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Photometric observations of the nucleus of IC 418

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Abstract. We discuss the observational characteristics of a recently proposed class of variable central stars of planetary nebulae. We summarize previous observations of the nucleus of IC 418, a prototype star of this class, and we analyze new photometry of this object, obtained in 1989 and 1991. We confirm that the characteristic timescale of the photometric variations is a few hours. No single period can fit all of our observational runs, implying that the variability is either irregular or multimodal. We discuss two possible explanations of the observed phenomena: (i) an unstable, radiatively driven wind and (ii) pulsational instability driven by the κ-mechanism. We also consider the possibility that the observed variability is produced by a combination of both mechanisms and that they may influence each other.

Key words: stars: post-AGB, oscillations, mass-loss, individual: HD 35914 – planetary nebulae: IC 418

1. Introduction

One of the first and most extensive observational studies of the central star of the planetary nebula IC 418 was presented in a series of papers by Mendez et al. (1983, 1986), drawing attention to the unusual features of this object. Irregular spectroscopic and photometric variations over timescales of hours were unambiguously detected. However, it has turned out to be very difficult to come up with a plausible interpretation of these variations. The most likely explanation seemed to be wind variability. Since then, several other planetary nebulae whose central stars show similar behaviour were identified. These include: He 2-131, He 2-138, PB 8, NGC 2392, IC 4593, NGC 6826, NGC 6543, Hu 2-1, IC 3568, NGC 40, IC 2149 (Bond & Ciardullo (1989); Bond & Livio (1990); Hutton & Mendez (1993)). The common characteristics of these objects are:

- the presence of a compact, high-surface-brightness nebula, suggesting that they are nuclei of relatively young planetaries
- relatively low effective temperature, in the range between 27 000 and 50 000 K
- spectral type mostly between O4f and O7f, in some cases Of-WR or WC (for a definition of the spectral characteristic "f" see Mendez et al. (1990))
- the presence of strong stellar wind, as revealed by ultraviolet and/or optical spectroscopic observations
- short-term radial velocity variations and/or changes in emission features and P Cygni profiles
- photometric variability up to $0\overset{m}{.}15$ over timescales of several hours and/or differences in light level by a few hundredths of a magnitude from night to night
- the observed photometric and spectroscopic changes do not show any well-defined periodicity

Some of these features are not unusual for nuclei of planetary nebula (PNN), and are in good agreement with the standard models for post-asymptotic giant branch (post-AGB) evolution. For example, young planetaries are predicted to possess nuclei of relatively low effective temperatures.

Photometric variations of PNN are often caused by eclipses or hemispheric heating effects produced in binary systems. Until now, we know about a dozen cases of such PNN (Kuczawska & Mikołajewski 1993, and references therein). Unfortunately, none of the objects listed above show satisfactory evidence of binarity. Also, they obviously can not be associated with the group of nine PNN known to show multiperiodic, nonradial g-mode pulsations, which are all extremely hot, hydrogen deficient pre-white dwarfs with periods in the range between 10 and 30 min. (Bond et al. 1993). Therefore, the PNN listed above constitute a separate, new group still waiting for a complete observational and theoretical description.

In what follows, we attempt an analysis of the nucleus of IC 418 – a prototype star of this group.

2. Previous observations

The planetary nebula IC 418 contains the relatively bright ($V = 10^{m}$) central star HD 35914. Heap (1977) classified HD 35914 as an O7f star.

Gilra et al. (1978) reported variability of HD 35914 in the ultraviolet stellar flux from Netherlands Astronomical Satelite

Send offprint requests to: E. Kuczawska data. Over a 5 h interval, the photometric variations reached 4% at 3300 Å and 15% at 1550 Å (about $0\overset{\mathrm{m}}{.}1$). Apart from photometric variations, they also discovered spectroscopic changes in the intensity of the stellar C IV doublet at 1550 Å. The observations were not made frequently enough to determine a periodicity.

Mendez et al. (1983) obtained spectra of HD 35914. They noticed that all stellar absorption lines move in phase (with the C IV absorptions usually more blueshifted than the rest). Stellar emission in the C III line was almost stable, while stellar He II emission was varying in antiphase with the absorption features. They failed to find a well-defined period in this variability, although on some nights the variability could be well fitted with any of the following periods: $0\overset{\mathrm{d}}{.}165$, $0\overset{\mathrm{d}}{.}198$ or $0\overset{\mathrm{d}}{.}248$. They also detected photometric variations of HD 35914 on a timescale of about $0\overset{\mathrm{d}}{.}2$ with a mean amplitude of about $0\overset{\mathrm{m}}{.}05$ (in the y filter), which again did not appear to be periodic.

In a subsequent study Mendez et al. (1986) performed simultaneous spectroscopic and photometric monitoring of HD 35914. The $ubvy$ light curve revealed variations with a timescale of $0\overset{\mathrm{d}}{.}17$ and an amplitude between $0\overset{\mathrm{m}}{.}06$ and $0\overset{\mathrm{m}}{.}1$. On the basis of color changes they estimated the upper limit for surface temperature variations to be 1 000 K. As for spectroscopy, none of previously suggested periods was confirmed. The radial velocity of stellar C IV absorptions seemed to increase very abruptly by 20–30 km s^{-1} and decrease quickly to the same value it had before the "high velocity episode", i.e. about 50 km s^{-1} more negative than the nebular velocity. On some nights, the duration of the whole episode was as short as $0\overset{\mathrm{d}}{.}1$. They found a positive correlation between stellar brightness and C IV equivalent width.

Jasniewicz (1987) observed substantial variations of the nucleus of IC 418, (for brevity we denote the nucleus of IC 418 by IC 418, hereafter), but failed to obtain any period. Bond & Ciardullo (1990) described IC 418 as irregularly variable, although they noticed sinusoidal variations on some nights. Włodarczyk & Zoła (1990) reported photometric observations in which the light curve appeared sinusoidal. They estimated a period of variability of about 5 h. Very recently, a photometric multisite campaign devoted to IC 418 (Handler et al. 1996) revealed two kinds of variability: irregular light modulation with a time scale of days and cyclic variations with a time scale of 6.5 hours.

3. New photometric observations

In 1989 we observed IC 418 at Mt. Suhora Observatory of the Cracow Pedagogical University, using the 60-cm Cassegrain telescope with a double-beam photometer. The star BD -12.1174 has been used as a comparison star. The diaphragm had a diameter of 40″, which ensures that the contribution of the nebula to the total observed flux was stable all the time (since the angular diameter of the main bright shell is equal to 12″.4; Meatheringham et al. 1988). The integration time was 30 sec. The differential B light curve of IC 418 (in the sense HD 35914 plus nebula minus BD -12.1174) is shown in Fig. 1. The first observational run was already presented in a preliminary report of Włodarczyk & Zoła (1990), but we include it here for completeness. The maximum range of variation in the B filter was about $0\overset{\mathrm{m}}{.}04$.

Table 1. The results of Fourier analysis applied to 2 groups of consecutive nights

Nights	Filter	Frequency (c d^{-1})	Error (c d^{-1})	Power
Jan. 27/28 and 28/29 1989	B	q = 3.45	±0.14	0.00124
Jan. 8/9, 9/10 and 10/11 1991	U	f = 0.50	±0.05	0.00245
		v = 3.99	±0.05	0.00238
	V	f = 0.52	±0.07	0.00135
		v = 3.95	±0.07	0.00152

In our analysis we also took into account the differential photometry of IC 418 obtained in 1991 by Jerzykiewicz (1994) at the South African Astronomical Observatory. These observations used the stars HD 36049 and BD -12.1174 for comparison. The extinction-corrected differential U and V magnitudes of IC 418 he obtained are presented in Fig. 2a, along with the $U-V$ color changes (Fig. 2b). The maximum range of variations reached $0\overset{\mathrm{m}}{.}053$ in the U filter and $0\overset{\mathrm{m}}{.}048$ in the V filter.

The variations reported in this paper refer to the total light (central star together with the surrounding nebula), thus they amount to the lower limit of stellar variability. Due to constraints imposed by light travel time and recombination time considerations, the nebula is not expected to vary over timescales reported in this paper, therefore we feel justified not to subtract the nebular contribution for our purposes.

We determined moments of minimum and maximum light using the Kwee and van Woerden method:

$$\mathrm{JD_{hel}\,(min)} \;=\; 2\,447\,554.322 \pm 0.001 \quad (1)$$

$$\mathrm{JD_{hel}\,(max)} \;=\; 2\,448\,266.446 \pm 0.002 \quad (2)$$

4. A search for periodicity

In spite of limited observational material we attempted to examine our observations for the presence of periodicities. We used the Deeming (1975) method of Fourier analysis of irregularly sampled data. We analyzed independently the data obtained in 1989 and 1991 (cf. Figs. 1 and 2a). The results are collected in Table 1.

For each group of nights we give the dominant frequencies along with the corresponding errors estimated with the use of a graphic procedure described by Schwarzenberg-Czerny (1991). The power corresponding to each frequency is given in arbitrary units. No high-frequency (i.e. above 10 cycles/day) signal has been detected.

We plotted the spectral windows and the power spectra of both groups of observations in one graph – see Fig. 3a, b. Since

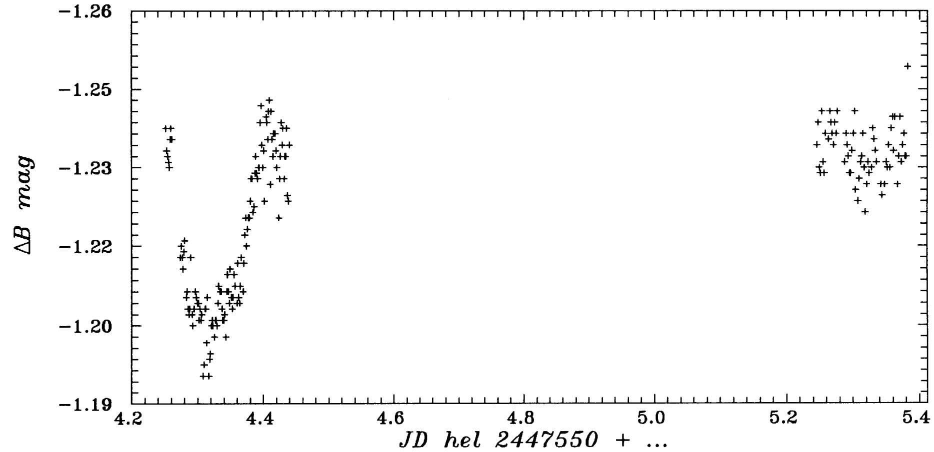

Fig. 1. The differential B light curve of IC 418 (in the sense HD 35914 + nebula – BD -12.1174), obtained on two subsequent nights in Jan. 1989. The observations have been binned (each bin consists of 10 observational points).

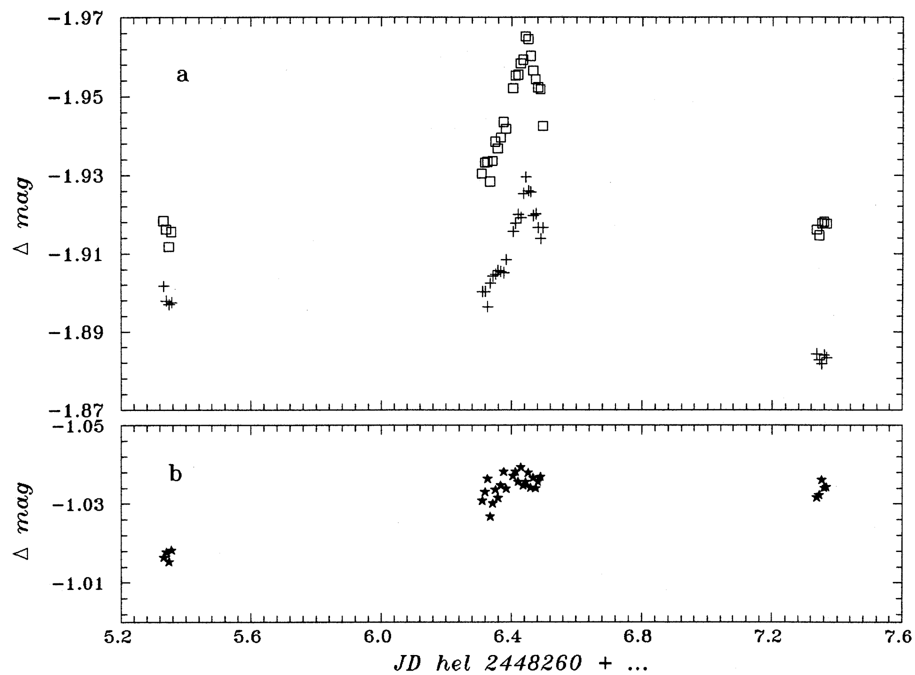

Fig. 2. a The differential light curve of IC 418, obtained on three subsequent nights in Jan. 1991. Squares and plus signs indicate filters U and V, respectively. The V light curve has been shifted upwards by 1^{m} for better display. **b** The $U-V$ color changes

the results for the filters U and V do not differ significantly, we have plotted only those corresponding to the U filter.

The power spectrum seems to show evidence for variability with a timescale of about 1/4 day (frequency v for observations obtained in 1991 and frequency q for observations from 1989).

Mendez et al. (1983), in their investigation of photospheric radial velocities, found that the periods $0^{d}.165$, $0^{d}.248$ and $0^{d}.198$ give the best fit to their spectrograms. These values can be identified with spikes at frequencies v+2, v and v+1 in our Fig. 3b. This coincidence can be considered as an argument for the reality of the frequency v.

Moreover, recent results of the photometric multisite campaign of IC 418 (Handler et al., 1996) revealed light modulation with a similar timescale (period=6.5h).

5. Discussion

In previous sections we have shown that IC 418 shows photometric variations with a timescale of about 1/4 day. No single period can fit all of our observational runs, implying that we have to do with either irregular (semiregular) or multimodal variability. We consider two possible explanations of the observed phenomena: (i) the mechanism of variable mass outflow rate and (ii) pulsational instability. We shall now discuss these possibilities in turn.

5.1. Observational evidence of wind variability

The evidence of fluctuating mass outflow via a stellar wind in IC 418 was provided by both ultraviolet and optical spectra (Harrington et al. 1980, Gilra et al. 1978, Mendez et al. 1986).

Cerruti-Sola & Perinotto (1989) found the terminal velocity of outflow to be equal to 940 km s^{-1} and the turbulent velocity to be roughly equal to 50 km s^{-1}. (The turbulent velocity is a fit-

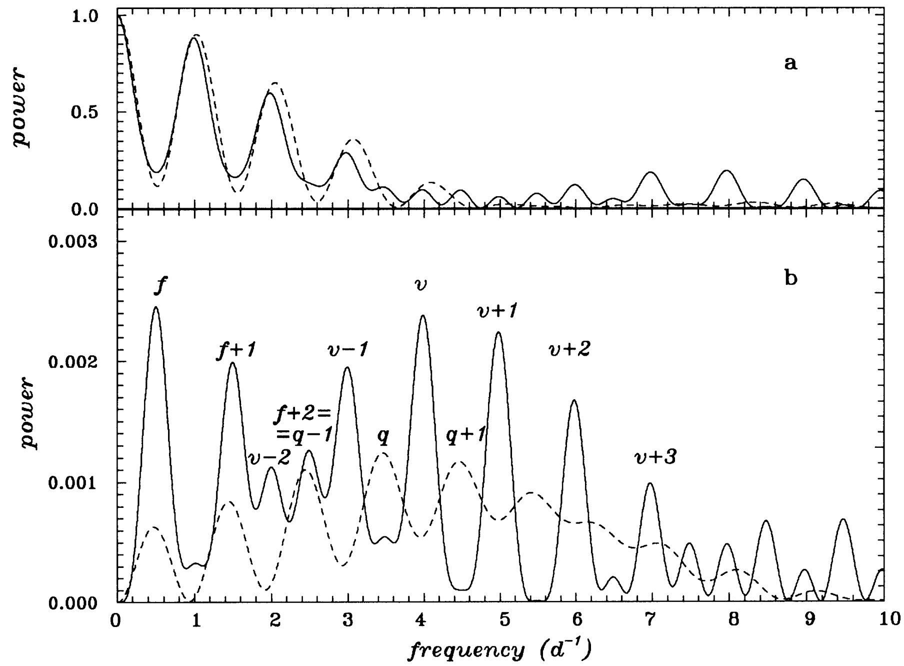

Fig. 3a and b. The spectral window (**a**) and the power spectrum (**b**), corresponding to the data obtained in 1989 (dashed line) and in 1991 (solid line)

parameter indicating some velocity structure superposed on the smooth velocity flow). Prinja (1990) demonstrated the presence of wind variability in IC 418 on the basis of profile changes that can be attributed to changes in the number, strength and velocity of opacity enhancements propagating through the wind.

5.2. Theoretical models of wind variability

There is very strong observational evidence (see e.g. Pauldrach et al. 1988) that winds of central stars of planetary nebulae are driven mainly by radiation pressure.

In the literature there are two different concepts of the radiatively driven wind. The first one, presented in e.g. the series of papers by Pauldrach et al. (1988, and references therein) assumes steady and smooth flow of the wind, with a velocity (and density) structure changing monotonically as a function of distance. Within this concept, Pauldrach & Puls (1990) attempted to explain the wind variability of LBV's by calculating a grid of wind models over a range of likely stellar parameters appropriate for P Cygni. The calculations demonstrated that P Cygni's wind is highly unstable against even extremely small changes in radius or luminosity that can produce quasi-periodic variability.

There is also a different approach to the radiatively driven wind, in which the wind is considered as an intrinsically time-dependent mechanism. As an example we refer to the series of papers by Rybicki et al. (1990). A radiatively driven wind is highly unstable and as a result, small fluctuations in, e.g., the wind flow speed are greatly amplified, eventually steepening into shocks. The source of the initial fluctuation can be e.g. sound waves or stellar pulsations. One-dimensional non-linear instability simulations (Owocki et al. 1988) show that even small-amplitude perturbations near the wind base can result in a highly structured wind, with dense and relatively slow shells (or clumps) separated from rarefied, high-speed regions by strong shocks. Such clumpiness of the wind can account for the presence of discrete absorption features observed for IC 418 by Prinja (1990) as well as for the velocity structure seen in IC 418 as "the turbulent velocity" (Cerruti-Sola & Perinotto 1989).

The present models of variable radiatively driven winds (Pauldrach & Puls 1990; Owocki et al. 1988) are still not quantitatively applicable to the central stars of planetary nebulae (and IC 418 in particular). Nevertheless – because of the same driving mechanism at work (Pauldrach et al. 1988), and because of the observational similarities in the wind characteristics (Prinja 1990) – one can expect qualitatively similar instabilities arising in IC 418. In accordance with the models above, the photometric variations of IC 418 can be ascribed to the changes in optical thickness caused by the formation and propagation of dense shells or clumps above photospheric level, while the observed variations in the photospheric velocities (Mendez et al. 1986) can be due to the variable mass outflow at the base of the wind.

5.3. Pulsational instability in the nucleus of IC 418?

New stellar opacity tables (Iglesias et al. 1992) have helped to resolve several problems regarding pulsations in main sequence stars, but it still remains to be seen what the effects of the new opacity will be on more evolved stars. The theoretical instability strip extends well above the β Cephei region in the HR diagram, widening in both directions above a certain M_{bol} (Moskalik & Dziembowski 1992). Thus, it seems conceivable that the same driving mechanism as present in β Cephei may generate the still unexplained microvariability of the LBV's and variability of post-AGB stars.

In an exploratory investigation of the linear stability of envelopes of post-AGB stars Gautschy (1993) used observational constraints to model IC 418. It turned out that instability of the fundamental radial pulsation is possible in this star. From his modal diagram one can find that the theoretical period of pulsations of IC 418 lies between $0^{\mathrm{d}}.15$ and $0^{\mathrm{d}}.32$. Thus, period of 1/4 day, tentatively suggested by us in Sect. 4, is within this range.

In his analysis Gautschy assumes that the surrounding medium and velocity field arising in the envelope due to the stellar wind have neglible influence on the pulsations. Although this must be the case for the deep stellar regions where the pulsations originate, nevertheless we do expect an influence on the propagation of waves through the photosphere due to, for example, the wind blanketing. Thus, a variable rate of outflow can distort or mask the pulsational characteristics, perhaps leading to the observed irregularities in the the light curve.

Zalewski (1993) performed a linear stability analysis of post-AGB stars and obtained results consistent with those of Gautschy (1993). Additionally, he considered nonlinear pulsations in selected models. He has shown that the nonlinear approach results in irregular light and photospheric radial velocity variations. He obtained asymmetrical radial velocity curves, with the rising branch steeper then the descending one, due to the propagation of shocks through the photosphere. It would be very interesting to perform nonlinear hydrodynamic modelling with parameters corresponding specifically to IC 418, in order to compare the results with simultaneous photometric and spectroscopic observations of this object.

In their observational study Mendez et al. (1986) ascribe the brightness variations of IC 418 to significant stellar radius fluctuations, which together with the lack of substantial color changes (cf. our Fig. 2b) might suggest the presence of non-radial pulsations in this star. However, other observational facts, such as the jagged radial velocity curves and lack of absorption line profile variations (at least in case of He II absorptions), argue against the presence of non-radial pulsations in IC 418.

Summing up, preliminary pulsational models of post-AGB stars have encouraging points of correspondence with observations, but they still do not explain all phenomena observed in IC 418.

6. Conclusions

Recent theoretical results (Gautschy 1993; Zalewski 1993) provide arguments that the variablity of IC 418 might be due to pulsations. Our photometric observations of IC 418 confirm that the characteristic timescale of variability is a few hours. No single period can fit all of our observational runs. Perhaps the full description of the light curve will require taking into account several pulsational modes, or interpretation in terms of nonlinear models of pulsations. Because of the lack of significant color changes the possibility of non-radial pulsations should also be examined.

The unstable outflow as described in Sect. 5.2 (possibly induced by a pulsational instability of the stellar envelope) may also play a key role in the observed photometric and radial velocity variations, either by itself or in interplay with the stellar pulsations.

Further observations of IC 418 and similar PNN are obviously needed in order to disclose the source of variability of these objects. In particular, long and continuous series of photometric data would answer the question whether IC 418-like PNN constitute a new class of pulsators.

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