occur at $(B - V)$ = +0.35 ± 0.10, which is an implausible value for an O star with $E(B - V)$ = 0.21, as determined in Sect. 3.1. From the measurements of Shaw & Kaler (1989) we can infer $(B - V) = -0.17 \pm 0.08$ for HD 35914 (since this value could be influenced by the stellar variability, we did not adopt it as our working $B - V$). This suggests that the color variability is intrinsic to the star and is not caused by an insufficient compensation for the nebular flux. However, we emphasize that this effect is marginal, and that the scatter in Fig. 5 is larger than the observational uncertainties.

Can we detect a cyclical variation in the $(B - V)$ data? To answer this question, we calculated the spectral window and

[1] In Fig. 5, it appears that there could be an error in the V magnitude zeropoint, since the SPM data seem to be shifted relative to the other measurements towards fainter V. However, when generating the same plot without the first two nights from SPM, this effect is no longer present. Since the instrumental setup was not changed during the run, we conclude that HD 35914 was indeed fainter at the beginning of the campaign.

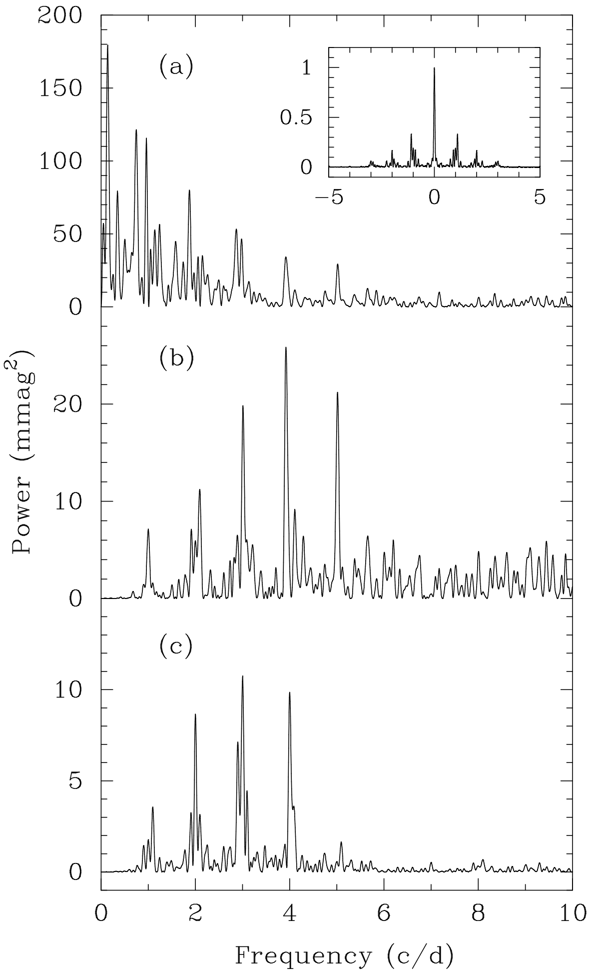

Fig. 6. a power spectrum of the $(B-V)$ measurements (spectral window inserted); **b** power spectrum of the color data after adjustment of zeropoints; **c** power spectrum of a simulated data set. This figure shows that we cannot detect a signal with a timescale of a few hours in these data (see text)

power spectra of these data, before and after adjusting the zeropoints of the different runs (Fig. 6).

Inspection of Fig. 6a suggests again, that there is no convincing evidence for a periodic signal in the data. However, it is interesting to note that the two peaks near 1 c/d can also be found in Fig. 2, implying that the color variability is associated with the trends in the mean magnitude of HD 35914. On the other hand, the prominent peak near 0.15 c/d in the color data is not present in Fig. 2.

In Fig. 6b we have plotted the power spectrum after adjustment of the $(B-V)$ zeropoints for each run. A peak near 4.0 c/d appears to dominate the power spectrum together with its aliases. However, keeping in mind the long-term trends in the data (Fig. 1), it is dangerous to accept such a frequency as real. Note also that the relative amplitudes of the apparent 1 c/d aliases compared to the central peak are different from those in the spectral window.

Due to the long-term trends in the HD 35914 magnitude, we are confronted with a sawtooth-like structure in the data after the zeropoints are adjusted. It is well known that Fourier analysis of such data yields peaks at frequencies corresponding to the spacing of the times of zero amplitude and its harmonics. To illustrate the consequences of such trends in our data, we created an artificial data set, sampled exactly as our $(B-V)$ measurements, and introduced magnitude changes – linearly rising by 0.01 mag per 8 hours – in each run. The power spectrum of this artificial data set is plotted in the lower panel of Fig. 6. There is a striking resemblance to the middle panel. Again, we see peaks near integer frequencies (since our data do not have 100 % duty cycle and can be regarded as combined single-site observations), and an apparent alias structure different from that expected from the spectral window. The latter reflects the different run lengths and that the signal is not coherent. It should also be noted that the occurrence of the highest peak at different frequencies for the real data and the simulation is not disturbing, since we only simulated trends towards decreasing magnitudes, while the measurements contain trends towards both increasing and decreasing brightness of HD 35914.

We conclude that we are unable to detect a periodic or cyclic signal in our color photometry. There is, however, evidence that the color variations of HD 35914 are connected with the changes in the mean brightness of the star.

We should also comment on the result of KZW, who suggested that HD 35914 is bluer when brighter, opposite to our finding. This difference is easily explained: KZW did not remove the nebular flux from their data, and therefore any statement about color variability in their study is doubtful.

4.3. Summary of observational results

We have found that HD 35914, the central star of the Planetary Nebula IC 418, exhibits light variations with the following characteristics:

1. It varies on two different timescales: of the order of a few days and of the order of a few hours.
2. The long-term light variations show no evidence of periodicity.
3. The short-term modulations are not periodic, but they appear to be semiregular with a timescale of 6.5 hours.
4. The star is in general redder when it is brighter.
5. The $(B-V)$ color variability is related to the long-term variations, but it is not related to the light modulations occurring on a timescale of hours.

5. Reanalysis of published observations

Here, we wish to compare the results of previous extensive studies of HD 35914 with ours. We will examine the data of MVK, MFL and Jasniewicz (1987), concentrating on the short-term variations, since the data sets are not well suited to analyse the slower variability.

5.1. The 1984 and 1985 photometry of Jasniewicz

Jasniewicz (1987) observed HD 35914 on 20 nights in 1984 and on 9 nights in 1985 in the Geneva system. However, several of the runs consisted of only 2 measurements per night. These were not included in our analysis. Moreover, his runs were all shorter than 3.3 hours. Although such data are not well suited for a search for periodicities of several hours or longer, we can get an idea of the timescales present.

We only considered runs longer than 1.5 hours. Therefore, we restrict ourselves to the examination of 12 nights between HJD 2445965 and HJD 2445981 in 1984 as well as 4 nights between HJD 2446322 and HJD 2446327 in 1985.

For the 1984 data set we obtain a "best" frequency of 5.77 c/d. However, because of the short runs we must be aware of the effects of zeropoint adjustments, which were, regrettably, necessary. Calculating a power spectrum of a single sinusoid with a frequency of 3.77 c/d sampled in the same way as the original data and adjusting the nightly zeropoints also yields the highest peak at 5.77 c/d. Since the 3.77 c/d frequency is similar to that we found in Sect. 4.1, we conclude that the behavior of HD 35914 might have been the same in 1984 as it was in 1993.

The runs acquired by Jasniewicz in 1985 were shorter than those from 1984. A frequency analysis of these data does not give evidence that the star's behavior was different from 1993.

5.2. The 1979 – 1984 data of Méndez et al.

MVK acquired 4 nights of photometry in 1983 and several nights of spectroscopy in 1979 to 1982, while MFL obtained 3 nights of simultaneous photometry and spectroscopy in 1984.

Frequency analysis of the 1983 photometry does not allow us to extract much information, but we estimate that the time scale of the light variations was approximately the same like the one present in all the data we analysed so far. Upper limits for possible periodic radial velocity changes are about 10 km/s for the 1980 data, but 20 km/s in 1982.

The power spectrum of MFL's photometric data after nightly zeropoint adjustments shows the highest peak near 7.0 c/d. However, since two of the three runs obtained by Méndez et al. were longer than 5.5 hours and thus sampled more than one cycle per night, we cannot solely make zeropoint adjustments responsible. We conclude that at least during the last two nights of measurement by MFL the dominating timescale of the light variations of HD 35914 was shorter than in most of the other photometric observations.

We searched for similar behavior in our new light curves. Indeed, when considering only the first two nights of our SAAO data, we see that the variability also appears to occur on a shorter timescale. A power spectrum of these two nights only exhibits two dominating peaks of about the same height near 5.9 and 6.9 c/d, very similar to the power spectrum of the MFL photometry. Since these SAAO light curves were also used for the (O-C) diagram (Fig. 4, they constitute the first 4 points), we cannot construct sufficient evidence from the 1984 photometry of MFL to conclude that HD 35914 behaved substantially differently.

As in most other data sets, the dominating timescale present MFL's C IV absorption radial velocity variations is a few hours. There is some similarity to the radial velocity behavior in 1980, but not to the simultaneous photometric data. For the latter, we refer to the discussion of MFL; we will comment on them in Sect. 6.3 as well.

Finally, we re-examined the dependence of the brightness of HD 35914 to the equivalent width of the stellar C IV absorptions. Considering each of the two nights separately, we find no correlation. This suggests that the trend discovered by MFL can, if real, only be associated with the long-term light variations of HD 35914.

5.3. The behavior of HD 35914 in the last 15 years

From the analyses and discussion above, we have found no convincing evidence that the star has substantially changed the characteristics of its variations. Although we are aware that the term "semiregular" is somewhat diffuse and can be misused, we are careful to note that we have presented evidence for an underlying regularity in the light variations (Fig. 4). Our interpretation, that HD 35914 shows semiregular light variations with a timescale of about 6.5 hours can also be applied to the older data we re-analysed. The observations reported by KZW as well as Maene et al.'s (1994) photometry (Bond, private communication) are also consistent with this picture. It appears reasonable that HD 35914 exhibited the same kind of variability over the last 15 years.

6. Discussion

To interpret the nature of the light variations of HD 35914, we need to consider four possible scenarios: rotational modulation of surface features, binarity, pulsations and stellar wind variations. Some of those interpretations were already discussed by previous authors. However, since we wish to present some new arguments, we will carefully consider all possibilities.

6.1. Rotational modulation

Light modulation of HD 35914 generated by co-rotating surface features would require a relatively high rotational velocity. Therefore, it is important to test whether this is plausible. An estimate of the rotational period of the nucleus of IC 418 can be obtained by using

$$P_{crit} = \frac{2\pi R_{eq}^{3/2}}{(GM)^{1/2}}, \quad (1)$$

where R_{eq} is the equatorial radius of the star. Following the discussion by Reid et al. (1993), we estimate $R_{eq} = 1.5\,R$, where R is the radius of HD 35914, if it were not rotating. Adopting results of model atmosphere analyses by Méndez et al. (1992): T_{eff} = 36000 K, log g = 3.45 and $M = 0.67\ M_\odot$, we find P_{crit} = 25 hours. This is much longer than the time scale of the short-period light modulations of HD 35914. Therefore, an interpretation involving co-rotating surface features would require at least 4 “spots”. However, these spots cannot be concentrated in small surface areas, since we would then see light curves with very nonsinusoidal shapes. Consequently, geometric cancellation effects will become important and significantly reduce the photometric amplitude of the light variations. Therefore, we would expect substantial line profile variations. However, spectrograms mentioned by MFL did not give evidence for line-profile variability of HD 35914.

Thus, rotational modulation cannot be the cause for variability of HD 35914 with a time scale of 6.5 hours. Moreover, we can rule out that this effect is responsible for the long-term variability, since the star would in this case be bluest when brightest, opposite to the result of Sect. 4.2.

6.2. Binarity

Several central stars of Planetary Nebulae have been shown to be close binaries. Their light variations are caused by eclipses as well as reflection effects of the heated hemispheres on cool companions to the hot primary. The orbital periods are between a few hours and a few days, similar to the variations we found for HD 35914. The secondary stars in such binaries are typically M dwarfs, i. e. stars less massive than about 0.5 $M_{\odot}$ (e. g. see Chen et al. 1995). Could HD 35914 be an early stage of such a system?

It should be pointed out that the failure to find a clear short-term periodicity in our and in the earlier data does not preclude that HD 35914 is a component of a binary system. Since the star is by far larger than a pre-white dwarf ($R \approx 2.6 R_{\odot}$, as inferred from the spectroscopic results of Méndez et al. 1992), there will still be mass transfer between the components. It is well known that mass transfer can “mask” the orbital period of a binary. Therefore, we cannot immediately rule out a binary hypothesis; we must carefully examine this possibility. Moreover, the light variations in close binary systems have a double-wave pulse shape, and therefore we must adopt twice the photometric period as our working orbital period.

Assuming reasonable secondary masses, we can now compute the primary’s radial velocity amplitude, again using the results by Méndez et al. (1992). Making use of our knowledge that the semi-amplitude of the short-period radial velocity variations of HD 35914 was less than 10 km/s in 1980 and 1984, we can then infer an upper limit for the inclination of the orbital plane of our hypothetical binary. This can then easily be converted in the probability that the binary hypothesis is feasible by assuming a random orientation of the orbital plane. The result of this simulation is shown in Fig. 7.

The probability that HD 35914 is the primary star in a binary with an orbital period of about 13 hours is very low. If the secondary had a mass of 0.2 $M_{\odot}$, the probability of not detecting orbital motion of HD 35914 is less than 12 % (Fig. 7). Thus, we conclude that the binary hypothesis is not very promising.

It is tempting to infer the orbital inclination by assuming that the rotation of HD 35914 is synchronized with the orbital period of the hypothetical binary. Then, one can determine sin i by assuming possible secondary masses and comparing the re-

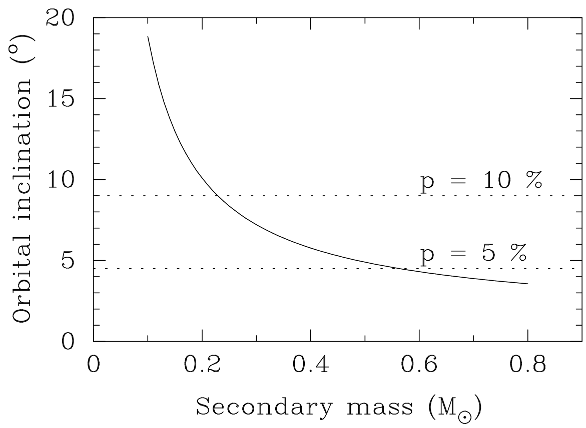

Fig. 7. Maximum orbital inclination of a hypothetical binary with HD 35914 as primary component versus secondary mass (see text)

quired rotational velocity with the measured one. However, a nonrotational source of line broadening seems to exist for early O stars (see the discussion by Heap 1977). Therefore, we cannot assume a rotational velocity of HD 35914 and cannot further constrain the orbital inclination of the hypothetical binary.

One might speculate that the long-term light variation could be caused by binarity. However, in Sect. 4.1 and Sect. 4.2 we failed to detect periodicity in the long-term modulations. For accepting the view that HD 35914 is contained in a wide binary, we would however expect periodic light variations, since such a binary would be detached, i.e. no mass transfer would mask the signatures of a reflection effect.

6.3. Pulsation

If we suppose that the 6.5-hour variability of HD 35914 is due to pulsation, we can calculate the pulsation “constant” Q, adopting M, T_{eff} and log g quoted above and find Q = 0.055 d. Fig. 2 of Gautschy (1993) suggests Q = 0.05 d for the radial fundamental mode found to be unstable by him for a model of HD 35914. It is also conceivable that the star does not pulsate regularly (in analogy to semiregular variables), explaining the (O-C) diagram (Fig. 4).

As already noted by KZW, the model light and radial velocity curves reported by Zalewski (1993) are highly interesting in this context. His hottest model shows light curves very similar to those we and other researchers acquired for HD 35914: they are not strictly periodic, but rather semiregular with occasional features suggesting a shorter timescale of variability. Moreover, his radial velocity curves do not resemble his light curves closely, but they appear to be at least more regular; this is consistent with the behavior of HD 35914 reported by MFL. Together with KZW, we strongly suggest that such calculations should be extended to models with temperatures similar to HD 35914, as this might substantially improve our understanding of the nucleus of IC 418 and related objects.

On the other hand, since we did not find evidence for color variability with a time scale of 6.5 hours in agreement with

MFL, it is hard to explain the star's light variations in terms of pulsation. However, since we adopted $(B-V)$ to monitor color variations, any color variability may be hidden in the noise of the observations. Finally, we could also be confronted with nonradial pulsations, which will cause smaller color variations than radial modes.

Although we cannot currently prove or reject a pulsational origin of the light variations of HD 35914, we want to point out one intriguing possiblity: the period change of a pulsating star can be expressed as

$$\frac{d\ \ln P}{dt} = -0.69\frac{dM_v}{dt} + 3\frac{d\ \ln T_{eff}}{dt} + \frac{d\ \ln Q}{dt} + \frac{d\ \ln M}{dt} \qquad (2)$$

Equation 2 can be easily inferred by substituting into the formula for the period-mean density relation $Q = P\sqrt{\rho_*/\rho_\odot}$, for the latter see Cox (1980).

Neglecting all the terms on the right hand side of Eq. 2 except the effective temperature term (which is by far the largest in this case), we can easily estimate an expected change in the pulsational period of HD 35914 by adopting the evolutionary temperature changes of the 0.625 $M_\odot$ post-AGB model of Blöcker (1995), which comes closest to the spectroscopic mass of HD 35914 (0.67 $M_\odot$). This would yield a large dP/dt of about 2.5×10^{-6} s/s which could be measured within one observing season, despite the fact that the light variations of the star are not strictly periodic. Moreover, due to the strong dependence of the evolutionary speed of post-AGB models on their mass, this would offer the unique chance to determine the masses of some CSPN.

6.4. Wind variations

Line profile variations in OB stars can occur on time scales shorter than one hour, and are associated with variable "Discrete Absorption Components" (DACs). Spectroscopic observations suggest a highly structured, evolving nature of the winds. Physically, the most promising idea to generate this phenomenon appears to be line-driven instability, resulting in dense clumps propagating through the wind (e. g. Feldmeier 1995 and references therein). Such a mechanism might also cause photometric variability.

It is interesting that the time scale of DAC variability appears to be correlated with the rotational period of the star (e. g. Kaper et al. 1996). However, it is not yet clear whether DACs and the wind structure repeat over several rotation cycles, remaining in the same phase. It is also unknown what mechanism should tie the time scale of the wind variability to the rotational period. One hypothesis is the existence of a localized magnetic field causing a non-axisymmetric wind.

If we attribute the short-term light modulations of HD 35914 to variations in the structure of its wind, we must explain that the light maxima and minima occur with some phase scatter, but with underlying regularity. The idea invoking a weak magnetic field is conceivable in this context, but (as discussed in Sect. 6.1) since the rotational period of HD 35914 is at least 4 times larger than the time scale of its short-term variability, we would also expect cancellation for disk-integrated observations. Therefore it is also hard to explain the short-term variations of the star by wind variations. Another possibility may be that the mechanism generating wind variability of massive O stars is different from that operating in CSPN.

On the other hand, if the wind variability of HD 35914 were responsible for the long-term light variations, we are able to speculate on the fact that the star is redder when it is brighter: as the density enhancements in the stellar wind move away from the photosphere, they increase the optical thickness of the atmosphere and thus the star appears brighter. But they also cool, thus generating a redder color.

To explore the connection of the variable wind of HD 35914 to the star's brightness variations, we have organised a second multisite campaign for this intriguing object. Both photometric and spectroscopic data were acquired (mostly simultaneous). These data are currently being reduced and analysed and will be published elsewhere (Méndez et al., in preparation).

7. Summary and conclusions

We conducted a multisite campaign of HD 35914, the central star of the Planetary Nebula IC 418. From 120 hours of photometric data acquired using both photomultipliers and CCD detectors, we found that the star varies on two different time scales: of the order of days and of the order of 6.5 hours. The long-term light variations show no evidence of periodicity, but are accompanied by color variations, in the sense that the star is generally redder when it is brighter. On the other hand, the short-term light modulations are neither (multi-)periodic, nor are they irregular.

We ruled out rotational modulation of surface features for both kinds of variability, and showed that binarity is very unlikely. On the other hand, we found evidence that the star could be a pulsating variable and thus be the prototype of a new class of pulsators. We also considered the case of wind variability, but could not quantify its role because of a lack of suitable spectroscopic observations.

In case it can be shown that HD 35914 and related objects are pulsating, it will be very interesting to apply pulsation theory to these objects. This will offer the possibility to check results of determinations of stellar parameters by spectroscopy. Moreover, we would have the unique chance to trace stellar evolution in this part of the HR diagram by measuring period changes, which are expected to be enormous. The most intriguing possibility is, however, the chance to determine the masses of several central stars of Planetary Nebulae.

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References

Balona, L. A., 1992, MNRAS 254, 404
Blöcker, T., 1995, A&A 299, 755
Bond, H. E., Ciardullo, R., 1991, ASP Conf. Ser. 11, 529
Breger, M., 1990, Communications in Asteroseismology 20, 1 (University of Vienna)
Breger, M., Handler, G., 1993, Baltic Astronomy 2, 468
Chen, A., O'Donoghue, D., Stobie, R. S., et al., 1995, MNRAS 275, 100
Cox, J. P., 1980, *Theory Of Stellar Pulsation*, Princeton University Press, p. 8
Dziembowski, W. A., 1977, Acta Astron. 27, 203
Gautschy, A., 1993, MNRAS 265, 340
Gilra, D. P., Pottasch, S. R., Wesselius, P. R., van Duinen, R. J., 1978, A&A 63, 297
Handler, G., 1995, IBVS 4216
Heap, S. R., 1977, ApJ 215, 609
Howell, S. B., Jacoby, G. H., 1986, PASP, 98, 802
Howarth, I. D., Bolton, C. T., Crowe, R. A., et al., 1993, ApJ 417, 338
Jasniewicz, G., 1987, PhD thesis, Universite de Strasbourg
Kaper, L., Henrichs, H. F., Nichols, J. S., et al., 1996, A&AS 116, 257
Kuczawska, E., Zola, S., Wlodarczyk, K., 1996, A&A, in press (KZW)
Maene, S. A., Ciardullo, R., Bond, H. E., 1994, BAAS 26, 1386
Martinez, P., Koen, C., 1994, MNRAS 267, 1039
Méndez, R. H., Verga, A. D., Kriner, A., 1983, Rev. Mex. Astron. Astrofis. 8, 175 (MVK)
Méndez, R. H., Forte, J. C., López, R. H., 1986, Rev. Mex. Astron. Astrofis. 13, 119 (MFL)
Méndez, R. H., Kudritzki, R. P., Herrero, A., 1992, A&A 260, 329
Napiwotzki, R., Schönberner, D., Wenske, V., 1993, A&A 268, 653
Prinja, R. K., 1988, MNRAS 231, 21P
Reid, A. H. N., Bolton, C. T., Crowe, R. A., et al., 1993, ApJ 417, 320
Reid, A. H. N., Bohlender, D., Bolton, C. T., et al., 1995, in *Astrophysical Applications Of Stellar Pulsation*, eds. R. S. Stobie & P. A. Whitelock, IAU Coll. 155, p. 309
Shaw, R. A., Kaler, J. B., 1989, ApJS 69, 495
Stetson, P., 1987, PASP, 99, 191
Szatmary, K., Vinko, J., Gal, J., 1994, A&AS 108, 377
Zalewski, J., 1993, Acta. Astron., 43, 431

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