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# Zusammenfassung

Eine neue Klasse veränderlicher Sterne wird vorgeschlagen. Es handelt sich um variable Zentralsterne junger Planetarischer Nebel, welche sinusförmige (halb)regelmäßige photometrische und/oder Radialgeschwindigkeitsvariationen auf Zeitskalen von mehreren Stunden aufweisen. Zehn dieser Objekte wurden identifiziert, die noch zwei weitere wichtige Merkmale teilen: ihre Temperaturen sind geringer als 50 000 K und alle zeigen wasserstoffreiche Spektren. Der wahrscheinlichste Grund für die Veränderlichkeit ist Pulsation der Sterne. Eine andere Möglichkeit wäre variabler Massenverlust der Zentralobjekte, aber in diesem Falle muß der zugrunde liegende Mechanismus verschieden von jenem, der in massiven O-Sternen arbeitet, sein.

# Abstract

A new class of variable star is proposed. These are variable central stars of young Planetary Nebulae exhibiting roughly sinusoidal (semi)regular photometric and/or radial velocity variations with time scales of several hours. Ten of these objects have been identified and they share two more important characteristics: their temperatures are less than 50 000 K and all show hydrogen-rich spectra. The most likely reason for the variability is stellar pulsation. Another possibility would be variable stellar mass loss, but in that case the mechansism causing it must be different from that operating in massive O stars.

# Preface

"Gerald, I really appreciate that you want to work on these stars. Afterwards you can recommend everybody not to deal with them." This has been said by an established astronomer as a young graduate student told him he wants to make a thesis on variable central stars of young Planetary Nebulae.

This student pursued his project, however, and what one can find in the following thesis are the results obtained so far and a bit more. It appears useful to give some background information on how this work and its structure are to be understood before starting off with the science itself.

This dissertation is not written in the usual style, i.e. lengthy introductions followed by the work itself put in a form so that everything yields a pretty unity. Most of this work consists of published papers (however not always in the actually published form: referees ask for conciseness, and so some figures and discussions which cannot be found in the respective papers are added here), which means that specialised introductions are given in each chapter, but there may be some repetition in it. The advantage is clearly that each chapter can be read (and hopefully understood) separately.

The plan of the thesis is as follows: Chapter 1 contains a short introduction into the problem, Chapters 2 and 3 are published papers on individual objects, Chapter 4 reports a survey in the Northern Hemisphere, which is hoped to be completed in the Southern Hemisphere and therefore not published at this point and Chapter 5 presents the overall conclusions. Chapter 6 is not part of the central work of this thesis. During the survey work I happened to stumble over a very interesting star which needed to be followed up. This object is in a later evolutionary stage than those generally studied here, but there is a definite connection. Therefore, and because of the astrophysical importance of this particular star, I decided to include it here.

After these, in my opinion, important remarks, let us turn to science.

# Chapter 1

# Introduction

## 1.1 A short overview of stellar evolution

We know of three common endpoints of the evolution of single stars: white dwarfs, neutron stars, and black holes. Which of these stages will be reached, depends on the mass of the progenitor(s). Neutron stars and black holes are the remnants of stars much more massive than our Sun. Massive stars are rare, however, and therefore the most common final stage in the life of a star is that of a white dwarf.

How do stars become white dwarfs? Let us for instance consider a model star about as massive as the Sun. As it has exhausted its nuclear fuel as a main sequence star (core hydrogen), it briefly contracts until hydrogen is re-ignited in a shell. As hydrogen shell burning continues and the star becomes cooler on the outside, the core, which is mostly composed of helium, shrinks and heats until degeneracy of the electron gas occurs. Therefore, the temperature cannot increase anymore, but the pressure still increases. The hydrogen burning shell still supplies matter to the core and at some point helium ignites almost explosively; a "helium flash" occurs. During the increase of core mass the star increases its luminosity by a large amount; it is now a red giant. The energy released at the helium flash causes the stellar envelope to expand. Consequently, quiescent helium core burning starts, since the degeneracy is lifted and the core expands as well. However, this decreases the energy output of the shell burning source, and the surface luminosity drops, while the surface temperature rises. In the core, helium is burnt to carbon and oxygen, and these materials form yet another core. Then nuclear burning occurs in two shells until the hydrogen shell has moved that far outward that its burning extinguishes. The helium burning shell still moves outwards and can trigger another phase of hydrogen shell burning. In the meantime, heavier elements deeper in the stellar interior can also be ignited. Shell burning becomes unstable in this phase, resulting in thermal runaways, leading to cyclic phenomena called "thermal pulses". This does not effect the carbon/oxygen core which continues to grow. These thermal pulses trigger mass loss and a circumstellar envelope is formed. After a critical fraction of the envelope

mass has been lost, the remaining envelope shrinks, but the circumstellar envelope still expands. The core still heats up, and when reaching a temperature high enough, it begins to ionize the surrounding neutral material: a Planetary Nebula is born. The former core of the red giant star is now visible again and is called the central star of this Planetary Nebula. This central star becomes hotter and hotter, finally exhausts its remaining nuclear fuel and turns into a white dwarf.

## 1.2 Astrophysical applications of Planetary Nebulae and their exciting central stars

After this very general introduction, let us consider Planetary Nebulae (PN) and their central stars in more astrophysical detail. As already noted in the introduction, almost all stars about as massive as our Sun pass through the PN stage. These objects are therefore the transition stage between Asymptotic Giant Branch (AGB) stars and white dwarfs. Hence, studying Planetary Nebulae and their central stars contributes to the understanding of a substantial fraction of late stellar evolution.

PN are very short-lived phenomena: according to dynamical studies (e. g. McCarthy et al. 1990) and to model calculations (e. g. Blöcker 1995), the objects spend at best a few thousand years in this stage before the central stars enter the white dwarf cooling track; the nebulae dissipate on about the same time scale.

Nevertheless, numerous astrophysical applications of PN exist: nebular spectra, for example, provide constraints on atomic data, stellar nucleosynthesis processes, or the primordial helium abundance. Detailed hydrodynamical calculations are needed to explain the many different nebular shapes. Fast winds from the central stars may also play a role here, but they can be used to refine radiation-driven wind theory as well. Finally, although distances to individual PN are not easy to derive, they are useful standard candles for extragalactic systems because of their stable luminosity function.

The central stars of Planetary Nebulae (CSPN) are of considerable astrophysical interest as well. Before starting a short description of these objects, it needs to be realized that there are two distinct populations of CSPN: most have a solar helium-to-hydrogen ratio, but also hydrogen-deficient (Wolf-Rayet) objects have been found. For the latter, which are not well understood, we refer to Schönberner (1997), who strongly points out that observed properties of WR-CSPN must not be compared with existing evolutionary calculations.

When leaving the Asymptotic Giant Branch (AGB), CSPN evolve rapidly towards higher effective temperatures (as noted before), and their surface luminosity is still supplied by hydrogen and/or helium (shell) burning. Mass loss plays an important role for the speed of the evolution of proto- and very young CSPN, see e. g. Schönberner (1989). In the later stages of the PN phase, the evolutionary speed is determined by hydrogen burning, i.e. by the ratio of the envelope mass to the hy-

drogen luminosity. Since the envelope mass of a CSPN decreases, but its luminosity increases with increasing mass, there is a strong dependence of the CSPN lifetime on mass.

Interestingly, several CSPN which show temporal variations in their brightness or spectral signatures have been discovered (although this is still considered unusual by most researchers). This can of course be used as an additional tool to study the physics of these objects. We start the description of variable stars with their probably most famous representatives, which are located in the hottest part of the HRD occupied by CSPN: pulsating nuclei (PNNV = Planetary Nebula Nucleus Variable).

## 1.3 Variable central stars of Planetary Nebulae

### 1.3.1 Pulsating hot CSPN

The discovery of multiperiodic pulsations in the hot central star of the PN K1-16 (Grauer & Bond 1984) and in several related objects opened up a new area of PN research: asteroseismology of the central stars. These pulsating hot nuclei share their spectral characteristics with the GW Vir stars, variable DO white dwarfs with spectra dominated by O VI, C IV, He II between 3200 and 4800 Å (Sion et al. 1984, Werner et al. 1991), the so-called PG 1159-type spectra. Only about 30% of stars showing PG 1159-type spectra are indeed pulsating variables (see e.g. Dreizler 1998). The best investigated pulsator so far is the prototype PG 1159-035 (= GW Vir) itself. For this star, Winget et al. (1991) resolved the light curve into more than 100 pulsation periods, all of which could be identified with nonradial g-modes. This allowed an unprecedented investigation of the object's inner structure by means of precision asteroseismology. Similar analyses of other GW Vir stars have been performed in recent years (e. g. O'Brien 1998).

Ciardullo & Bond (1996) carried out a time-series photometric survey of all CSPN with spectra of PG 1159 type or spectra dominated by O VI brighter than about 17 mag. They found six pulsators with effective temperatures similar that of the GW Vir stars. The pulsational periods (typically between 1000 and 2000 seconds) of the PNNV are longer than those of GW Vir stars, and can also be attributed to the presence of nonradial g-modes. The excitation mechanism (cyclical ionization of carbon and oxygen, Starrfield et al. 1985) may be the same, but the higher luminosities of the PNNV and their association with a visible Planetary Nebula may indicate that these are two different kinds of object. Two multisite campaigns on these PNNV have been carried out. The amplitude spectra of the stars are simpler than that of PG 1159-035 and also indicate that the pulsational frequencies and amplitudes may not be stable over several years (Bond et al. 1996, Ciardullo & Bond 1996).

However, the amplitude variations helped to perform an asteroseismological analysis of the central star of NGC 1501 (Bond et al. 1996), since archival photometry could be used together with multisite data to determine periods of modes which were not present in all data sets. Consequently, the mass and rotation rate of this object could be determined.

In any case, asteroseismology of pulsating hot CSPN is presently a very active area of research, and more results are expected in the near future. Still, there are many more CSPN which show temporal variations, and only few of them can be separated in distinct classes. Nevertheless, a brief overview of further variable CSPN should be given.

### 1.3.2 A Zoo[1] of variable CSPN

A number of PN possess **close-binary nuclei** (see Livio 1997 for the latest review), which generates a number of possibilities for variability. Obviously, the presence of **eclipsing binaries** can be expected, and indeed there are four such systems known. These are useful for studying close-binary post-AGB evolution, in particular after a possible common envelope phase and also to derive independent distances to individual PN. In addition to the eclipsing close-binary CSPN, seven systems showing a **reflection effect** (atmospheric heating of the optically brighter cool companion by the much hotter central star generating variability with the orbital period) have been discovered.

Another subclass of binary CSPN are the **Abell 35-type stars** (three members). The optically dominating components are non post-AGB objects whose variations are interpreted to result from rotational modulation of starspots (e.g. see Jasniewicz et al. 1996).

Furthermore, a number of "unique" variable objects is known. Peña & Ruiz (1998) detected spectroscopic and photometric variability in the (hot) **central star of PRTM 1**. The photometric variations can reach an amplitude of about 1 mag in $V$ and seem to be cyclic. A definite explanation for this variability has not yet been found, but a binary scenario seems most probable.

The **central star of NGC 2346** is a spectroscopic binary, which shows large optical variations with a modulation similar to the orbital period. These are interpreted in terms of a fragmented dust cloud passing in front of the binary central star (Costero et al. 1993 and references therein).

The Wolf-Rayet central star of He 3-1333, **CPD-56 8032**, exhibits light variations with a $V$ amplitude of almost 1 magnitude. This is best interpreted as being related to the R CrB phenomenon, i.e. ejected carbon clouds condensing in the line of sight and obscuring the star (Pollacco et al. 1992). An even more extreme

[1]To avoid confusion of possible inexperienced readers, the different groups or objects are **highlighted**

example may be **V348 Sgr**, varying with $\Delta V \sim 6$ mag (Heck et al. 1985, Hecht et al. 1998).

**FG Sge** is another case of a CSPN (that of He 1-5) apparently related to the R CrB stars (Jurcsik 1993). Furthermore, it evolved across the HR diagram within less than 100 years and it showed signs of pulsation as well. The reason for this rapid evolution is most likely a final helium-shell flash of the CSPN, generating a born-again red giant. **Sakurai's object** (e.g. Duerbeck & Benetti 1996) and **V 605 Aql** (Seitter 1987) are further candidates for such very late pulses.

During the last years, additional examples of variable central stars of Planetary Nebulae have been discovered. In the literature, these objects were usually only mentioned in scattered remarks; their variability could not be easily interpreted. However, these stars appear to share some common characteristics which will be summarized in the following.

### 1.3.3 Variable central stars of young Planetary Nebulae

Before the beginning of this investigation, four CSPN were known to show quite similar photometric and radial velocity variability, which could not be explained by any "standard" hypothesis. They comprise the central stars of: IC 418 (Méndez et al. 1983, 1986), IC 4593 (Bond & Ciardullo 1989), He 2-131 and He 2-138 (Hutton & Méndez 1993). The photometric behaviour of these PNNV is often described as irregular, but sometimes sinusoidal variations with time scales of some hours were reported (e.g. by Wlodarczyk & Zola 1991, Bond & Ciardullo 1991).

The basic physical parameters of these CSPN were determined from model atmosphere calculations (Méndez et al. 1988, 1990) and it has been noticed that these objects appear to constitute a remarkably homogenous class of variables:

- They have effective temperatures of 25 000 – 50 000 K
- They possess compact nebulae of high surface brightness
- Photometric and radial velocity variations with time scales of several hours and several days are observed
- No well-defined single periodicity seems to be present in these variations
- Most (if not all) of the central stars show winds, which are sometimes variable

The temperatures of the central stars and appearance of the nebulae suggests that all these variables are located within young PN.

There are some further candidates which may be added to this group, central stars showing photometric variations (see the list in Bond & Ciardullo 1991), but no light curves had been published. Variable winds (Patriarchi & Perinotto 1997, Méndez et al. 1988, 1990) have been claimed in a number of objects.

At this point it is important to note that the same kind of behavior exists in massive O stars as well. 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).

Coming back to the variable central stars of young PN, several hypotheses (or speculations) for the cause of their variability can be found in the literature. The simplest explanation would be binarity, but most authors disregarded this idea. Méndez et al. (1983, 1986) suggested that wind variations are – in their words – "the least unlikely" interpretation, while Wlodarczyk & Zola (1991, later detailed by Kuczawska et al. 1997) favored a pulsational origin of the photometric and radial velocity variations.

On the theoretical side, some exploratory calculations of pulsational models have been carried out. Gautschy (1993) found several unstable pulsation modes in his CSPN models by assuming parameters resembling the central star of IC 418. These modes are driven by the $\kappa$-mechanism in the Z-bump, similar to the pulsations of $\beta$ Cephei stars. Zalewski (1993) undertook nonlinear computations and obtained complicated light and radial velocity curves, which could basically explain the behavior of these objects as described above. Finally, Gautschy (1995) explored pulsational instability for Wolf-Rayet-type CSPN and found again many unstable normal and strange modes (e.g. see Saio et al. 1998 for a discussion of the latter). He suggested that pulsations could initially trigger strongly enhanced mass loss. Later, the pulsations would die out, leaving only a variable stellar wind behind.

If these variations could be attributed to (nonradial) pulsation, a wealth of opportunities to investigate the physical state of these stars could be exploited:

- identification of specific pulsation modes will immediately put tight constraints on the mean density of the star, thus allowing a comparison with stellar parameters determined by spectroscopy (or other methods)

- possible mode splitting can lead to a reliable determination of the rotational velocity, which in turn constrains model atmospheres

- period changes (which are easy to detect due to the rapid evolution of PNN) would provide a direct measure for the evolutionary speed. Therefore evolutionary calculations under the influence of mass loss can be calibrated, thus linking observation and theory stronger than previously

- discovery of pulsation will strongly encourage theorists to calculate appropriate models to describe the pulsational characteristics. As we have learned from the pulsating white dwarf stars, this may lead to intriguing results, such as accurate determinations of masses, luminosities, magnetic field strengths,

compositional stratification (Winget et al. 1991) and even distances (Bradley 1993). It should be pointed out, that the reliable determination of distances to individual Planetary Nebulae is one of the major observational problems in PN research (e.g. see the review by Lutz 1989).

For these reasons, it was deemed interesting to carry out a more extensive study of these objects, and the results of this effort are reported in the following. As a first step, we decided to conduct a photometric multisite campaign on the best studied object, HD 35914, the central star of IC 418.

# Chapter 2

# Multisite Photometry of IC 418

## 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.

## 2.1 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 time scale 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 (Kuczawska et al. 1997, 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. 2.2 we describe our observations, Sect. 2.3 is devoted to data reduction, and in Sect. 2.4 we analyse our data. Section 2.5 contains a re-analysis of the data by Jasniewicz (1987) as well as those by MVK and MFL. We discuss the results in Sect. 2.6 and summarize our findings in Sect. 2.7.

## 2.2 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 $1024 \times 1024$ 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 2.1.

## 2.3 Data reduction

### 2.3.1 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, i.e. an amplitude spectrum of the magnitude differences of the comparison star data contained no peak higher than 1 mmag. Consequently, standard $B$ and $V$ magnitudes for all stars were calculated from the SAAO data, since the SAAO time series were generally preceded by measurements of E-region standards. The magnitudes of the comparison stars were defined to be the same for

Table 2.1: 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 |

each telescope/photometer combination. Some zero-point deviations from observatory to observatory were found, however, but they were very small compared to the amplitude of the light variations of HD 35914.

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 H$\beta$ (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.

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. It is interesting to know the accuracy of our data after nebular subtraction. Although the quality of the data is typical for a multisite campaign, the subtraction procedure also increases the scatter of the variable star measurements. 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.

### 2.3.2 CCD observations

In total, our CCD observations consisted of 173 $1024 \times 1024$ 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. Although this operation eased the burden of data handling, it in no way affected the subsequent data reductions, since the data from each original frame were always analysed independently.

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. Therefore, in the presence of cirrus, the counting statistics for our comparison stars dominates the noise.

The constancy of the comparison stars was checked; no evidence for variability for any of these objects was found within the 3 nights of observation. Consequently, the magnitude zeropoints of the comparison stars were determined, corresponding shifts applied, and averages of these magnitudes for each time of measurement calculated. These averages were subtracted from the measurements of the individual stars and their constancy was again checked. Again, none of them appeared to be variable. 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 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 $9.87 \pm 0.05$ 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. 2.1.

## 2.4 Analysis

### 2.4.1 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[1]. 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. 2.1). 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. 2.3.2). A power spectrum calculated for these data (Fig. 2.2) 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. 2.1 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.

[1]The SPM data have a somewhat lower duty cycle than the remainder. However, application of corresponding weights did not change the results reported below.

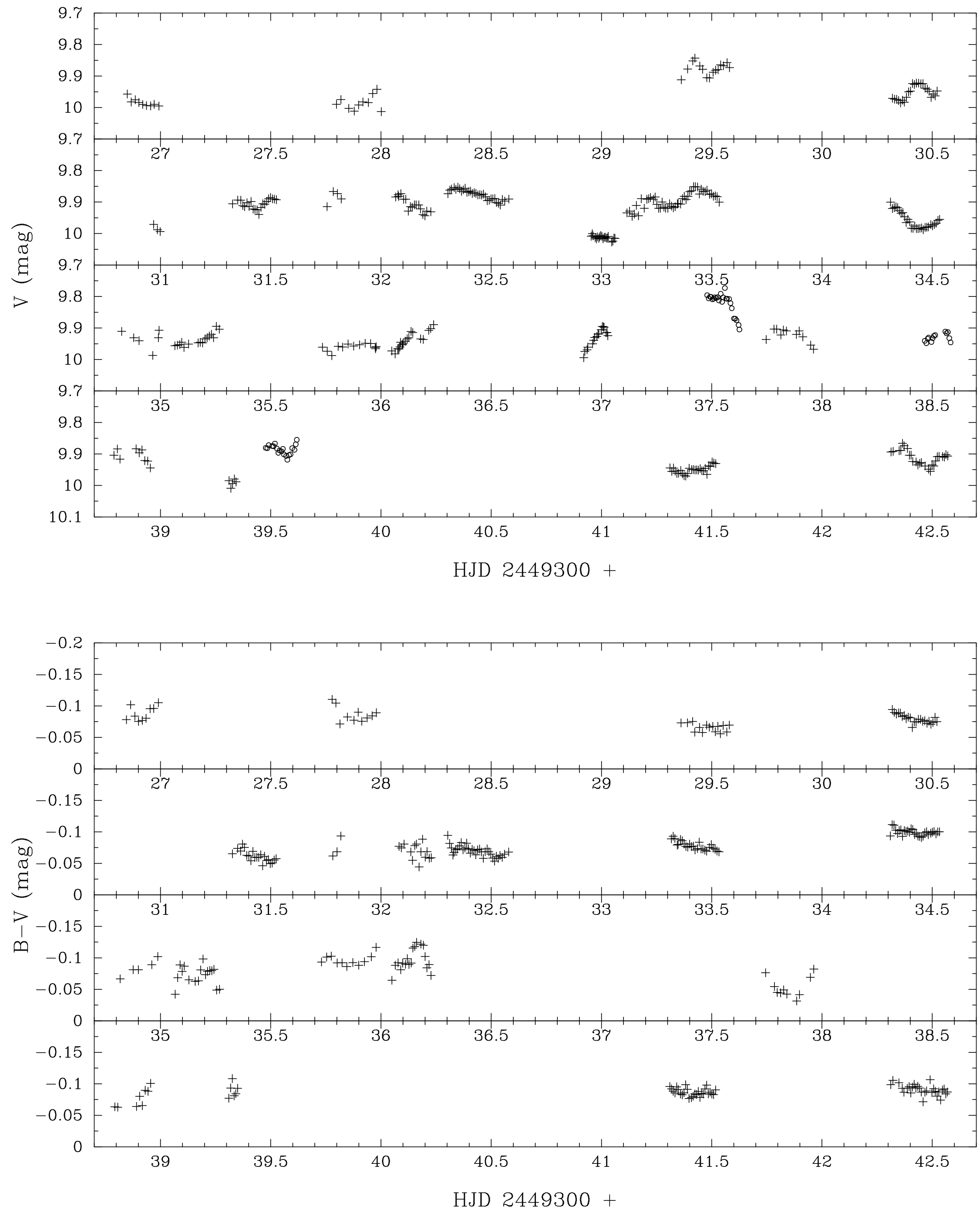


Figure 2.1: Upper panel: Multisite $V$-filter light curves of HD 35914, high speed photometric as well as CCD data are binned (see text) Crosses: photoelectric measurements, open circles: CCD data. Lower panel: $(B-V)$ color variations of HD 35914

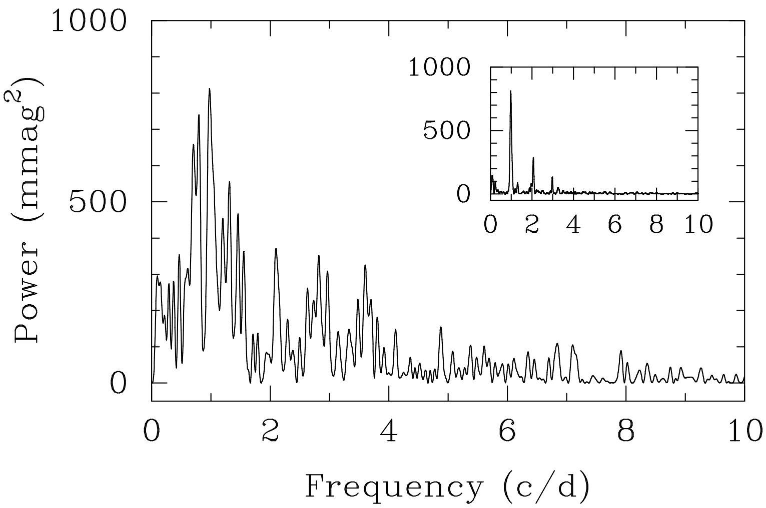


Figure 2.2: Spectral window (inset) and power spectrum of the data displayed in the upper panel of Fig. 2.1, but without the CCD data. We have calculated the spectral window by transforming a single sinusoid of frequency 0.976 c/d, corresponding to the highest peak in the lower panel, sampled exactly 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

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. 2.3.

The broadening of peaks in Fig. 2.3b relative to Fig. 2.3c is due to the different distribution of the measurements in the data subsets. In Fig. 2.3a, many of the higher peaks are split. This 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. 2.3a near 3.7 c/d. That peak is also prominent in Figs. 2.3b and 2.3c, and is present in Fig. 2.2 as well. For the (O-C) diagram (Fig. 2.4) we have used both maxima and minima in the light curves, since they are generally sinusoidal (there is no evidence for a significant harmonic near 7.4 c/d in Fig. 2.3). 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. 2.3a, would cause a smooth, sinusoidal trend in the (O-C) diagram; this is not the case in Fig. 2.4. 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

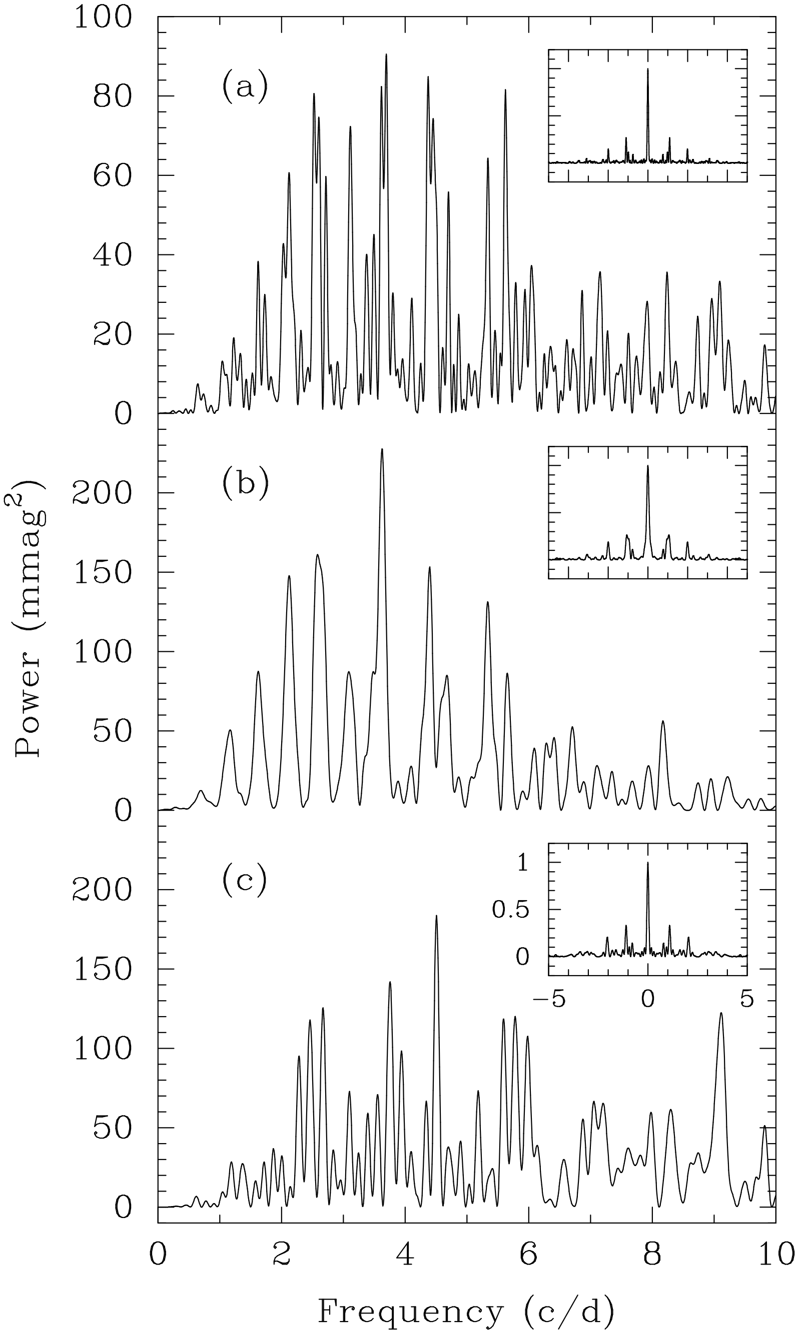


Figure 2.3: Amplitude spectra and spectral windows (insets) of the HD 35914 data corrected for variations of the mean light level. Panel (a) shows the transform of the full data set, (b) that of the first subset (see text) and (c) that of the second subset. Note the different ordinate scale of Panel (a)

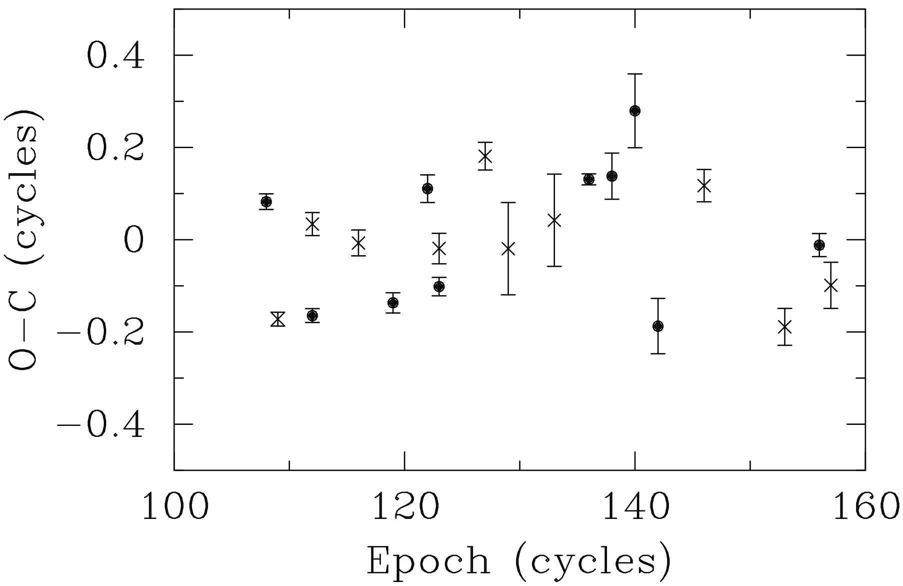


Figure 2.4: (O-C) diagram for $f = 3.7$ c/d. Dots represent timings determined from light maxima, crosses those derived from minima (shifted by 0.5 cycles)

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

### 2.4.2 Color variability

The $(B-V)$ color variations (Fig. 2.1) do not resemble the $V$ filter data at all. On the other hand, as shown in Fig. 2.5, our measurements do suggest that the star

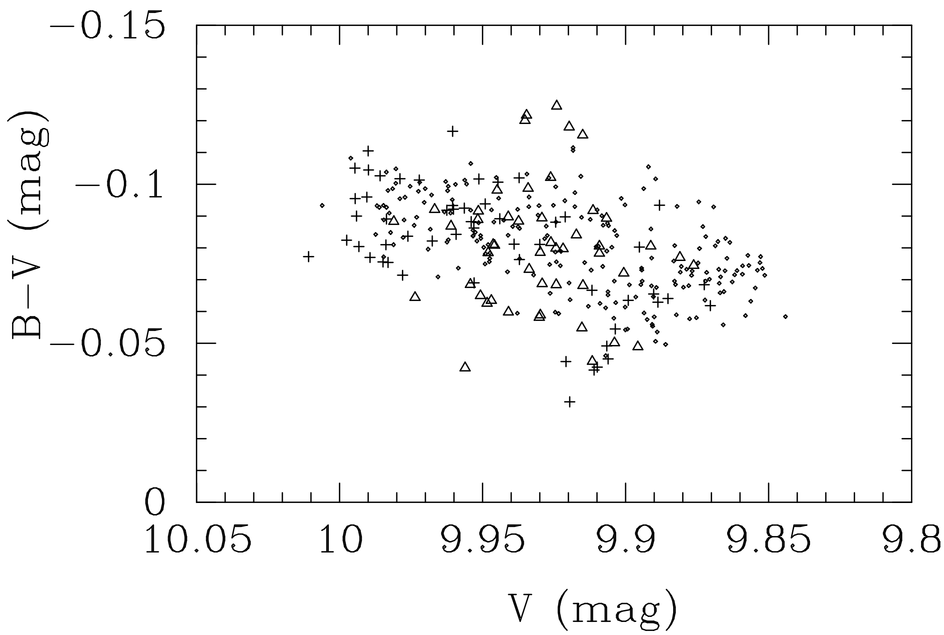


Figure 2.5: The $(B-V)$ color of HD 35914 against its $V$ magnitude. A general trend exists in the data, in the sense that HD 35914 is redder when it is brighter. Dots represent SAAO data, crosses are SPM data, triangles are Perth data. The trend occurs in the data of all three sites

is redder when it is brighter[2]. 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 $(B-V) = +0.35 \pm 0.10$, 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

[2]In Fig. 2.5, 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, yielding eight nights of useful data, we conclude that HD 35914 was indeed fainter at the beginning of the campaign.

emphasize that this effect is marginal, and that the scatter in Fig. 2.5 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 power spectra of these data, before and after adjusting the zeropoints of the different runs (Fig. 2.6).

Inspection of Fig. 2.6a 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. 2.2, 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. 2.2. Let us now search for higher frequencies in the $(B-V)$ data.

In Fig. 2.6b we 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. 2.1), 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. 2.6. 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.

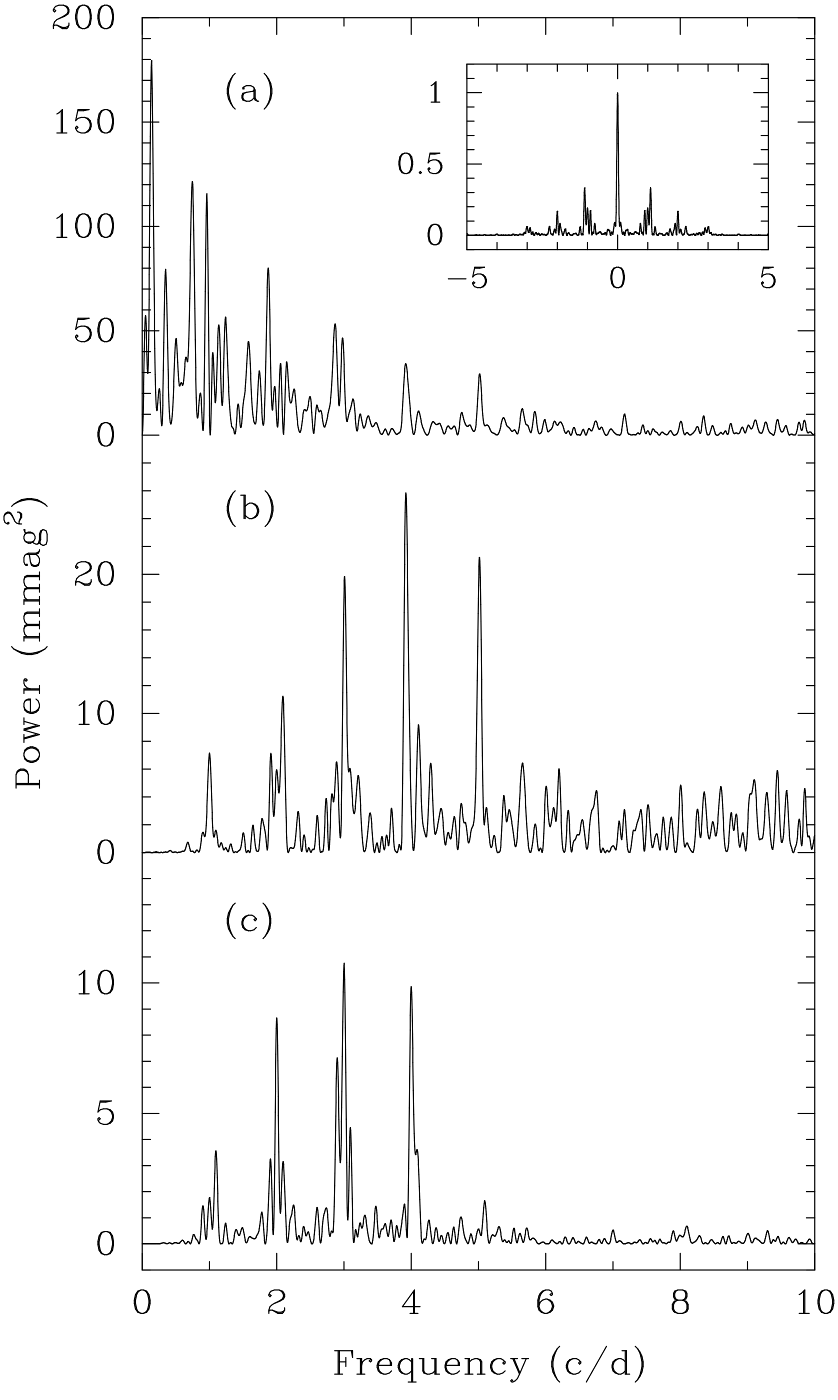


Figure 2.6: (a) Power spectrum of the $(B-V)$ measurements (spectral window inset); (b) power spectrum of the color data after adjustment of zeropoints; (c) power spectrum of a simulated data set. This figure shows that we cannot detect a signal with a time scale of a few hours in these data (see text)

### 2.4.3 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 time scales: 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 time scale 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 time scale of hours.

## 2.5 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.

### 2.5.1 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 time scales 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. The power spectrum of the 1984 data is shown in Fig. 2.7a.

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. To examine the effects of zeropoint adjustments, we calculated 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 (Fig. 2.7b). Since the 3.77 c/d frequency is similar to that we found in Sect. 2.4.1, we conclude that the behavior of HD 35914 might have been the same in 1984 as it was in 1993.

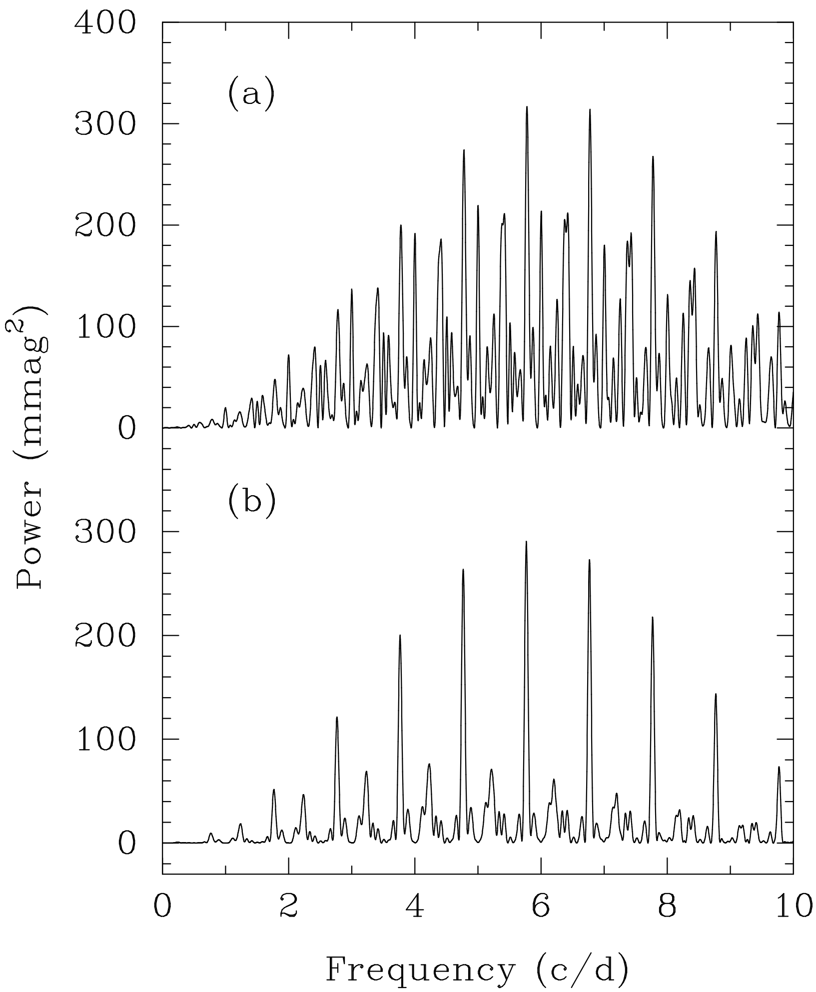


Figure 2.7: (a) Power spectrum of the 1984 data of Jasniewicz, taken in Geneva $V$; (b) power spectrum of a pure sinusoidal variation with $f = 3.77$ c/d, sampled and "reduced" in the same way as the real data

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 that observed in 1993.

### 2.5.2 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.

We performed frequency analysis of the 1983 photometry. and display a power spectrum of these data in Fig. 2.8a. Since the star did not show substantial variations in its mean magnitude, we did not adjust the nightly zeropoints. 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 as the one present in all the data we analysed so far. In Figs. 2.8b and 2.8c we have plotted power spectra of the He II 4541Å absorption radial velocities acquired in 1980 (HJD 2444535–HJD 2444539) and of the C IV 5801/5811Å absorption radial velocities from 1982 (HJD 2445042–HJD 2445044). These suggest that there is a change in the time scale as well as in the amplitude of the radial velocity variations. Upper limits for possible periodic radial velocity changes are about 10 km/s for the 1980 data, but 20 km/s in 1982. However, the variation of the time scale is not real, since the time series of the blue spectrograms possess a longer nightly timebase, and therefore the zeropoint adjustments give rise to this effect. The change in the amplitude could be real, but we caution that the timebase of the 1982 radial velocity measurements is shorter, which can cause a spurious increase in the amplitude. We also note that the highest peak in Fig. 2.8c is near 5.0 c/d, and so we might see a superposition with radial velocity variations occurring on a longer time scale (see the discussion in Sect. 2.4.2).

The power spectrum of MFL's photometric data after nightly zeropoint adjustments shows (Fig. 2.8d) 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 time scale 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 time scale. 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. 2.4, they constitute the first 4 points), and do not show larger scatter than the other measurements, we cannot

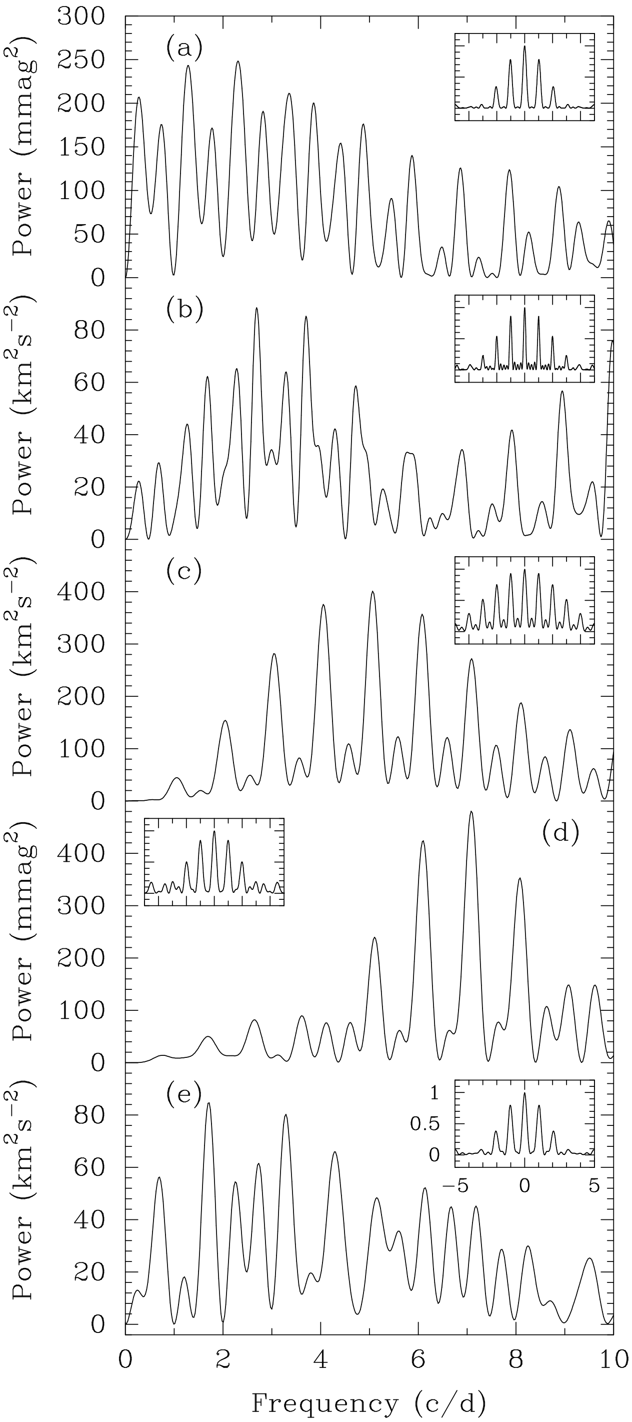


Figure 2.8: (a) Power spectrum of the 1983 photometry of MVK; (b) Power spectrum of the 1980 He II absorption radial velocities reported in the same paper; (c) Power spectrum of the 1982 C IV absorption radial velocities of MVK; (d) Power spectrum of the 1984 photometry of MFL; (e) Power spectrum of MFL's C IV absorption radial velocities; a spectral window is inserted in each panel

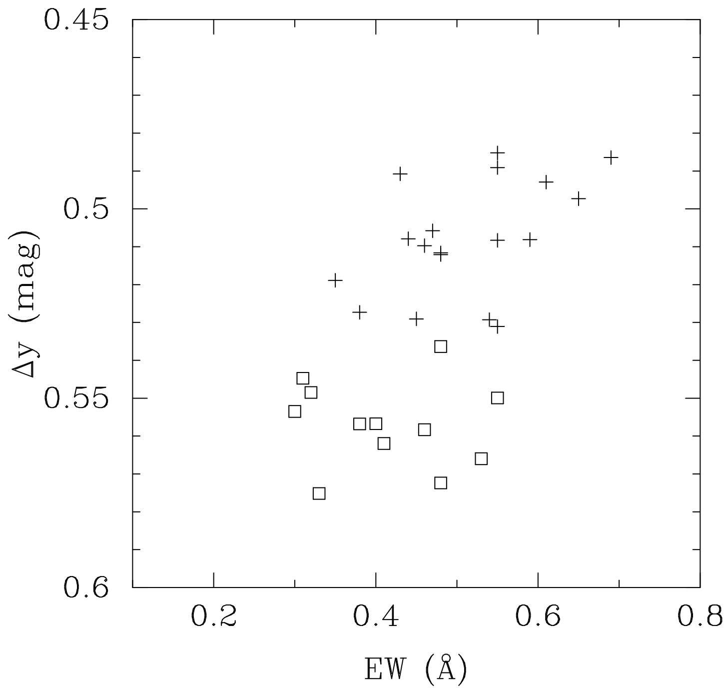


Figure 2.9: Correlation between the C IV absorption radial velocities and y magnitudes reported by MFL, but with different symbols for the two nights of measurement (see text)

construct sufficient evidence from the 1984 photometry of MFL to conclude that HD 35914 behaved substantially differently.

We also computed a power spectrum of the C IV absorption radial velocities acquired by MFL (Fig. 2.8e). As in most other data sets, the dominating time scale present MFL's C IV absorption radial velocity variations is a few hours. It should be noted that this power spectrum bears some resemblance to Fig. 2.8b, but not to the simultaneous photometric data. For the latter, we refer to the discussion of MFL; we will comment on them in Sect. 2.6.3 as well.

Finally, we re-examined the dependence of the brightness of HD 35914 on the equivalent width of the stellar C IV absorptions (Fig. 2.9). We have indicated the data from Nov 8, 1984 with open squares and those from Nov 9, 1984 with plus signs. 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. If the star did not change its mean brightness during the observations of Maene et al. (1994), this would be a natural explanation why they did not find a relationship between the star's brightness and the intensity of its wind.

### 2.5.3 The behavior of HD 35914 in the last 15 years

Now we can attempt to describe the behavior of HD 35914 since the discovery of its variability. From the analyses and discussions 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. 2.4). Our interpretation, that HD 35914 shows semiregular light variations with a time scale 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.

## 2.6 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 other authors. However, since we wish to present some new arguments, we will carefully consider all possibilities.

### 2.6.1 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

$$P_{crit} = \frac{2\pi R_{eq}^{3/2}}{(GM)^{1/2}}, \tag{2.1}$$

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. If we estimate the amount of geometric cancellation of four spots by comparing it with that of a nonradial $\ell = 4$ mode (Dziembowski 1977), we see that the ratio of the photometric amplitude to

the intrinsic amplitude is about 1/50. 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. 2.4.2.

### 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 (Figs. 2.8b, 2.8e), 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. 2.10.

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. 2.7). 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 required rotational velocity with the measured one. However, a nonrotational source

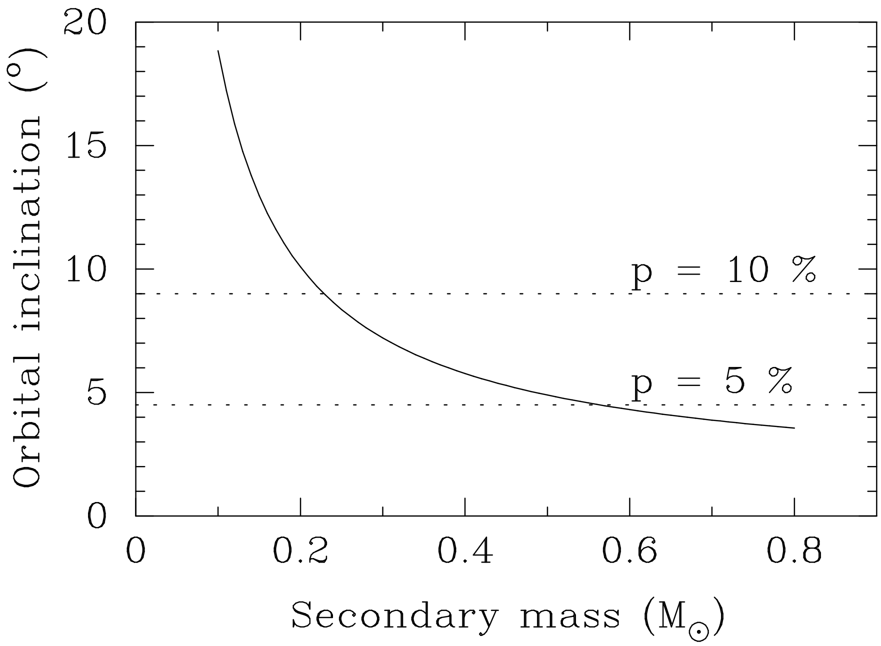


Figure 2.10: Maximum orbital inclination of a hypothetical binary with HD 35914 as primary component versus secondary mass (see text)

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. 2.4.1 and Sect. 2.4.2 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.

### 2.6.3 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. Figure 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. 2.4).

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 time scale 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 possibility: the period change of a pulsating star can be expressed as

$$\frac{d\ln P}{dt} = -0.69\frac{dM_v}{dt} + 3\frac{d\ln T_{\mathit{eff}}}{dt} + \frac{d\ln Q}{dt} + \frac{d\ln M}{dt} \tag{2.2}$$

Equation 2.2 can be easily obtained by substituting into the formula for the period-mean density relation $Q = P\sqrt{\rho_*/\rho_\odot}$, (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 $2.5 \times 10^{-6}$ 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.

### 2.6.4 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 attributed 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. 2.6.1) 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).

## 2.7 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.

# Chapter 3

# A photometric study of M2-54


## Abstract

We acquired 63.8 hours of time-series photometry of the variable central star of the young Planetary Nebula M2-54. This object exhibits light variations with a peak-to-peak amplitude of up to 0.3 mag. Two different time scales (several days and several hours) are present. While the long-term variations appear to be nonperiodic, the short-term modulations are (quasi)periodic with a time scale of either 8.9 or 14.3 hours. An analysis of the HIPPARCOS photometry of this object did not allow us to infer which of these two time scales is the correct one.

The possible causes for the observed variability are examined. The slow variations can be explained by either a spot hypothesis or variations in the stellar mass loss, while the short-term modulations are most consistent with stellar pulsation. All this behaviour is strikingly similar to that of the best studied representative of this class of variable star, the central star of IC 418, strongly suggesting that the physical cause of the variability of these two objects is the same.

While it appears quite attractive to suspect that we are in the presence of a new class of pulsating variables, further work is needed to confirm or reject this. Consequently, some suggestions in this direction are given.


## 3.1 Introduction

Intrinsic variability of central stars of Planetary Nebulae (CSPN) is widely believed to be a rare phenomenon. However, recently a number of such variables have been discovered. Among the hottest CSPN (of the PG 1159 spectral class), several exhibit pulsations with time scales of a few minutes (e.g. see Ciardullo & Bond 1996), while others pulsate with multiple periods of 30 minutes or longer (e.g. Handler et al. 1998, Chapter 6.2). One at this point enigmatic object is the central star of PRTM 1 (PN G 243.8-37.1, Peña & Ruiz 1998).

Furthermore, several cooler CSPN are variables. First, there is the Abell 35-type objects, which have binary nuclei. The optically dominating components are non post-AGB objects whose variations are interpreted to result from rotational modulation of starspots (e.g. see Jasniewicz et al. 1996). Second, photometric and radial velocity variations have been discovered in a number of post-AGB central stars. The best studied of those is HD 35914, the central star of IC 418 (Handler et al. 1997, Chapter 2 and references therein. HD 35914 varies on a time scale of about 6.5 hours; the observations can only be explained by either pulsations or variations in the stellar mass loss (spots are ruled out and binarity is improbable). Furthermore, non-periodic variability with a time scale of several days is superposed on the light curves.

To distinguish between these two possibilities, Handler (1998, Chapter 4) carried out a survey for photometric variability among bright Northern Hemisphere CSPN. He observed 24 objects and found that more than 30% of CSPN with effective temperatures between 25 000 and 50 000 K indeed exhibit luminosity variations similar to those of HD 35914.

An outstanding object among these variables is LSIII+51 42, the central star of M2-54 (we will use the name of the nebula for the central star throughout the remainder of this paper) whose variability was discovered by Handler (1996, 1998). It is the highest amplitude variable discovered so far: its light variations reach 0.3 mag in Johnson $V$ without removal of the nebular contribution to the measurements, i.e. the intrinsic amplitude is even higher. For this reason and since M2-54 is significantly cooler than HD 35914, it was considered to be a promising target for a more detailed study. The results of such an effort are reported below. Furthermore, variability of M2-54 was also detected in HIPPARCOS photometry (ESA 1997). These measurements are analysed as well.

## 3.2 Observations and reductions

Photoelectric time-series photometry of M2-54 was acquired with the 0.9m telescope at McDonald Observatory, Ft. Davis, Texas, USA. It was attempted to obtain runs as long as possible to be able to sample a full cycle of the variations during one night of measurement. Furthermore, since experience with HD 35914 (and M2-54) showed that mean light variations with time scales of several days can be exhibited by the objects studied, a long time baseline is required to examine those in detail. We were awarded three weeks of observing time. An overview of the acquired measurements is given in Table 3.1.

Our measurements were carried out differentially with respect to the comparison stars HD 235981 ($V \approx 9.2$, F0) and HD 235982 ($V \approx 9.8$, F8), already used during the discovery observations. Depending on the brightness of sky background, either a $27''$ or a $36''$ aperture was used. Both included the whole nebula, which has an

Table 3.1: Journal of the observations

| Date (UT) | Start (UT) | Length (hrs) |
|---|---|---|
| 23 Sep 97 | 2:18:00 | 8.3 |
| 25 Sep 97 | 8:39:20 | 1.7 |
| 28 Sep 97 | 6:00:40 | 2.5 |
| 30 Sep 97 | 5:26:10 | 2.4 |
| 1 Oct 97 | 2:26:00 | 4.9 |
| 2 Oct 97 | 1:55:20 | 7.9 |
| 3 Oct 97 | 1:37:50 | 7.8 |
| 4 Oct 97 | 3:14:10 | 6.5 |
| 5 Oct 97 | 3:38:10 | 5.4 |
| 6 Oct 97 | 3:03:10 | 5.6 |
| 7 Oct 97 | 4:16:00 | 1.0 |
| 9 Oct 97 | 1:30:30 | 7.9 |
| 10 Oct 97 | 1:44:00 | 1.9 |
| Total | | 63.8 |

angular diameter of 4″ (Acker et al. 1992). The Johnson V filter was used, since it represents the best compromise between minimizing the influence of the nebula and maximizing the number of photons counted. We integrated for 60 seconds on the comparison stars, but we measured the brightness of M2-54 for 100 seconds (since it is much fainter than the comparison stars). This yielded a mean separation of 6.5 minutes between consecutive data points.

Data reduction was started with subtraction of sky background (due to the low count rates, no correction for coincidence losses was applied). Then we corrected the data for extinction by fitting straight lines to the nightly magnitude vs. air mass plots of the comparison stars. The mean extinction coefficient from both comparison stars was adopted for all objects measured. Finally, the times of observations were converted into Heliocentric Julian Date (HJD), the nightly light curves were joined into a combined data set, differential magnitudes were calculated and subjected to further analysis. We note that we did not attempt to perform a subtraction of the nebular contribution to the data, since only one instrumental setup was used for the observations and since the intrinsic amplitudes of the light variations are not important for the interpretation of the results.

No evidence for variability of either of the two comparison stars was found; an amplitude spectrum of the differential measurements of these objects showed no significant peak (Fig. 3.1). The standard deviation of a single comparison star measurement was 2.4 mmag, confirming the excellent photometric conditions during

the observations. However, this cannot be taken as an estimate for the accuracy of the measurements of M2-54; for this $V = 12.1$ mag object we estimate an rms error of 5.0 mmag per single data point. The observed light variations of M2-54 are displayed in Fig. 3.2.

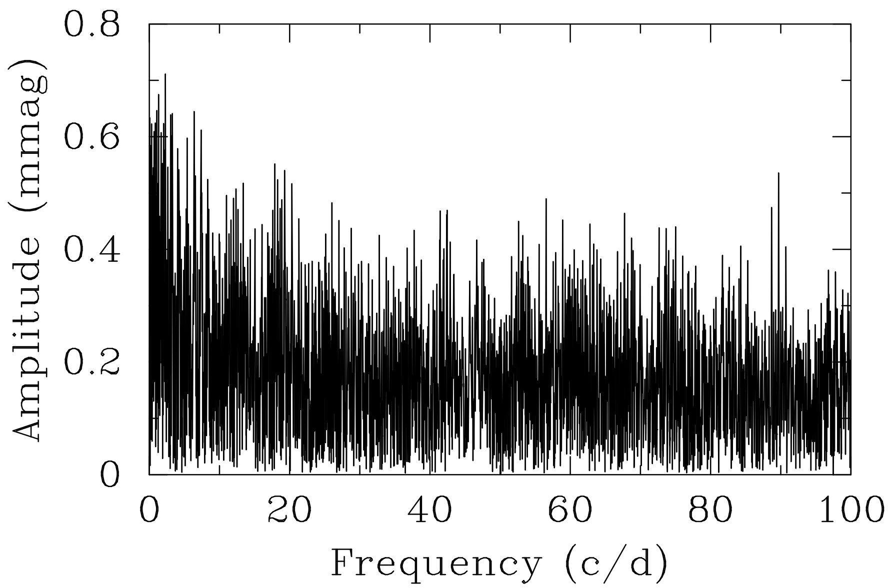


Figure 3.1: The amplitude spectrum of the differential measurements of the comparison stars

## 3.3 Analysis of the light curve

We made use of a period-finding package consisting of single-frequency Fourier and multiple-frequency least-squares techniques (Breger 1990). First, an amplitude spectrum of the whole data set was computed out to the Nyquist frequency ($\approx$ 100 cycles/day). No variations with time scales shorter than 2 hours were found and therefore the analysis was restricted to frequencies smaller than 12 c/d.

In Fig. 3.2 one can readily see that two different kinds of variability are present: long-term variations with a time scale of days and variations with a time scale of several hours; this is quite similar to the behaviour of HD 35914 (Chapter 2).

We first searched for possible periodicities in the long-term variations, since these appear to dominate the light curve. No periodic signals were found, again similar to HD 35914. Therefore, we turned to the short-term variability.

However, at this point caution is warranted: to examine the faster variations, one first needs to filter out the long-term variability, e.g. by adjusting the nightly zeropoints. Since we never observed a full cycle of the short-term variations during a single night, this can generate artifacts. In particular, signals with periods longer

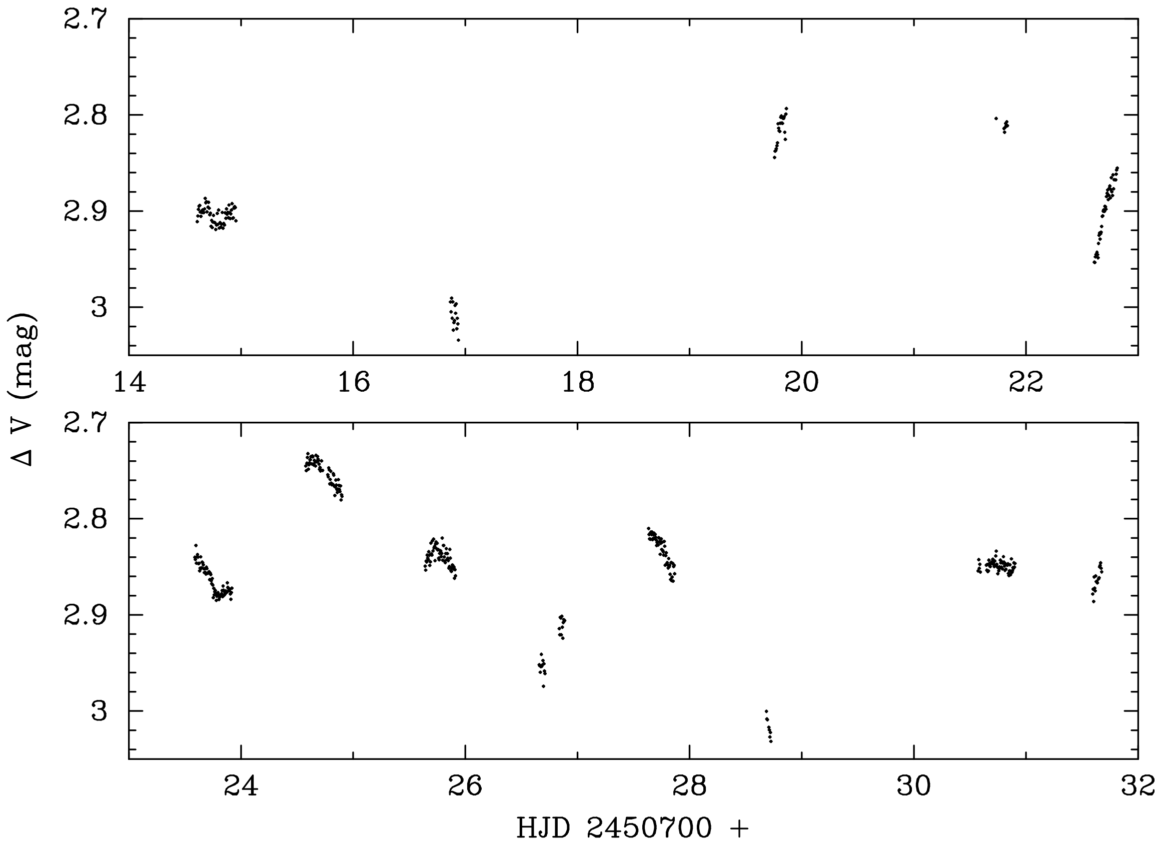


Figure 3.2: The light curve of M2-54 during our observations. Magnitudes are relative to those of the brighter comparison star (HD 235981). Variability with a total amplitude of 0.3 mag is obvious.

than an observing night will be suppressed. We refer to Chapter 2 for a more detailed discussion of this problem (and how to take care of it).

To start a search for a typical time scale present in the short-term variations, we begin with an estimate of its possible range. As can be seen from Fig. 3.2, we never covered a full cycle during a single observing night. Therefore, the time scale must be longer than 8 hours.

Keeping the limitations above in mind, we set all nightly mean magnitudes to zero and calculated an amplitude spectrum of these data. This is shown in Fig. 3.3. A peak at 2.69 c/d with its alias structure dominates. To check how much the zeropoint adjustments affect this analysis, we computed an amplitude spectrum of the longest runs ($T > 4.5$ hours) only. Such a plot closely resembles Fig. 3.3, suggesting that the zeropoint adjustments of the short runs have negligible influence on our results.

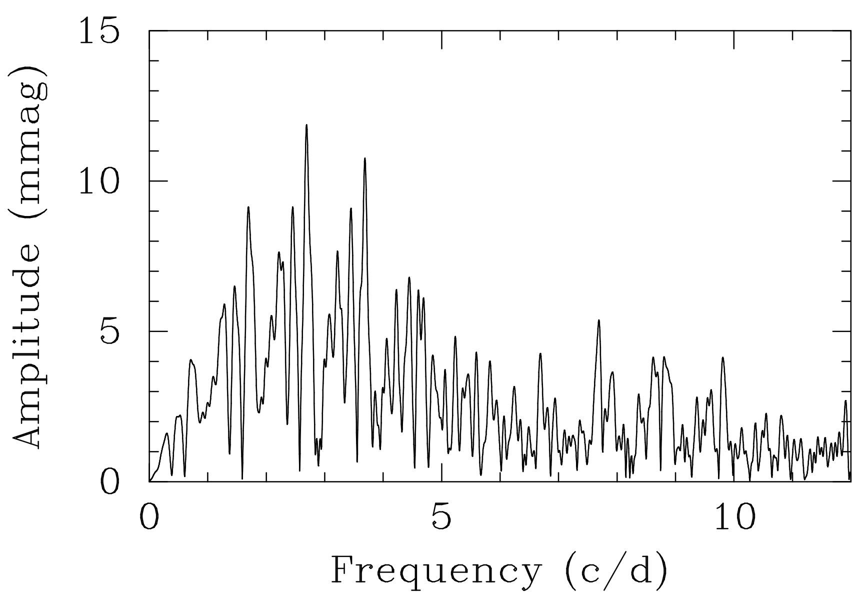


Figure 3.3: The amplitude spectrum of the M2-54 data after adjusting the nightly zeropoints

What is the underlying time scale of the short-term variations? Three peaks in Fig. 3.3 are interesting, namely those at 1.68, 2.69 and 3.69 cycles/day. The latter peak must be an alias, since it corresponds to a period of 6.5 hours. Therefore, we should have seen a full cycle of such variations in five of our runs, which is not the case.

Calculating single-frequency fits to our data (and adjusting the zeropoints accordingly) yields somewhat lower rms residuals for the 2.69 c/d variation compared to the 1.68 c/d time scale (11.6 mmag vs. 12.1 mmag). However, we do not dare to suggest that this is the correct frequency, since these residuals are considerably

higher than the scatter per single data point estimated in Sect. 3.2. This can be due to two reasons:

- The variations are not strictly periodic.
- The long-term variability could not be completely removed from the data. Therefore, remaining trends affect the analysis. This may also result in different amplitudes for different cycles - which is apparent in Fig. 3.2.

The first hypothesis can be checked by calculating (O-C) diagrams. However, since we did not observe too many light maxima or minima, such an analysis is not of much use. The remaining possibility is to calculate phase diagrams relative to the two frequencies under consideration. We did this and show the result in Fig. 3.4.

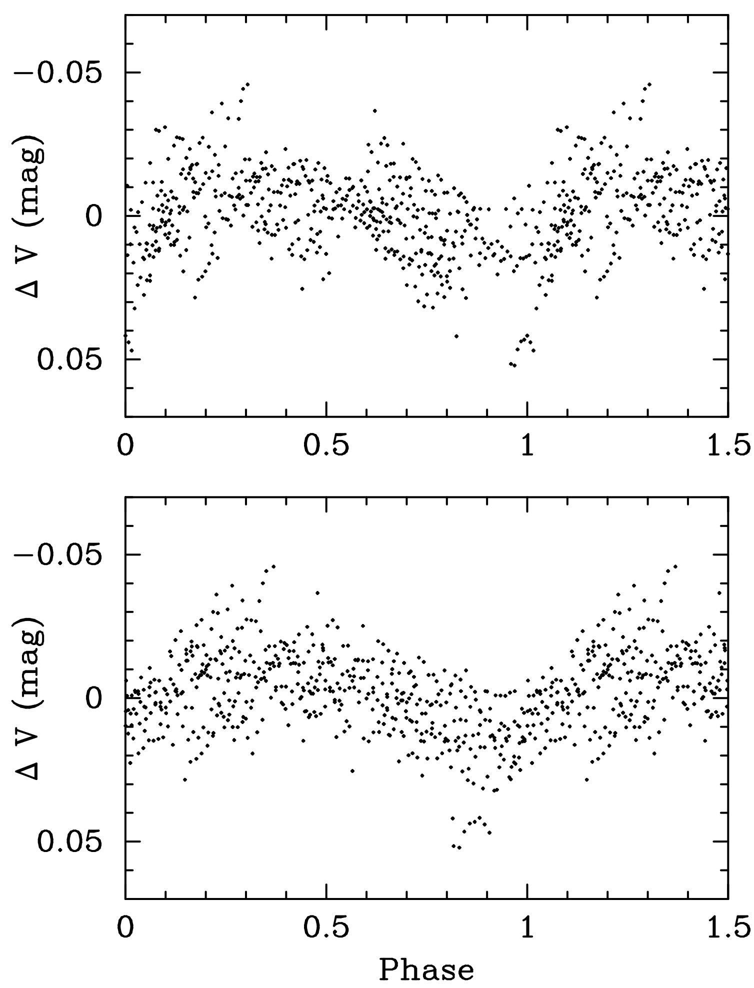


Figure 3.4: Upper panel: a phase plot of the adjusted M2-54 data relative to a frequency of 1.68 c/d. Lower panel: the same, but relative to the 2.69 c/d frequency

The most interesting feature in Fig. 3.4 clearly is that the phase diagram relative to the 2.69 c/d frequency is much smoother. This also suggests that this frequency is more likely to correspond to the correct time scale of the short-term light variations of M2-54.

To summarize the results of our light-curve analysis, the variability of M2-54 is quite similar to that of HD 35914 (Chapter 2). Two time scales are present: apparently non-periodic variations of the mean magnitude with a time scale of days plus quasiperiodic variability with a time scale of several hours. The latter time scale is most likely about 8.9 hours, but a 14.3-hour modulation cannot be ruled out.

## 3.4 HIPPARCOS photometry

M2-54 was also a target observed by the HIPPARCOS satellite (ESA 1997) and found to be variable. Consequently, these observations may be helpful to constrain the time scale of the light variations of the central star. However, the mean standard deviation of these measurements is more than 0.06 mag per single data point, an order of magnitude higher than the accuracy of our photometric data. For that reason and because of the time distribution of the HIPPARCOS observations one must again be careful when analyzing these data.

We first examined the results of the 117 accepted transits. From these data, one extreme outlier (more than 1 mag brighter than the average HIPPARCOS magnitude) and another point with a standard deviation larger than 0.15 mag were rejected. For the given time distribution of the data, we then created data sets consisting of random noise with the same standard deviation as the HIPPARCOS photometry. Both the original and the randomized data were then Fourier analysed. The result is displayed in Fig. 3.5.

The amplitude spectra shown in Fig. 3.5 supported by some more simulations (e.g. Fourier spectra of zeropoint adjusted data or data with artificially introduced variations) imply that the quality and the quantity of the HIPPARCOS observations are unfortunately too low to be of help in determining secure time scales of light variation of M2-54. We note that the amplitude of the signal we found in our data was 12 mmag, much smaller than the noise level in the HIPPARCOS data.

## 3.5 Discussion

To examine the physical reason of the variability of M2-54 (following the discussion in Chapter 2, see there for more details), we first need to estimate the star's position in the HR Diagram. We start with its effective temperature.

Two indirect determinations are available: using a modified Stoy method, Kaler (1983) suggested that the effective temperature of M2-54 is around 30 000 K. Fur-

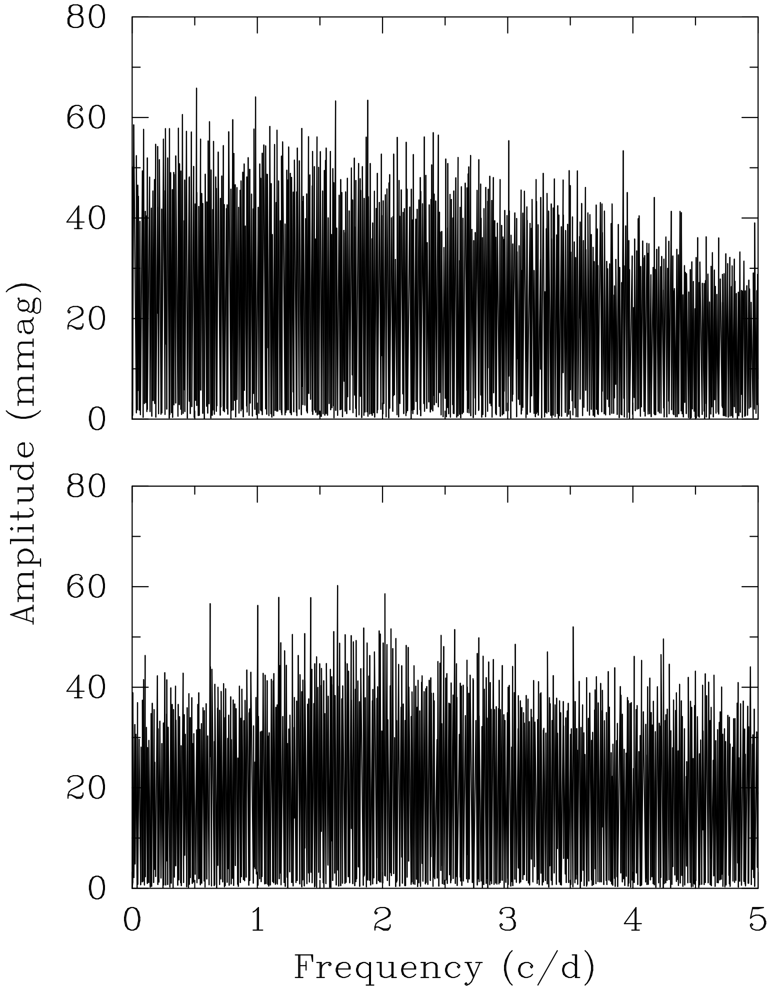


Figure 3.5: Upper panel: the amplitude spectrum of the HIPPARCOS photometric data of M2-54. Lower panel: an amplitude spectrum of a random data set, sampled exactly as the HIPPARCOS data and having the same standard deviation

thermore, Stasińska et al. (1997) derived a Zanstra temperature of 20 000 K. Consequently, we adopt $T_{\rm eff} = 25\,000 \pm 5\,000$ K.

Turning to mass and luminosity, we make use of the results of Stasińska et al. (1997), who list $M_* = 0.563 M_\odot$ for M2-54. Inserting this and the effective temperature above into the evolutionary tracks of Schönberner (1983), one obtains $\log L = 3.56$. Since Stasińska et al. (1997) did not give any error estimates for their derived parameters, we assume an error size of $\pm 0.2$ in $\log L$. Combining all the estimates, one obtains $R_* = 3.2 \pm 1.5 R_\odot$.

Since we do not have time-series spectroscopic data of M2-54 available, we cannot examine a binary hypothesis here. However, it is possible to say something about a spot hypothesis. With the parameters inferred above, the critical rotation period,

which can be calculated as

$$P_{\rm crit} = \frac{2\pi R_{\rm eq}^{3/2}}{(GM)^{1/2}}, \tag{3.1}$$

where $R_{\rm eq}$ is the equatorial radius of the star ($R_{\rm eq} = 1.5\,R_*$), becomes $39^{+30}_{-24}$ hours for M2-54. Only by assuming a 14.3 hour modulation to be correct and only by adopting the lower limit of the critical rotation period a spot hypothesis becomes feasible; it is therefore not very likely. Still, we cannot rule it out, as we did for HD 35914.

If we assume wind variability to be the cause for the short-term light variations and if we assume that the mechanism causing it is the same as for hot massive stars, we would expect the time scale to be correlated with the stellar rotation period as well (e.g. see Kaper et al. 1996). Consequently, this hypothesis is also only possible with improbable assumptions, just as the spot hypothesis. On the other hand, both ideas may explain the long-term variations in M2-54 (and HD 35914).

The only remaining possibility for the short-term light variations is that they originate from stellar pulsations. We again follow the methods applied in Chapter 2 to examine its feasibility. First, we calculate the pulsation "constant" $Q$ for the two possible periods recovered in the frequency analysis. If the 14.3 hour period is correct, one obtains $Q = 0.078^{+0.124}_{-0.034}$ while for the 8.9 hour period $Q = 0.049^{+0.076}_{-0.022}$ is found. We note that the large upper limits originate from error propagation of our inferred stellar parameters - which we consider to be very conservative.

Now we make use of Gautschy's (1993) pulsational model calculations for post-AGB objects. In his models the radial fundamental mode as well as the first overtone are pulsationally unstable at $T_{\rm eff}$ around 25 000 K. Since his models are for $M = 0.84 M_\odot$, we cannot directly take the periods, but we can compare the pulsation "constants" with those derived above. The models yield $Q = 0.06$ d for the fundamental mode and $Q = 0.04$ d for the first radial overtone. This is in good agreement with the pulsation "constants" derived from the observations. Hence, it is also the most consistent explanation of the short-term variations of M2-54.

## 3.6 Summary and conclusions

We carried out a time-series photometric study of the variable central star of the young Planetary Nebula M2-54. The behaviour of this object is strikingly similar to that of the best studied representative of this class of variable star, HD 35914, the central star of IC 418. The similarity between M2-54 and HD 35914 strongly suggests that the physical reason causing the variations is the same.

Our light-curve analysis showed that slow, apparent nonperiodic, light variations with a time scale of days and short-term variability with a time scale of several hours is present in M2-54. More specifically, the faster variations are (quasi)periodic with

a time scale of either 8.9 or 14.3 hours. We cannot definitely distinguish between these two possibilities because of aliasing ambiguities.

While the long-term variations of M2-54 may be explained by both a spot or a wind-variation hypothesis, the short-term variations are most likely due to stellar pulsation, suggesting that we are in the presence of a new class of pulsating star.

However, further work is needed to confirm or reject this claim. Observationally, the temporal behaviour of a number of central stars with well-known basic parameters, e.g. from model atmosphere analysis (e.g. Méndez et al. 1992) should be studied in more detail. Multisite observing campaigns (which do not require more than two or three sites well separated in longitude) during a time span of several weeks need to be undertaken. Besides time-series photometry, spectroscopic investigations would be very useful.

On the theoretical side, pulsational stability analysis, similar to that of Gautschy (1993) are required for a set of models of different mass and chemical composition. Close collaborations between theorists and observers are important for these stars being investigated in a satisfying manner.

# Chapter 4

# A Survey For Variability Among Bright Northern and Equatorial Central Stars of Planetary Nebulae

## 4.1 Introduction

As mentioned in Chapter 1, the amount of published data on variable central stars of young Planetary Nebulae was sparse at the beginning of this work and the available information was scattered over several references; claims of variability of several CSPN came as by-products of observing programs focused on other objects.

Only one systematic search for variability among central stars of young Planetary Nebulae has been undertaken (for He 2-131 and He 2-138, Hutton & Méndez 1993) and light curves have rarely been published. These comprise only the two stars mentioned before, IC 418 (Méndez et al. 1983, 1986, Jasniewicz 1987), IC 4593 (Bond & Ciardullo 1989) and NGC 6543 (Bell et al. 1994). Furthermore, Bond & Ciardullo (1991) mention photometric variability of the central stars of Hu 2-1, IC 2149, IC 3568, NGC 6826 and possibly NGC 40, while Méndez (1989) lists the central stars of PB 8, NGC 2392 and He 2-131 and He 2-138 as radial velocity variables on the basis of a few measurements.

Clearly, the amount of data quoted above is insufficient to examine possible systematics of the variability these objects. The time scales of light variation were only estimated for five CSPN; actually mostly limits on them could be derived. Although it has been noted (Kuczawska et al. 1997, see also Section 1.3.3) that these variables appear to share some common characteristics, no comprehensive study had been published. Another possible finding, which is often not considered to be interesting enough to publish, but is important to understand the whole phenomenon, concerns the question whether there are also constant stars with similar physical

parameters as the variables.

To improve the situation, we conducted a survey for photometric variability of CSPN. At the outset of this work, we hoped to be able to answer two main questions:

- Is the observed range of effective temperatures of variable central stars consistent with that predicted by pulsational model calculations or does it agree better with the temperature range in which variable winds are observed?
- Are the time scales of the variations comparable with the time scales expected for low-order p-mode pulsation or is there a dependence on the stellar rotation period (as it is the case for wind variations of massive O stars, e. g. Kaper et al. 1996)?

The result of this investigation and its implications are reported below.

## 4.2 Observations

The survey was undertaken during a stay of the author at the University of Texas and McDonald Observatory from August 1995 to March 1996. 24 CSPN were observed using both the 0.9 m and 2.1 m telescopes of McDonald Observatory; 178 hours of useful photoelectric photometry were acquired. A journal of the observations is given in Table 4.1.

Some comments on the adopted observing strategy are necessary. First, we wanted to search for light variations on time scales of a few hours. Therefore, we attempted to acquire at least one run of 4 – 5 hours for each of the targets. Since variations on time scales of days could also be present, we obtained a number of additional short runs to check this possibility. It should be stressed that we performed rough data reduction as soon as possible (sometimes already when measuring the "next" target, i.e. being at the telescope) to get an idea of possible variability. If variability was detected in this way, we attempted to acquire follow-up observations to constrain the time scale of the variations better.

Second, the time-series photometric observations were acquired through apertures large enough to include the whole nebula. This does only affect the search for light variations by reducing the observed amplitudes due to the inclusion of the nebular flux. The latter is not expected to be variable on similar time scales as the central stars, since the recombination time scales of the electrons in the nebulae are much longer. The aperture sizes varied between $27''$ for faint stellar-like PN, while a $55''$ aperture had to be used for the most extended objects (e.g. NGC 2392).

Third, the filters used were selected to yield the best signal-to-noise ratio to detect stellar variability. In general, the Johnson V filter is to be preferred to the Johnson B filter, since it is less affected by nebular emission. Only in cases of very bright, extended nebulae with bright central stars, the Strømgren y filter was chosen to suppress the nebular contribution as much as possible.

Table 4.1: Journal of the observations

| Object | Date (UT) | Start (UT) | Δt (hrs) | Fil. | Telscp. | Comparison stars |
|---|---|---|---|---|---|---|
| M 1-77 | 18/8/95 | 5:23:30 | 6.20 | V | 0.9 m | S 50704, S 50708 |
| | 21/8/95 | 7:58:20 | 3.55 | V, y | 0.9 m | |
| | 23/8/95 | 8:08:00 | 3.33 | V | 0.9 m | |
| | 24/8/95 | 2:25:50 | 0.50 | V | 0.9 m | |
| | 25/8/95 | 8:32:30 | 1.44 | V | 0.9 m | |
| | 29/8/95 | 8:59:30 | 0.47 | V | 0.9 m | |
| IC 4634 | 19/8/95 | 2:24:50 | 2.99 | V | 0.9 m | H 153742, H 153362 |
| | 26/8/95 | 3:39:10 | 0.44 | V | 0.9 m | |
| WhMe 1 | 19/8/95 | 5:30:00 | 3.45 | V | 0.9 m | H 230990, H 231007 |
| | 25/8/95 | 7:54:30 | 0.57 | V | 0.9 m | |
| | 29/8/95 | 7:25:40 | 0.55 | V | 0.9 m | |
| NGC 6891 | 19/10/95 | 1:29:20 | 4.17 | y | 0.9 m | H 357082, H 357093 |
| | 21/10/95 | 1:06:30 | 2.78 | V | 0.9 m | |
| NGC 6572 | 21/8/95 | 2:30:20 | 5.38 | V | 0.9 m | S 123244, B+9 3651 |
| | 25/8/95 | 6:42:20 | 0.49 | V | 0.9 m | |
| Cn 3-1 | 21/8/95 | 2:30:20 | 5.38 | V | 0.9 m | S 123244, B+9 3651 |
| | 25/8/95 | 6:42:20 | 0.49 | V | 0.9 m | |
| | 28/8/95 | 2:17:50 | 0.61 | V | 0.9 m | |
| M 2-54 | 22/8/95 | 8:29:30 | 0.62 | V | 0.9 m | H 235982, H 235981 |
| | 29/8/95 | 9:31:30 | 0.57 | V | 0.9 m | |
| | 30/8/95 | 3:47:30 | 7.11 | V | 0.9 m | |
| | 23/10/95 | 2:12:20 | 6.26 | V | 0.9 m | |
| Sa 3-151 | 23/8/95 | 3:38:00 | 4.49 | V | 0.9 m | B-0 3615, S 142901 |
| | 25/8/95 | 7:16:10 | 0.59 | V | 0.9 m | |
| | 29/8/95 | 6:51:00 | 0.50 | V | 0.9 m | |
| VV 3-5 | 25/8/95 | 2:14:50 | 4.42 | V | 0.9 m | S 161649, H 171664 |
| | 28/8/95 | 2:55:20 | 0.57 | V | 0.9 m | |
| | 29/8/95 | 2:15:50 | 4.38 | V | 0.9 m | |
| M 1-55 | 25/8/95 | 2:14:50 | 4.42 | V | 0.9 m | S 161649, H 171664 |
| BD+30 3639 | 28/8/95 | 3:47:10 | 4.97 | V | 0.9 m | H 184500, S 68485 |
| | 29/8/85 | 7:58:40 | 0.40 | V | 0.9 m | |
| M 1-46 | 29/8/95 | 2:15:50 | 4.38 | V | 0.9 m | S 161649, H 171664 |
| NGC 6629 | 29/8/95 | 2:15:50 | 4.38 | V | 0.9 m | S 161649, H 171664 |

Table 4.1: Journal of the observations (continued)

| Object | Date (UT) | Start (UT) | Δt (hrs) | Fil. | Telscp. | Comparison stars |
|---|---|---|---|---|---|---|
| Hb 12 | 29/8/95 | 10:09:30 | 0.66 | V | 0.9 m | H 240296, H 240279 |
| | 17/10/95 | 6:28:30 | 3.77 | V | 0.9 m | |
| | 23/10/95 | 8:33:10 | 0.54 | V | 0.9 m | |
| | 28/10/95 | 1:11:00 | 8.43 | V | 0.9 m | |
| Vy 1-1 | 29/8/95 | 10:52:40 | 0.72 | V | 0.9 m | H 232151, H 232161 |
| | 18/10/95 | 4:46:20 | 5.82 | V | 0.9 m | |
| | 19/10/95 | 5:52:30 | 4.63 | V | 0.9 m | |
| | 23/10/95 | 9:11:30 | 0.33 | V | 0.9 m | |
| | 24/10/95 | 5:31:20 | 4.56 | V | 0.9 m | |
| NGC 6826 | 29/8/95 | 8:33:00 | 0.40 | V | 0.9 m | B+49 3094, S 31980 |
| | 22/10/95 | 1:18:10 | 4.42 | y | 0.9 m | |
| NGC 1535 | 22/10/95 | 5:53:40 | 4.40 | y | 0.9 m | H 26848, S 149470 |
| | 23/10/95 | 9:44:50 | 0.43 | y | 0.9 m | |
| | 25/10/95 | 5:46:00 | 2.33 | y | 0.9 m | |
| IC 4997 | 24/10/95 | 1:22:40 | 4.09 | V | 0.9 m | H 355464, H 355472 |
| | 27/10/95 | 1:12:00 | 4.25 | V | 0.9 m | |
| | 29/10/95 | 1:09:40 | 4.14 | V | 0.9 m | |
| NGC 7009 | 25/10/95 | 1:18:00 | 4.11 | y | 0.9 m | H 358112, H 200760 |
| IC 2149 | 27/10/95 | 5:35:50 | 4.25 | V | 0.9 m | S 40704, S 40728 |
| M 4-18 | 12/12/95 | 1:27:30 | 7.08 | V | 2.1 m | B+60 806, H 237245 |
| M 1-11 | 13/12/95 | 6:23:10 | 2.28 | V | 2.1 m | H 55096, H 57236 |
| M 1-12 | 13/12/95 | 6:23:10 | 2.28 | V | 2.1 m | H 55096, H 57236 |
| | 28/12/95 | 6:37:30 | 4.10 | V | 0.9 m | H 57143, H 57236 |
| NGC 2392 | 28/12/95 | 5:03:30 | 1.51 | y | 0.9 m | B+21 1613, S 79446 |
| | 29/12/95 | 3:38:50 | 2.43 | y | 0.9 m | |
| | 30/12/95 | 5:04:40 | 5.28 | y | 0.9 m | |
| Total | | | 178.09 | | | |

Star designation abbreviations: B=BD Number, H=HD Number, S=SAO Number

Fourth, the selection of comparison stars needs to be done with caution. They should not be too cool to avoid the occurrence of differential color extinction between themselves and the target. However, many hotter stars are pulsators (e.g. $\delta$ Scuti or $\beta$ Cephei stars), which can be variable on the same time scales as the CSPN under consideration. Therefore, colors and/or spectral types should be known, but they can of course not be assumed to be reliable in all cases. In the end, only one (HD 230990, Handler & Paunzen 1995) of the 42 observed comparison stars turned out to be variable within the accuracy of our measurements.

## 4.3 Data reduction and analysis

The photometric measurements were corrected for coincidence losses, sky background and extinction. All the times of measurement were converted into Heliocentric Julian Date (HJD). All the data reduced in this way are displayed in Figs. 4.1–4.9, where we have applied mean zeropoint shifts for plotting purposes. These reductions may appear to be rather crude. However, this should allow the reader to judge the quality of the data as objectively as possible, especially since the photometric conditions were somewhat variable during the whole survey.

### 4.3.1 Comments on all individual objects

#### Variable central stars

**IC 2149 and NGC 6826:** These CSPN have already been reported to be variable in the literature (Bond & Ciardullo 1991), but no light curves were given. They were included in our survey as a consistency check on the previous findings. The variability of both of these objects could be easily and convincingly confirmed (Fig. 4.1).

**M 1-77, M 2-54, M 4-18 and NGC 2392:** These are all new variables, whose discovery was already briefly reported (Handler 1995, 1996). Here we present all the light curves we obtained, (which confirm our earlier results) and attempt to determine the time scales of the light variations whenever possible.

The light variations of M 1-77 are very similar to those already observed in the central star of IC 418. Both short- and long-term variations are present, reaching an amplitude of 0.15 mag. A frequency analysis of our data does not yield conclusive results. It seems that the mean magnitude variations show some regularity, at least within our restricted data set. For the faster variations, it can only be said that their time scale must be longer than 8 hours. Further observations, preferably from more than one site, are necessary.

M 2-54 is by far the highest amplitude variable similar to the central star of IC 418: it varies up to 0.3 mag in Johnson V. Therefore, it was chosen for a more

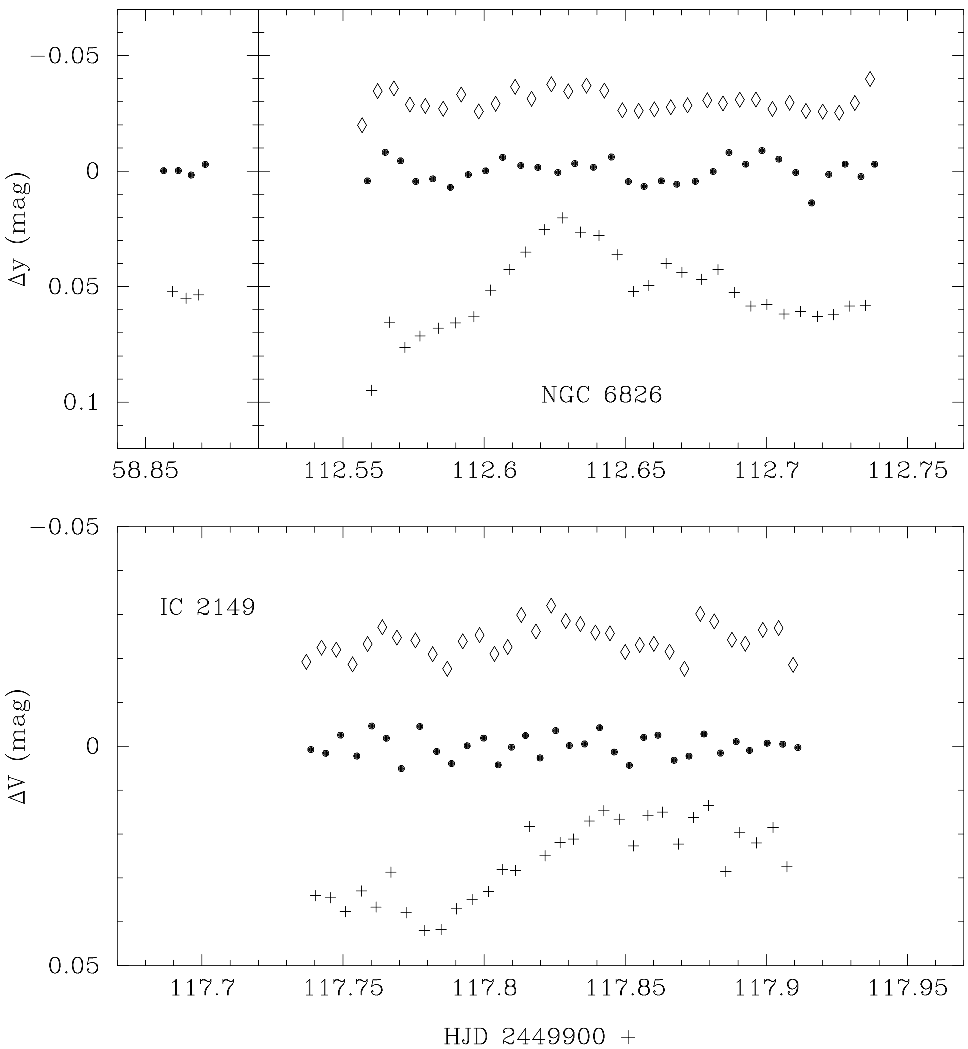


Figure 4.1: Light curves of CSPN reported to be variable in the literature; the variations of both objects are clearly confirmed. Filled circles and diamonds correspond to the magnitudes of the comparison stars while the crosses are the relative PN magnitudes (this scheme is kept for Figs. 4.1–4.9).

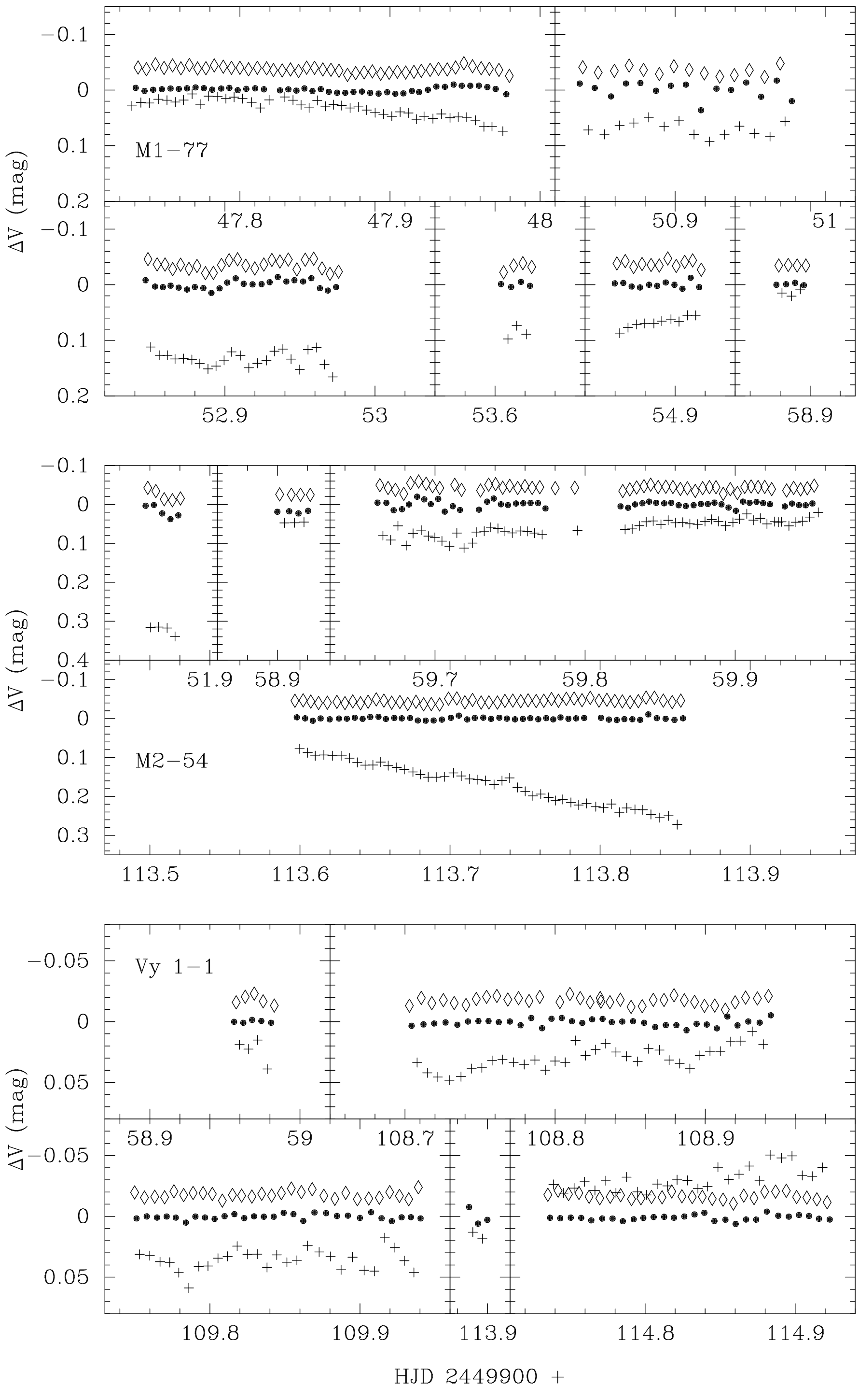


Figure 4.2: New variables discovered during this survey: M 1-77, M 2-54 and Vy 1-1 (see text for more information)

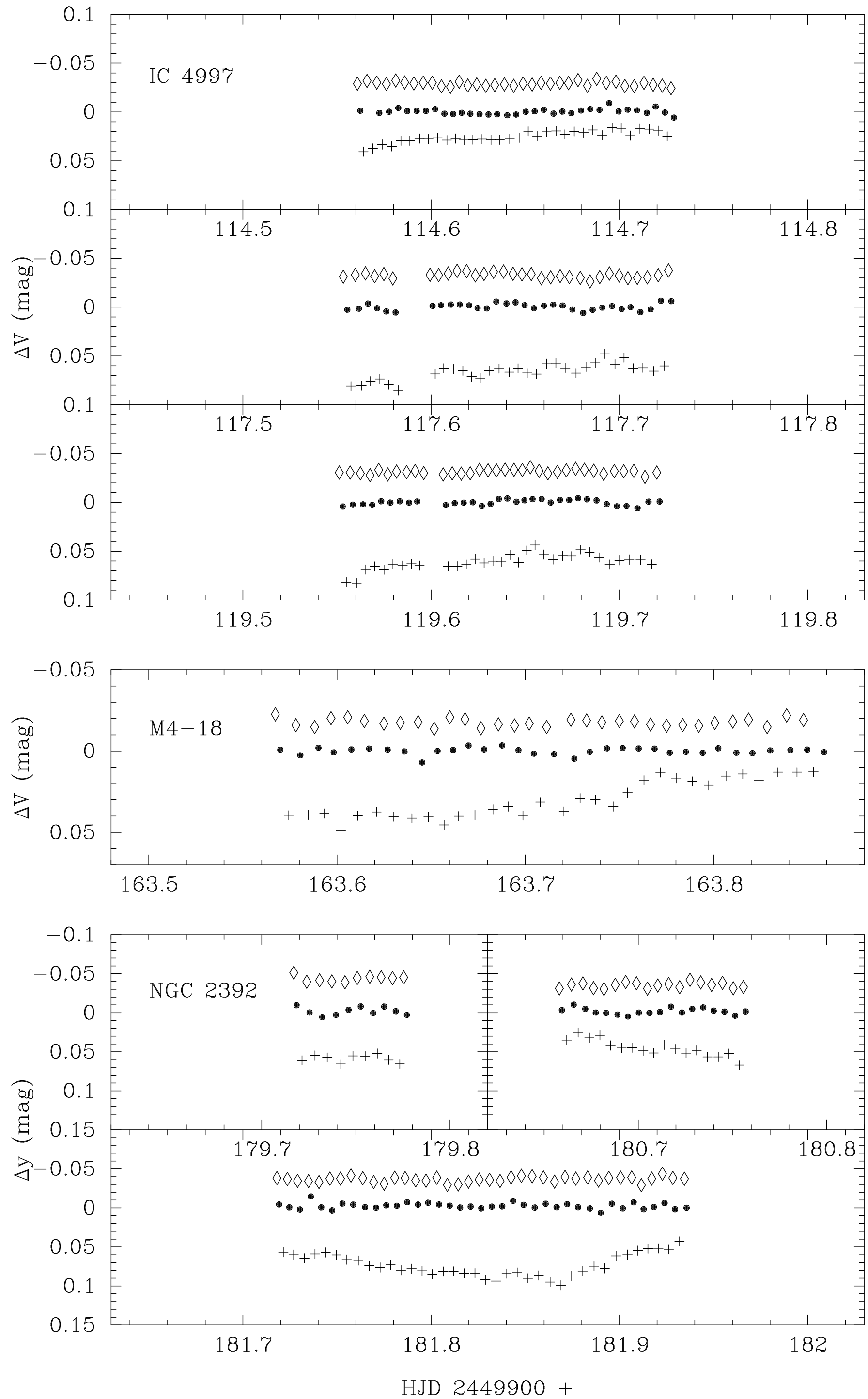


Figure 4.3: New variables discovered during this survey: IC 4997, M 4-18 and NGC 2392 (see text for more information)

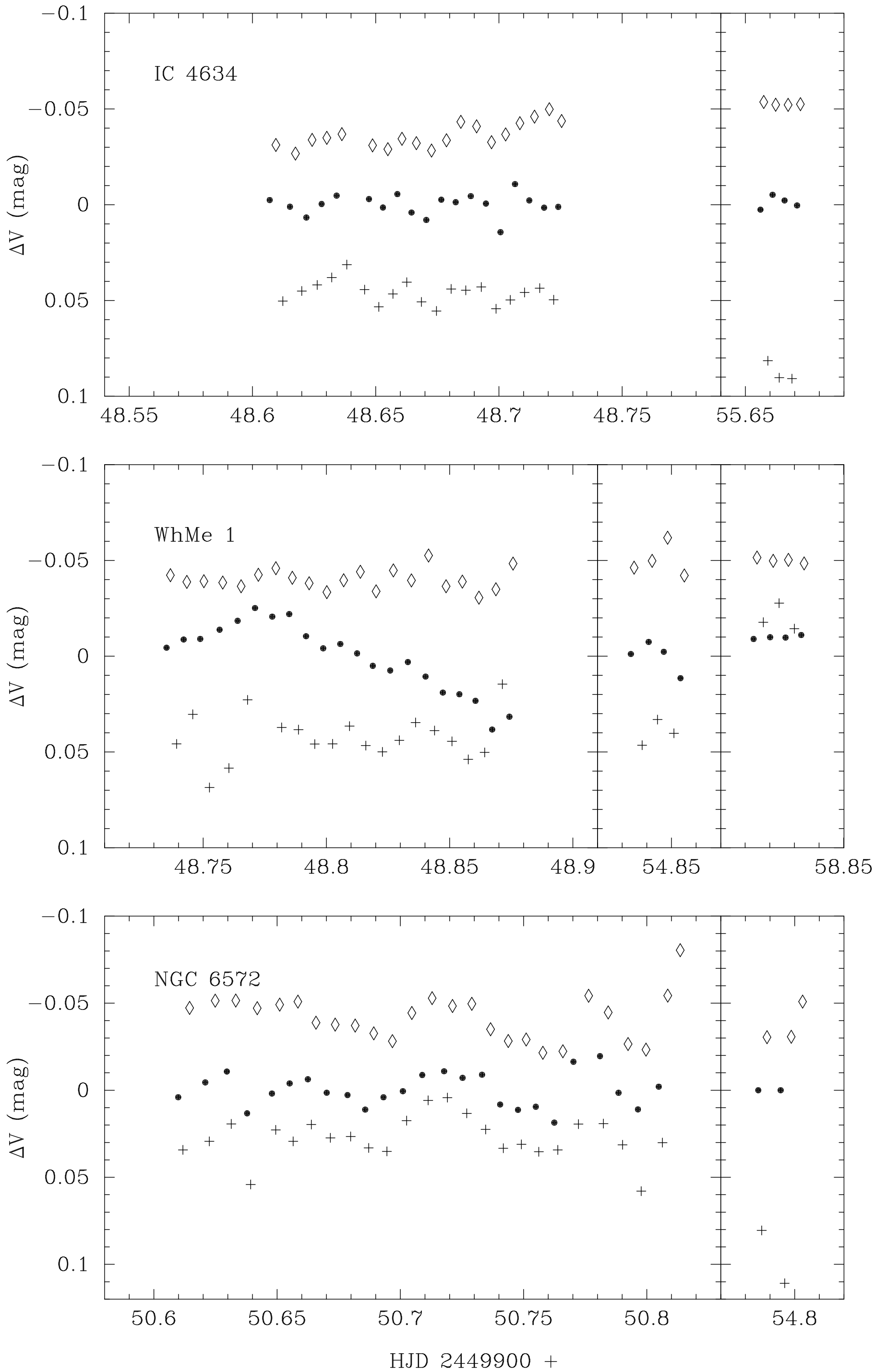


Figure 4.4: Suspected variables revealed in our survey: IC 4634, WhMe 1 (one comparison star (filled circles) turned out to be a $\delta$ Scuti variable) and NGC 6572 (see text for more information)

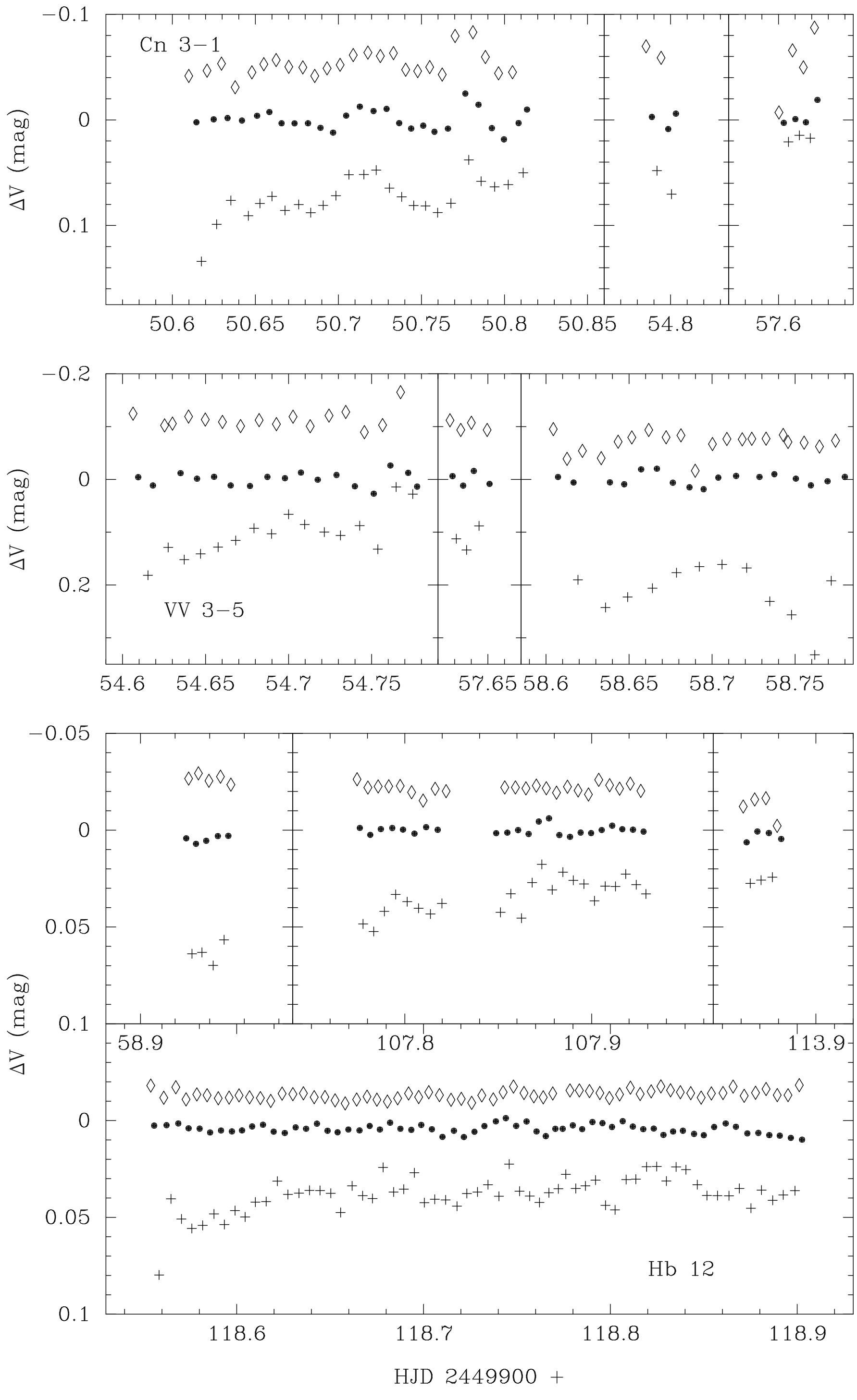


Figure 4.5: Suspected variables revealed in our survey: Cn 3-1, VV 3-5 and Hb 12 (see text for more information)

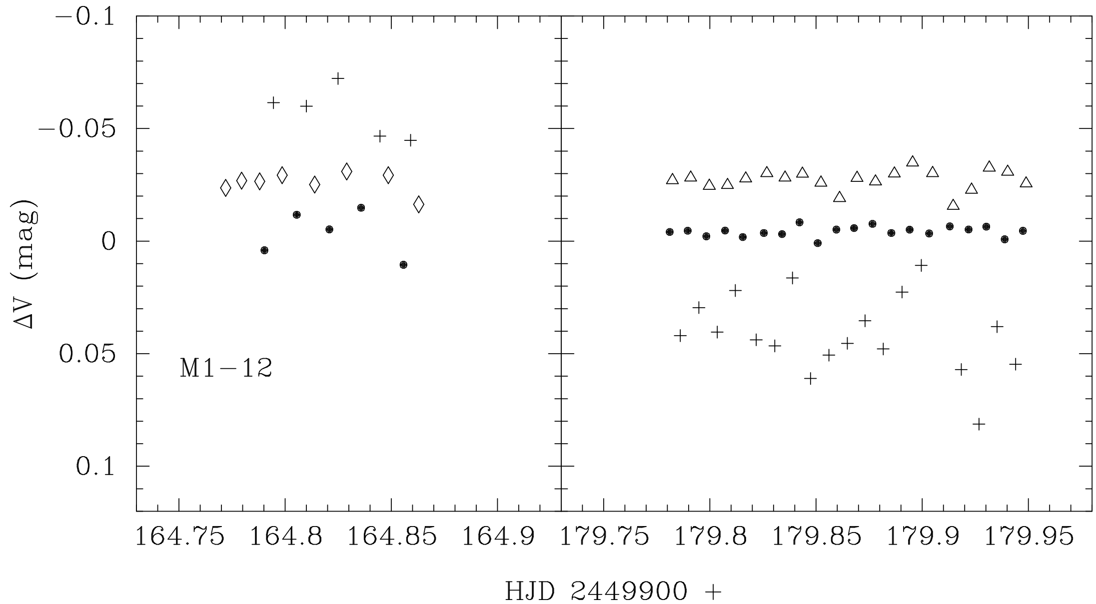


Figure 4.6: Suspected variable revealed in our survey: M 1-12 (see text for more information)

extensive study (Chapter 3). For M 4-18 only a single run is available, but its high quality leaves no doubt about the variability of the star; the time scale is longer than 7 hours.

The amplitude of NGC 2392 never exceeded 0.1 mag, but variability is clearly present. A frequency analysis of our light curves suggests that the time scale of the short-term variations is near 5.3 hours. Nevertheless, more data are needed to confirm this. It should also be noted that one of the comparison stars used appears slightly variable. However, since the time scale of these variations is similar to that of the CSPN, but their amplitude is much smaller, it cannot be said which of the two comparison stars is the candidate variable.

**Vy 1-1:** The variability of this object would probably have remained undetected, had we not (erroneously) suspected that one of the comparison stars was variable. Therefore we took three runs longer than four hours. During the last run, Vy 1-1 decided to change its mean magnitude by almost 0.1 mag compared to the previous observations. Slow light variations occured during two single nights.

We did not announce the variability of Vy 1-1 earlier, since we wanted to double-check our reductions before concluding anything. Now that this has been done, we consider it as a new discovery.

**IC 4997:** This CSPN has a long history of being reported as variable (e.g. see Kostyakova 1997). However, the time scales investigated were on the order of years.

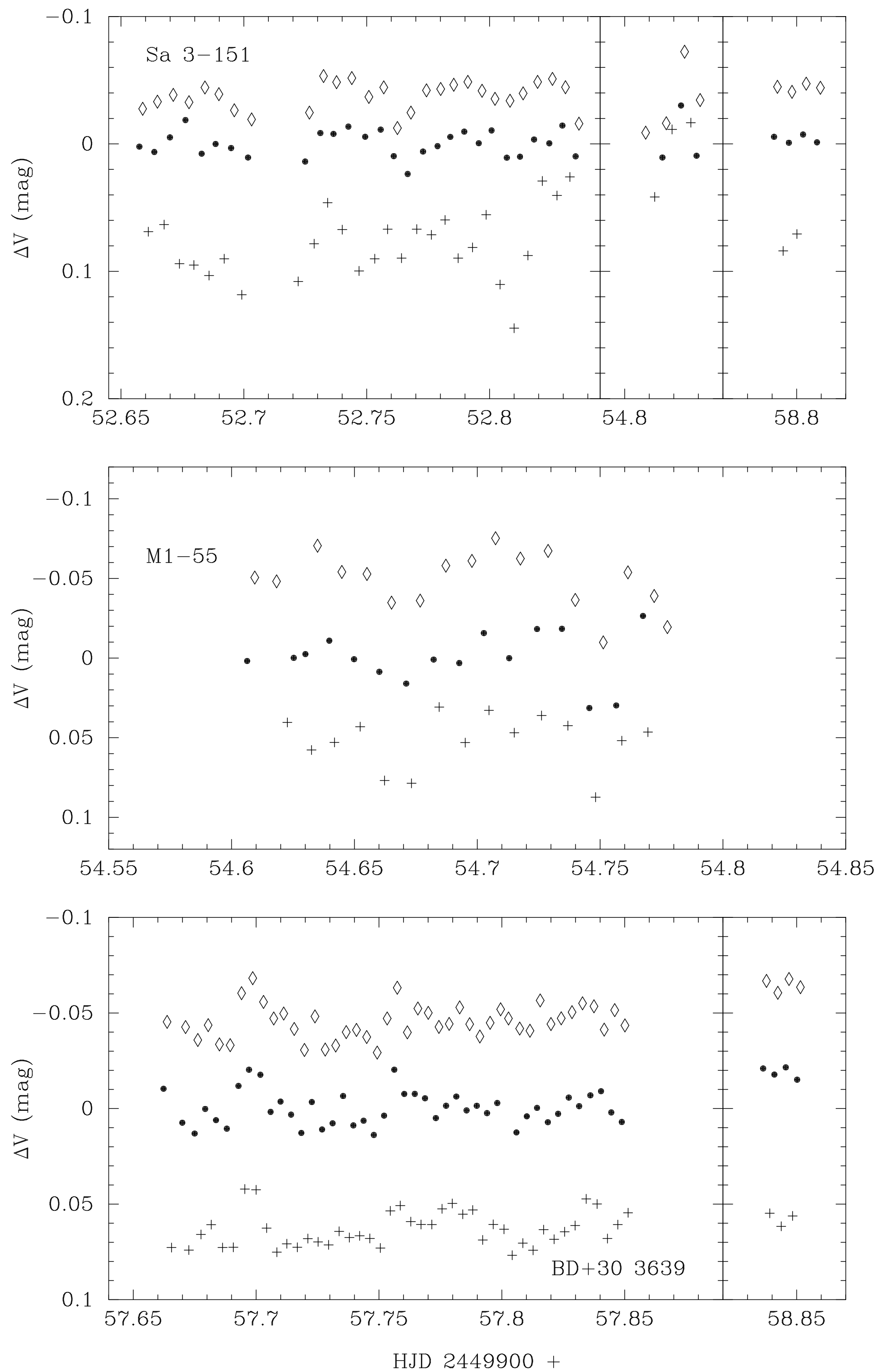


Figure 4.7: CSPN where no convincing light variations were found: Sa 3-151, M 1-55 and BD+30° 3639

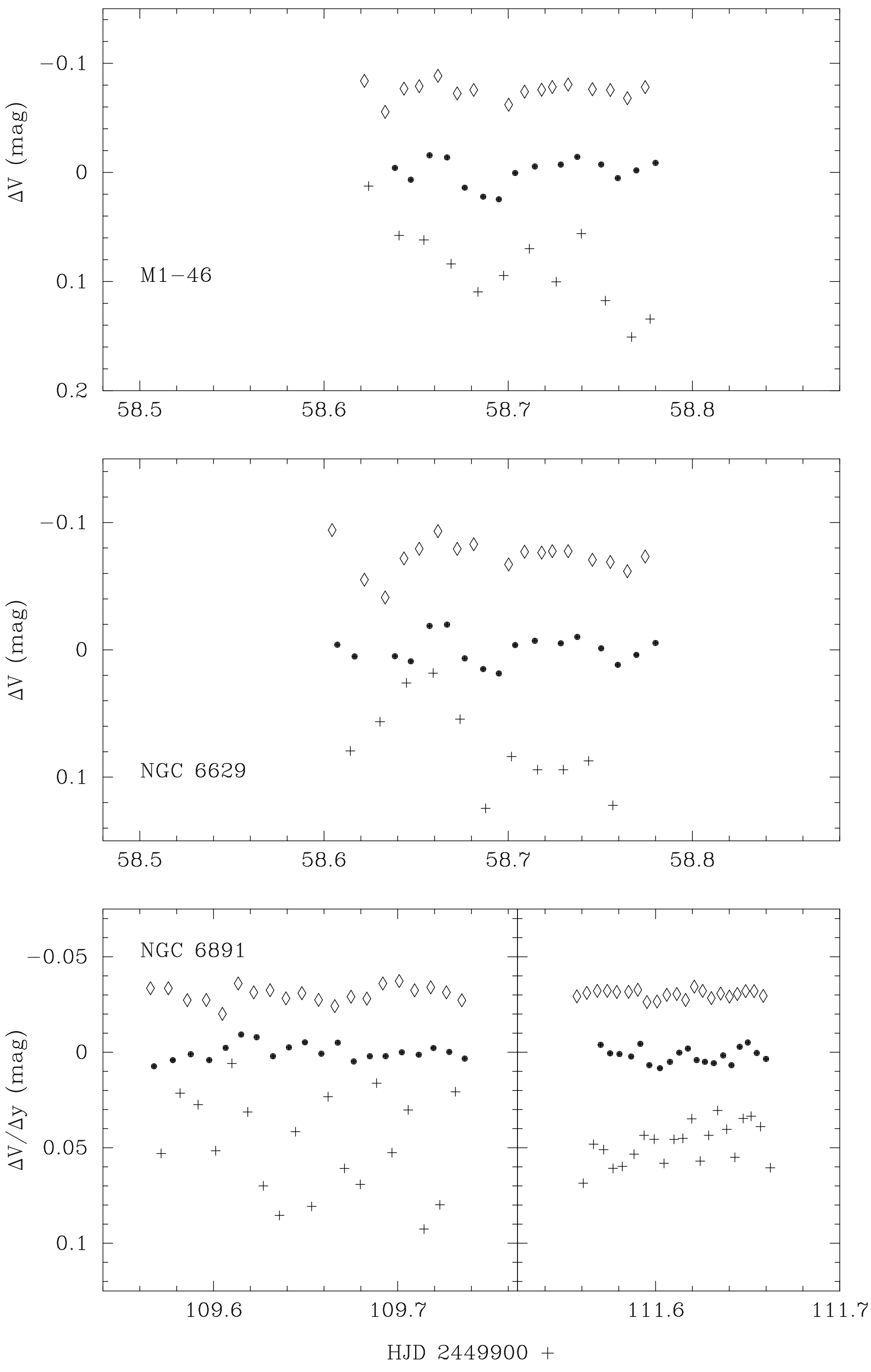


Figure 4.8: CSPN where no convincing light variations were found: M 1-46, NGC 6629 and NGC 6891

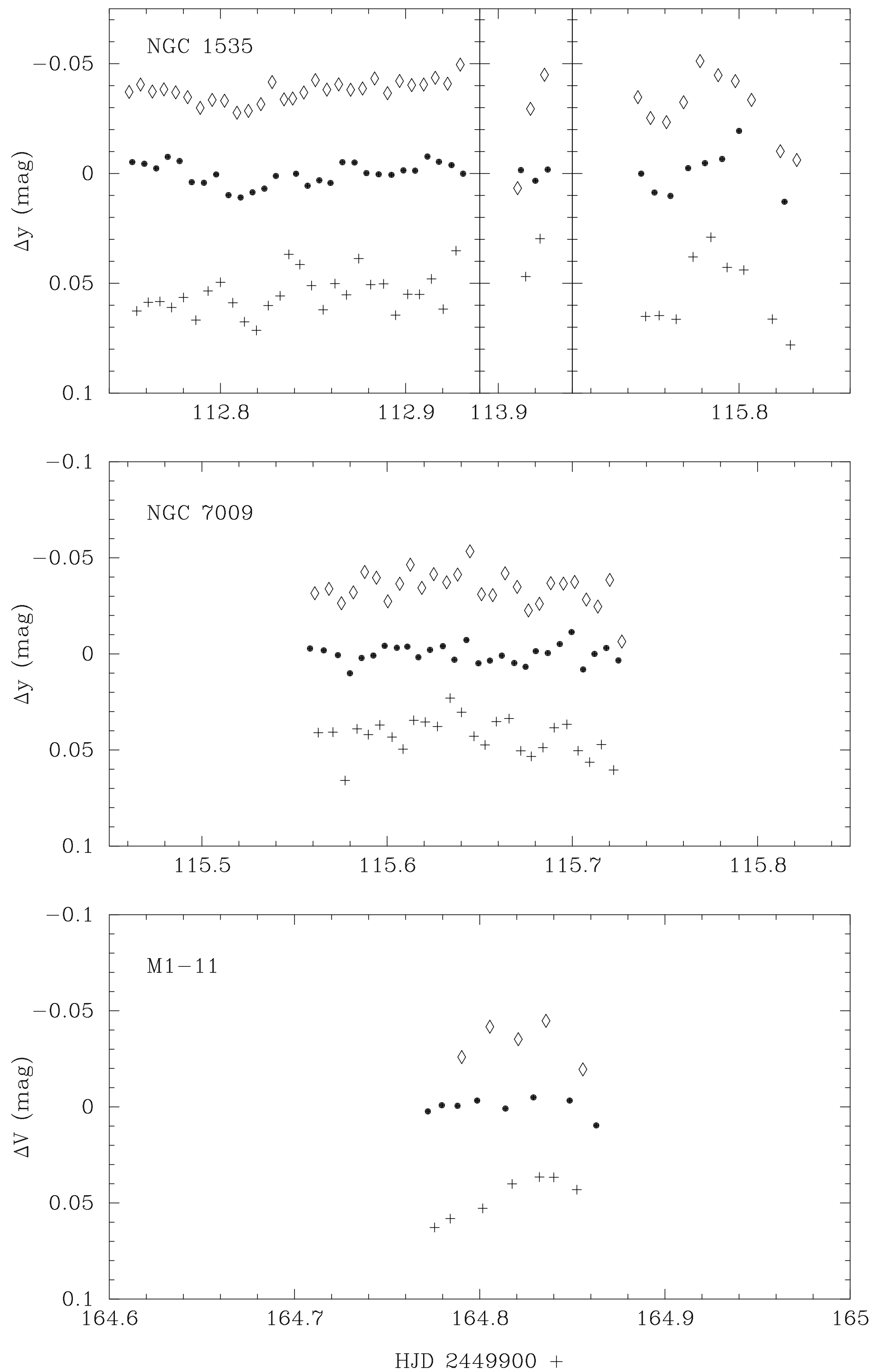


Figure 4.9: CSPN where no convincing light variations were found: NGC 1535, NGC 7009 and M1-11

Our observations show for the first time that slight variability on a time scale of a few days or less is present as well.

### Suspected variables

For all the objects classified as suspected variables, some variation was found in the data, but we feel it is necessary to re-observe them before making stronger statements.

**IC 4634, NGC 6572, Cn 3-1:** These objects appear to show variations in their mean magnitude. However, the observations were taken during marginal photometric conditions due to the presence of dust in the air (like almost all observations in August 1995), and therefore we refrain from claiming the detection of convincing light variations.

**WhMe 1:** The same comment as above applies to this object, but furthermore one of the comparison stars used (HD 230990) turned out to be a $\delta$ Scuti-type variable (Handler & Paunzen 1995), suggesting even more caution.

**VV 3-5:** This star appears to exhibit both short-term as well as longer light variations, quite similar to the well-studied variables. However, our measurements were difficult not only due to the non-ideal photometric conditions, but also because of the high air mass during the observations and due to the presence of a relatively bright close companion to the CSPN.

We consider this object to be a very promising candidate for further study, however preferably with a CCD from a Southern Hemisphere observatory.

**Hb 12:** That object may also be variable, but we consider the data to be inconclusive. The (suspected) variations during the October run are of quite low amplitude, and the single run taken in August does not only show a different zeropoint between the CSPN and the comparison stars, but also between the comparison stars themselves. Consequently, we cannot prove the delinquent being guilty of intrinsic light variation.

**M1-12:** There seems to be a variation in the mean magnitude of the star between the two runs. However, we note that only one comparison star was common to both runs, and they were taken at different telescopes; both could negatively affect our results.

**CSPN with no light variations detected**

**Sa 3-151:** It may be suspected that this object shows some mean magnitude variations based on the second run we obtained, but its photometric quality is so poor that we cannot even reasonably suspect intrinsic variability of the central star.

**M1-55, BD+30 3639, NGC 1535, NGC 7009:** There is no evidence of any light variations in either of this objects within the accuracy and time base of our observations.

**M1-46, NGC 6629:** Both of these stars were observed during the same run, and both appear to show a slow drift in their magnitudes. However, this drift is nicely correlated with air mass and may therefore not be intrinsic.

**NGC 6891:** This object was first observed through the Strömgren y filter, while the second run was taken with a Johnson V filter. Therefore, the nebular contributions are different and we cannot say anything about possible mean light variations. Furthermore, no convincing variations were found during the individual runs.

**M1-11:** It appears that there is a change in magnitude of M1-11 during our measurements, but we caution that this object is very faint (which does not let us estimate the precision of our observations reliably) and that our run had a very short duration.

### 4.3.2 HIPPARCOS observations

Several of our candidate objects were also targets of the HIPPARCOS mission (ESA 1997). These data have already been analysed by Acker et al. (1998) and we will not re-discuss them here. It should however be noted that Acker et al. (1998) detected long-term light variations in BD+30° 3639 and in the central star of He 3-1333 (which is probably related to the R CrB stars, see Chapter 1.2.3).

Of course, one can also attempt to use the HIPPARCOS photometry to determine time scales of the light variations of our objects of interest. Regrettably, the quality and time distribution of these measurements turned out to be insufficient to make a meaningful investigation. At best, variability of some stars can be claimed on statistical grounds. An example of an analysis of the HIPPARCOS photometry of one of our targets can be found in Chapter 3.5.

### 4.3.3 Results on CSPN variability

At this point it is useful to summarize the photometric results on our targets and to combine them with literature data. We determined the time scales of the light

Table 4.2: Variable CSPN similar to HD 35914

| Central star of | V (mag) | $P$ (hrs) | Reference for variability |
|---|---|---|---|
| He 2-131 | 11.01 | $> 9$ | HM93 |
| He 2-138 | 10.90 | $> 9$ | HM93 |
| IC 418 | 9.93 | $6.5 \pm 0.15$ | HMM97 |
| IC 2149 | 11.59 | $5.0 \pm 2.2$ | BC91, this work |
| IC 4593 | 11.20 | $> 4.5$ | BC91 |
| M 1-77 | 12.12 | $> 8$ | H95, this work |
| M 2-54 | 12.08 | 8.9 or 14.3 | H96, H99, this work |
| NGC 2392 | 10.53 | $5.3 \pm 1.1$ | H96, this work |
| NGC 6543 | 11.14 | $3.5 \pm 1.5$ | BC91, BPH94 |
| NGC 6826 | 10.41 | $3.8 \pm 1.7$ | BC91, this work |

References: HM93: Hutton & Méndez 1993; HMM97: Handler et al. 1997 (Chapter 2); BC91: Bond & Ciardullo 1991; H95: Handler 1995; H96: Handler 1996; H99: Handler 1999 (Chapter 3); BPH94: Bell et al. 1994

variations whenever possible, and we separate stars where short-term variability was detected (similar to the behaviour of HD 35914, the central star of IC 418) from those which only show mean light variations or slow drifts during one night or have insufficient data to determine time scales. Tables 4.2 and 4.3 contain the variability information.

## 4.4 Discussion

### 4.4.1 Derivation of basic stellar parameters

Before discussing the astrophysical implications of our survey, we need to determine the positions in the HR diagram of as many of our targets as possible. Several sources for the basic parameters of our CSPN are available.

In this respect, results of model atmosphere analyses of CSPN are very important. These are available for a large fraction of our targets and are listed in Table 4.4. The effective temperature and surface gravity are direct results from the model atmospheres, while the stellar masses are inferred from placing the stars in an log $T$ – log $g$ diagram and comparing the positions with evolutionary tracks (e.g. Blöcker 1995, Schönberner 1983).

Examining the masses in Table 4.4, they are all larger than the average mass for CSPN and white dwarfs (0.6 $M_{\odot}$) derived from a number of other studies (e. g.

Table 4.3: Further variable CSPN

| Central star (of) | V (mag) | $P$ | Reference for variability |
|---|---|---|---|
| BD+30° 3639 | 9.95 | months? | A98 |
| Hu 2-1 | 13.31 | ? | BC91 |
| IC 3568 | 13.45 | ? | BC91 |
| IC 4997 | 14.4 | days | this work* |
| M 4-18 | 13.96 | days? | H96, this work |
| NGC 40 | 11.58 | ? | BC91 |
| PB 8 | 13.60 | ? | M89 |
| Vy 1-1 | 14.19 | days | this work |

References: A98: Acker et al. 1998; BC91: Bond & Ciardullo 1991; H96: Handler 1996; M89: Méndez 1989
* concerning the variability time scale of days only

Stasińska et al. 1997 and references therein). While this systematic difference may at least partly be due to an observational selection effect (more massive CSPN are more luminous, therefore also apparently brighter, hence better targets for high-resolution spectroscopic studies), it also indicates a systematic error in the surface gravities determined in this way (see also Pottasch 1997). The luminosities of these objects should therefore be treated with caution (but the effective temperatures, which are more important for our work, appear to be reliable).

For the remainder of our objects, we need to invoke other determinations of effective temperature and mass (Table 4.5). Short comments on individual results are therefore in order.

For the effective temperatures, we followed the suggestion of Kaler & Jacoby (1991) to use Stoy temperatures whenever possible, since almost all our PN are of low excitation. We mainly adopted the values of Kaler & Jacoby (1991) and used the results of Preite-Martinez et al. (1989), Malkov (1997) and Kaler (1983) as a supplement. M1-77 has been spectroscopically studied by Sabbadin et al. (1983), who did not find the nebular [O III] 5007 Å emission excited. This allows one to estimate the central star temperature from Kaler & Jacoby's (1991) relation between the [O III] 5007 Å and Stoy temperature to be less than 26 000 K. The temperature of PB 8 has only been determined with the Zanstra method.

Turning to stellar masses, we mainly relied on the work of Stasińska et al. (1997) and Górny et al. (1997), whose results depend little on the underlying assumptions. For a number of other CSPN, we took the distance-independent masses derived by Zhang & Kwok (1993). The mass of M1-77 was calculated from the CSPN luminosity inferred by Sabbadin et al. (1983) by comparing it with the evolutionary

Table 4.4: Basic parameters of CSPN from model atmospheres

| Nebula | Central star | Spectral type | $T_{\rm eff}$ (kK) | log $g$ [cgs] | $M_*$ $M_\odot$ | Reference |
|---|---|---|---|---|---|---|
| He 2-138 | HD 141969 | O(H) | 27 | 2.9 | 0.68 | M92 |
| Hu 2-1 | AG82 330 | Of(H) | 33 | 3.35 | 0.64 | M92 |
| IC 418 | HD 35914 | Of(H) | 36 | 3.45 | 0.67 | M92 |
| IC 2149 | HD 39659 | Of(H) | 42 | 3.6 | 0.74 | H90 |
| IC 3568 | HD 109540 | O3(H) | 50 | 4.05 | 0.66 | M92 |
| IC 4593 | HD 145649 | O5f(H) | 40 | 3.6 | 0.68 | K97 |
| M1-11 | AG82 75 | Be? | 29 | 3.0 | 0.74 | M97 |
| NGC 1535 | HD 26847 | O(H) | 70 | 4.65 | 0.65 | M92 |
| NGC 2392 | HD 59088 | Of(H) | 47 | 3.8 | 0.73 | M92 |
| NGC 6629 | HD 169460 | Of(H) | 47 | 3.9 | 0.67 | M92 |
| NGC 6826 | HD 186924 | O3f(H) | 50 | 4.0 | 0.68 | M92 |
| NGC 6891 | HD 192563 | Of(H) | 50 | 4.0 | 0.68 | M92 |
| NGC 7009 | HD 200516 | O(H) | 82 | 4.9 | 0.66 | M92 |
| Vy 1-1 | AG82 3 | Of(H) | 60 | 4.2 | 0.76 | M97 |

References: M92: Méndez et al. 1992; H90: Herrero et al. 1990; K97: Kudritzki et al. 1997; M97: McCarthy et al. 1997

AG numbers correspond to the CSPN catalogue of Acker et al. (1982)

Spectral types are from Méndez (1991), except for Vy 1-1 (Méndez, private communication) and M1-11 (SIMBAD)

Table 4.5: Basic parameters of CSPN from other sources

| Nebula | Central star | Sp | $T_*$ (kK) | Reference | $M_*$ $M_\odot$ | Reference |
|---|---|---|---|---|---|---|
| Cn 3-1 | AG82 305 | WR-Of | 25 | KJ91 | 0.60 | ZK93 |
| Hb 12 | AG82 452 | [WN7]? | 38 | KJ91 | 0.61 | S97 |
| He 2-131 | HD 138403 | Of(H) | 26 | KJ91 | 0.57 | G97 |
| He 2-438 | BD+30° 3639 | [WC9] | 27 | KJ91 | 0.71 | ZK93 |
| IC 4634 | HD 153655 | cont. | 55 | KJ91 | 0.58 | G97 |
| IC 4997 | HD 193538 | Of-WR | 49 | KJ91 | 0.62 | S97 |
| M1-12 | | – | 29 | PM89 | 0.67 | ZK93 |
| M1-46 | AG82 310 | – | 35 | PM89 | 0.60 | ZK93 |
| M1-55 | | O? | 26 | PM89 | 0.60 | assumed |
| M1-77 | LS III+46 54 | OB? | $< 26$ | S83 | 0.61 | S83 |
| M2-54 | LS III+51 42 | B? | 30 | K83 | 0.56 | S97 |
| M4-18 | AG82 31 | [WC11] | 31 | M97 | 0.57 | M97 |
| NGC 40 | HD 826 | [WC8] | 32 | KJ91 | 0.57 | ZK93 |
| NGC 6543 | HD 164963 | Of-WR(H) | 45 | KJ91 | 0.60 | S97 |
| NGC 6572 | HD 166802 | Of-WR(H) | 60 | KJ91 | 0.61 | S97 |
| PB 8 | AG82 138 | Of-WR(H) | 44 | KJ91 | 0.56 | G97 |

References: KJ91: Kaler & Jacoby 1991; ZK93: Zhang & Kwok 1993; S97: Stasińska et al. 1997; G97: Górny et al. 1997; PM89: Preite-Martinez et al. 1989; S83: Sabbadin et al. 1983; K83: Kaler 1983; M97: Malkov 1997
AG numbers correspond to the CSPN catalogue of Acker et al. (1982)
Spectral types are from Méndez (1991), Acker et al. (1992) and SIMBAD

Table 4.6: CSPN with insufficient information

| Nebula | Central star | Sp | $T_*$ (kK) | Reference | $\frac{M_*}{M_\odot}$ | Reference |
|---|---|---|---|---|---|---|
| Sa 3-151 | | A | – | | – | |
| VV 3-5 | | A | 76 | PM89 | – | |
| WhMe 1 | SS 438 | ?+B9V | 68 | see text | – | |

Reference: PM89: Preite-Martinez et al. (1989)
Spectral types are from Acker et al. (1992)

tracks published by Blöcker (1995). Finally, we simply assumed the mass of M1-55 to be 0.6 $M_\odot$. We note again that it is the stellar temperatures which are most important for our purposes.

For three of the observed objects (Table 4.6), the available data do not allow us to place the central stars in the HR diagram in a meaningful way. For Sa 3-151 and VV 3-5 spectral classifications listed by Acker et al. (1992) could be found. Both indicate that the CSPN may be binaries (also suggested by the Stoy temperature of VV 3-5), but this needs to be confirmed. From the strength of the nebular [OIII] 5007 Å emission lines of VV 3-5 and WhMe 1 central star temperatures of 61 000 and 68 000 K, respectively, can be inferred. A comparison with the CSPN spectral types in Table 4.6 suggests that the stars are binaries (see also Whitelock & Menzies 1986 for WhMe 1). Since all three objects are rather bright, could be (or are) binaries, and especially since VV 3-5 and WhMe 1 are suspected variables from our survey, further observations of the central stars would be interesting. However, these objects will not be discussed further here.

### 4.4.2 Comparison of variable and nonvariable CSPN

At this point we are in the position to place our sample of CSPN in the HR diagram; the result is displayed in Fig. 4.10.

Examining the distribution of stars in Fig. 4.10, several conclusions can be drawn. First, photometric variations only occur in CSPN cooler than ≈ 60 000 K. Actually, the only variable object hotter than 50 000 K is the central star of Vy 1-1, which exhibited however only a mean magnitude shift in one night.

Second, some stars in the temperature range where (most) variables are found (25 000 – 50 000 K) did not exhibit convincing photometric light variations. However, if we recall that there are only two realistic possibilities for the cause of the variability (wind variations or pulsations), it must be said that for such types of object it is quite common that (apparently) constant stars are present among the variables. We also point out that these "constant" objects are generally those which were not too

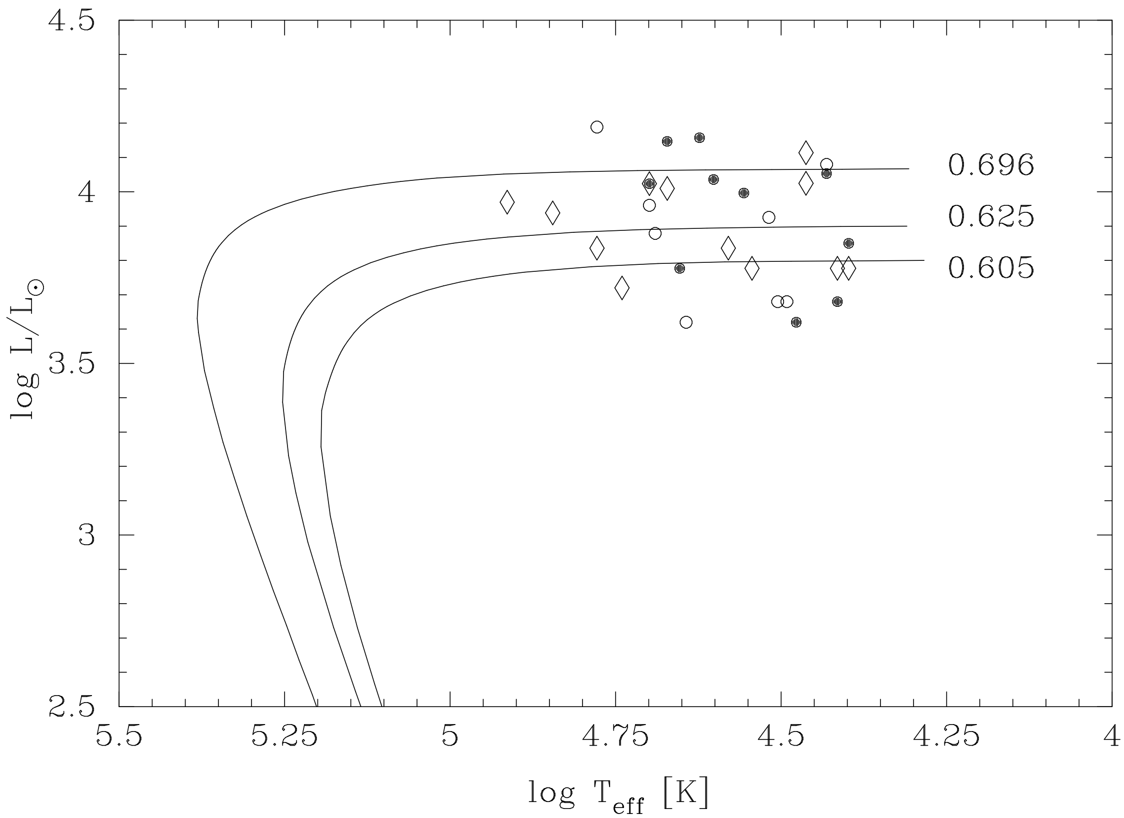


Figure 4.10: Theoretical HR diagram for the CSPN under study. Filled circles: variable objects from Table 4.2, open circles: variable stars from Table 4.3, diamonds: other CSPN photometrically observed. No error bars are given to avoid crowding. Evolutionary tracks for 0.605, 0.625 and 0.696 $M_{\odot}$ hydrogen-burning models (adopted from Blöcker 1995) are however shown for comparison.

extensively observed or are in fact suspected variables. Consequently we cannot give a meaningful ratio of constant to variable stars in this "variability domain" in the HRD. Still, we can safely assert that there are significantly more photometric variables than would be present if these objects were close binaries: in that case we would expect variations in only about 10% of the CSPN (cf. Bond et al. 1992).

Third, the stellar temperature range in which short-term photometric variations have been found is in excellent agreement with that predicted by pulsational model calculations (Gautschy 1993). These suggest that unstable pulsation modes are present for $T_{\rm eff} \leq 55\,000$ K.

Fourth, there seems no dependence of photometric variability on stellar mass, and hence on the proximity of the star to the Eddington limit, although we stress again that the masses and/or luminosities of our targets are likely to be less reliable than the stellar temperatures.

We now turn to wind variability. Here it should be pointed out that most of the studies of CSPN wind variations have been undertaken in the UV, therefore the optical behaviour could be, but is not expected to be, different. Patriarchi & Perinotto (1995, 1997) examined IUE spectra for fourteen CSPN and found variations in the stellar P Cygni profiles for seven objects (NGC 40, NGC 1535, NGC 2392, NGC 6543, NGC 6826, IC 4593 and BD+30° 3639). The central star of NGC 1535 (which we observed in three nights and judged to be constant in light) has an effective temperature of 70 000 K, much hotter than the hot boundary of the photometric instability domain. All the other objects exhibit photometric variations.

Two out of the seven CSPN which did not show wind variations (NGC 246, NGC 6210, NGC 6572, NGC 7009, **IC 418**, **IC 2149**, Lo 8) are clear photometric variables. Four of the stars above are (partly significantly) hotter than 50 000 K. For the remaining object, NGC 6210, we could not obtain useful measurements. Consequently, there seems to be no correlation between wind variability and photometric variations of CSPN.

Taking all the results above into account, the first question asked in the introduction can now be answered: the observed range of effective temperatures of variable CSPN is in better agreement with that expected if pulsations were the cause for the photometric variability compared to the hypothesis that variations in stellar mass loss are responsible.

### 4.4.3 Time scales of the short-term variations

In the following we will compare the feasibility of the wind variation and pulsation hypotheses for all objects in the same way as for the central stars of IC 418 (Chapter 2) and M2-54 (Chapter 3). We calculated the critical (i. e. break-up) rotational periods (Eq. 2.1 and 3.1) as well as the expected radial fundamental pulsation mode period (scaling the results of Gautschy (1993) for his IC 418 model) for all objects in Table 4.2 from the basic parameters in Tables 4.3 and 4.4, respectively.

To make the comparison more meaningful, we also included error estimates of both the observed time scales of variability as well as of the basic parameters of the CSPN. For those objects where results of model atmosphere analysis are available, we adopted the errors given in the corresponding references. For the remaining stars, we (conservatively) assumed the errors to be $\pm$ 15 % in $T_*$ and $\pm$ 0.2 in $\log L_*$. Our results are shown in Fig. 4.11.

The upper panel of this figure convincingly demonstrates that the idea of rotationally induced wind variability is completely inconsistent with the short-term photometric variability of any of our targets. On the average the light variations occur on a time scale of a factor of more than four too fast to be explained with that hypothesis. It should also be pointed out that the minimum rotation period is only a lower limit to the actual value. Therefore the actual disagreement is even larger.

The correlation between the time scales of possible radial fundamental mode pulsation and the observed values is much better (lower panel of Fig 4.11). However, there also is a systematic trend: hotter CSPN appear to vary "too slowly", while cooler CSPN seem to vary "too fast". This may be due to two reasons: first, the stellar temperatures we adopted may be systematically incorrect (mostly within the listed errors!), or the excited pulsation mode changes with temperature.

One can make a speculative, although reasonable, argument in favour of the second idea. Gautschy (1993) did not only find the radial fundamental mode to be unstable in his models; higher radial overtones were excited as well. Interestingly, the higher the overtone was, the lower the high temperature cutoff became. This may suggest that the actually excited pulsations shift to lower radial overtones as the stellar temperature increases. In particular, instability of the first overtone ceases at $T_{\rm eff} \approx 29\,000$ K, exactly in the region where our CSPN stop to vary "too slowly". It can further be speculated that for hotter CSPN the instability shifts to g-modes; this is reasonable since due to the higher gravities of these objects it becomes easier for them to pulsate in g-modes rather than in p-modes. (Gautschy (1993) only computed envelope models, therefore he could only investigate radial modes.) In any case, it is not to be expected that all the objects, if they pulsated, should have the same radial overtone excited: one of the conditions to obtain stable pulsations is that the thermal time scale of the driving region must be similar to the pulsation period. As the CSPN becomes hotter, the driving region (which is the partial ionisation zone of metals, the same for $\beta$ Cephei and slowly pulsating B stars) moves closer to the surface and hence towards shorter thermal time scales, and this general trend is present in our data.

Now we can also answer the second question asked in the introduction: the time scales of the photometric light variations are incompatible with the idea of rotationally induced wind variations. They are in much better agreement with possible pulsations, but this interpretation also has some difficulties.

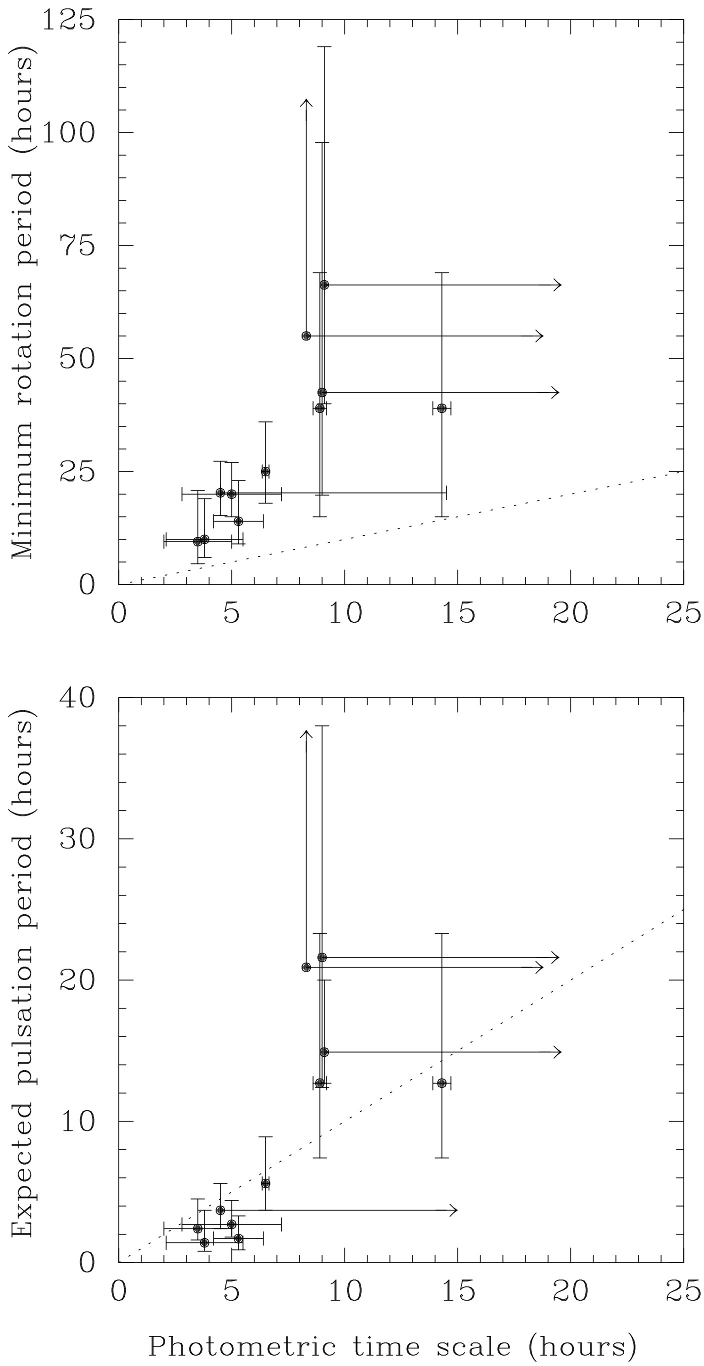


Figure 4.11: Dependence of the minimum rotation period (upper panel) and of the predicted fundamental radial mode pulsation period (lower panel) on the time scales of the photometric variations of central stars of young PN. Both possible variability time scales for M2-54 are used. Error bars are also indicated. In cases where only lower/upper limits to the time scales and physical parameters are available, an arrow is drawn. The dotted line corresponds to 1:1 agreement; note also the different ordinate scales

### 4.4.4 Wind variability vs. pulsation: further arguments

There is one another very interesting finding we did not mention so far (since this was a result not expected at the outset of this work). If one examines the spectral types of the stars where definite short-term light variations have been detected (Table 4.2), one only recovers hydrogen-rich objects. The remaining variable CSPN of Table 4.3 constitute a mixture of hydrogen-rich and hydrogen-poor spectral types.

If the short-term photometric variations were to be caused by wind variability, we would not expect this. Wolf-Rayet central stars have much stronger winds than O-type CSPN. Therefore the ratio of wind luminosity to photospheric luminosity should be significantly larger for WR-CSPN. Hence, wind variability should be much easier to detect photometrically for the latter objects. Since just the opposite is the case, this suggests that the light variability is (mainly) of photospheric origin.

Wind variability with a time scale of hours has however been spectroscopically detected for two WR-CSPN, namely those of NGC 40 (Balick et al. 1996) and BD+30° 3639 (Acker et al. 1997). While we cannot discuss NGC 40 here because of a lack of available photometric data, it is notable that we did not detect short-term photometric variations for BD+30° 3639. However, our observations were of course not taken simultaneously with the spectroscopy. Consequently, we could have just caught the CSPN in a "quiescent" state. The question remains whether CSPN wind fluctuations are able to generate photometric variability or not.

Finally, we would like to comment on the result of Gautschy (1995), who conjectured that violent strange-mode pulsations may trigger enhanced mass loss in WR-CSPN. The pulsation periods of such modes, as calculated by Gautschy, are shorter than the radial fundamental mode period. The absence of convincing short-term light variations of any of the WR-CSPN we observed argues against this scenario. Of course, Gautschy (1995) also pointed out that the pulsation spectrum will be influenced by the stellar wind as it changes the cavity. As it appears, the observational data do not support his idea.

## 4.5 Summary

We undertook a search for photometric light variations among CSPN. We acquired 178 hours of useful measurements of 24 central stars, among which we discovered five new variables (M 1-77, M 2-54, Vy 1-1, M 4-18 and NGC 2392), confirmed the variability of IC 2149 and NGC 6826 claimed in the literature and showed that the known long-term variable CSPN of IC 4997 also changes its brightness on time scales of days. Several objects are suspected to show light variations.

Based on a much larger sample and on more homogenous data of variable central stars of young PN than previously available, we examined possible common characteristics of these objects. Our major results are:

- Two time scales of light variation are present, of the order of several hours and of the order of (at least) several days.
- All variables exhibit the slow modulations, while not all show the faster variations. This suggests that the physical reason for the different behaviour may not be the same.
- The short-term photometric variability is confined to stellar temperatures below about 50 000 K.
- The ratio of variables to constant stars in this temperature region is too large for the variations to be caused by binarity, at least for most of the objects.
- The temperature range in which the photometric variations occur is in better agreement with the idea that the reason for the variability is due to stellar pulsation as opposed to wind variability.
- The time scales of the faster variations are clearly too short to be consistent with the hypothesis of rotationally induced wind variability.
- A pulsational origin explains the observed short-term variations much better than any other idea.
- All CSPN exhibiting short-term photometric variability are hydrogen-rich, suggesting that the variations are of photospheric origin.

In conclusion, each single piece of evidence we collected suggests that pulsations are the most likely cause of the short-term light variations in variable central stars of young Planetary Nebulae. The sum of the arguments puts much more weight on this interpretation. If the photometric variability were due to variations in the stellar wind, the mechanism causing it must be different from that operating in massive O stars.

# Chapter 5

# Conclusions

## 5.1 A summary of summaries

To approach the final conclusions of this work, we begin with a summary of all the findings of the previous three chapters.

The multisite campaign of the central star of IC 418 showed that it varies on two different distinct 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: the star is generally redder when it is brighter. The 6.5-hour light modulations are neither (multi-)periodic, nor are they irregular; this behaviour is present in all the data sets acquired for the star spanning 15 years.

Coming to the physical interpretation of the photometric variations, rotational modulation of surface features can be ruled out for the variability with both the long and the short time scales. Binarity is very unlikely. A pulsational origin of the short-term variations is consistent with the data. Wind variability is also unlikely to cause the faster modulations, but it may be responsible for the long-term variations.

An extensive single-site time-series photometric study of the variable central star of M2-54 showed that its behaviour is strikingly similar to that of the central star of IC 418: slow, apparent nonperiodic, light variations with a time scale of days and short-term variability with a time scale of several hours are present in M2-54. The faster variations are (quasi)periodic with a time scale of either 8.9 or 14.3 hours.

While the long-term variations of M2-54 may be explained by both a spot or a wind-variation hypothesis, the short-term variations are (again) most likely due to stellar pulsation. The similarity between the temporal behaviour of the central stars of IC 418 and M2-54 strongly suggests that the physical reason causing the light variations is the same.

Our survey for photometric light variations among CSPN revealed five new variables and confirmed the (in the literature not well documented) variability of two further objects. Another CSPN proved to be variable on a much shorter time scale than previously known and a number of suspected variables were also noted.

Table 5.1: CSPN defining the new class of variable star

| Central star of | Spectral type | V (mag) | $P$ (hrs) | $T_*$ (kK) |
|---|---|---|---|---|
| He 2-131 | Of(H) | 11.01 | $> 9$ | 26 |
| He 2-138 | O(H) | 10.90 | $> 9$ | 27 |
| IC 418 | Of(H) | 9.93 | $6.5 \pm 0.15$ | 36 |
| IC 2149 | Of(H) | 11.59 | $5.0 \pm 2.2$ | 42 |
| IC 4593 | O5f(H) | 11.20 | $> 4.5$ | 40 |
| M1-77 | OB? | 12.12 | $> 8$ | $< 26$ |
| M2-54 | B? | 12.08 | 8.9 or 14.3 | 30 |
| NGC 2392 | Of(H) | 10.53 | $5.3 \pm 1.1$ | 47 |
| NGC 6543 | Of-WR(H) | 11.14 | $3.5 \pm 1.5$ | 45 |
| NGC 6826 | O3f(H) | 10.41 | $3.8 \pm 1.7$ | 50 |

Among the variables discovered by us and the well investigated cases from the literature, again two time scales of light variation are present, of the order of several hours and of the order of several days. Only some variables show the faster modulations. The latter stars all have temperatures below about 50 000 K; in this temperature range photometric variability is quite common (arguing against a binary hypothesis). All these stars are hydrogen-rich, suggesting that the light variations are of photospheric origin. The temperature range in which the short-term photometric variations occur is in better agreement with a stellar pulsation hypothesis as opposed to wind variability and the time scales of the faster variations are clearly too short to be caused by rotationally induced wind variability. As a result, pulsations explain the observed short-term variations much better than any other idea. Were the photometric variability due to wind fluctuations, the mechanism causing it must be different from that operating in massive O stars.

Considering all the findings above, it becomes clear that the variable central stars of young Planetary Nebulae exhibiting short-term photometric variations are remarkably similar. This can only lead to one conclusion: they represent

## 5.2 A new class of variable star

To be conservative, we only admit a minimum number of objects for the definition of the class. We intentionally do not define any other criterion for the membership to the class except that photometric or radial velocity variations with time scales of several hours and shorter must be present. The defining CSPN are listed in Table 5.1, which is a conglomerate of Tables 4.2, 4.4 and 4.5; references can be found there.

The three most important common characteristics of these objects (other similarities are just trivial consequences of the points below) are:

- They exhibit roughly sinusoidal (semi)regular photometric and/or radial velocity variations with time scales of several hours.
- They have effective temperatures less than 50 000 K.
- They have hydrogen-rich spectra.

We recall that the most likely cause for the variability is stellar pulsation, but further proof for this idea is necessary.

## 5.3 Criticism and outlook

The main weakness of this work is definitely that our results are based on photometry only. (Simultaneous) spectroscopic observations would be required to check our conclusions. In fact, we conducted a multisite spectroscopic campaign on the central star of IC 418 in November 1994, but because of bad weather and because of the poor signal-to-noise of most spectra (Méndez, private communication) this project failed.

Another reason for concern is the small number of the objects available to define this new class of variable star, in particular the apparent exclusion of hydrogen-deficient CSPN. The latter stars are not as abundant as their hydrogen-rich counterparts, and our observations of them are not as numerous. Consequently, we may have just missed hydrogen-deficient CSPN which are short-term photometric variables.

One of the major motivations of this work was to find objects suitable for measurements of evolutionary period changes to trace CSPN evolution in the HR diagram. Since the photometric variations on time scales of hours proved not to be strictly periodic, this would still be possible, but an enormous amount of data is required to avoid running into artifacts. It is far from clear whether such an undertaking would be worth the effort.

Further useful observational work (besides simultaneous spectroscopic and photometric measurements) would consist of more detailed studies of the temporal behaviour of a number of central stars with well-known temperatures and luminosities. Multisite observing campaigns (which do not require more than two or three sites well separated in longitude) during a time span of several weeks need to be undertaken.

There are still possibilites to increase the sample of variable objects. Almost the whole Southern Hemisphere is still available for survey work, and a number of Northern objects not well observed or suspected of variability by us need to be examined as well. Particular emphasis should be given to hydrogen-deficient CSPN.

On the theoretical side, pulsational stability analyses, similar to that of Gautschy (1993) are required for a set of models of different mass and chemical composition; a more detailed mapping of the instability region is highly desirable. It would be very interesting to see whether the periods most likely to be excited in the models are comparable with the period-temperature relation of the real stars. However, this would require full CSPN models for hotter temperatures because of the conjectured presence of g-modes in these stars. The pulsational characteristics of such models may however be very sensitive to the assumed prior evolution.

# Chapter 6

# A Former Central Star of a Planetary Nebula: HS 2324+3944

## One step further towards white dwarfs

In the former chapters we elaborated on a class of variable star, for which pulsations have been theoretically predicted, are the most likely interpretation for the variations, and yet cannot unambiguously be proven to be present.

Just one step further in the context of stellar evolution we find a class of famous pulsating variables: the GW Vir stars (see Sect. 1.3.1 and 6.1.1). The driving mechanism of these variables was originally presumed to be very sensitive to the chemical composition of the objects. In particular, hydrogen-rich stars in the corresponding temperature region (which are direct successors of the objects studied in Chapters 2 – 5) should not pulsate.

In the course of obtaining the measurements presented in Chapter 4, we also observed one of these objects. As it turned out, that star was variable, and as it is shown below, this is due to pulsations.

## 6.1 Complex light variations of HS 2324+3944

### Abstract

We present 17.36 hours of new time-series photometric observations of the variable "hybrid" PG 1159 star HS 2324+3944. These data allow us to demonstrate the presence of four frequencies in the light variations with evidence for more. The dominating time scale of the variability (around 35 minutes) is much longer than that of GW Vir pulsators.

Binarity is not likely to cause the object's light variations. A pulsational origin of the variability seems more attractive. Recent theoretical investigations suggest

that pre-white dwarf pulsations can be excited despite the presence of hydrogen in the model's driving region.

### 6.1.1 Introduction

HS 2324+3944 is one of only four "hybrid" PG 1159 stars. The latter objects are a subgroup of DO white dwarfs, whose spectra are dominated by He II, C IV and O VI (Sion et al. 1985). On the other hand, the spectra of "hybrids" show an He II/C IV absorption trough similar to the "classical" PG 1159 stars, but also strong Balmer lines (Napiwotzki & Schönberner 1991).

About 30% of the PG 1159 stars are multiperiodic nonradial g-mode pulsators (the GW Vir stars). Driving of these pulsations is believed to be caused by the $\kappa$-$\gamma$-mechanism in the region of partial ionisation of carbon and oxygen (Starrfield et al. 1985).

Analyzing two weeks of almost continuous data gathered with the Whole Earth Telescope network, Winget et al. (1991) identified more than 100 pulsation modes in PG 1159-035. This allowed an unprecedented investigation of the object's inner structure by means of precision asteroseismology. Similar analyses of other GW Vir stars have been performed in the recent years (e. g. Kawaler et al. 1995).

However, according to model calculations, the efficiency of this $\kappa$-$\gamma$-mechanism seems to be very sensitive to the chemical composition in the driving region, which is located very close to the stellar surface. In particular, the presence of hydrogen in the driving zone is believed to inhibit pulsations (Stanghellini et al. 1991). Regrettably, asteroseismological investigations were not helpful in constraining the structure of the driving regions, since the eigenfunctions of the observed modes have little weight in these parts of the models.

The spectral analysis by Dreizler et al. (1996) places HS 2324+3944 in the GW Vir instability strip. However, their analysis shows the presence of hydrogen as well. Dreizler et al. suggested that HS 2324+3944 should be observed photometrically to look for pulsational variability. This, they suggested, would provide a test for Stanghellini et al.'s (1991) models which predict no pulsations when the partial ionization zone is contaminated by hydrogen.

Silvotti (1995, 1996) obtained two nights of time-series photometric data of HS 2324+3944. He discovered the star to be variable with a period of about 35 minutes and suggested this is due to high-order g-mode pulsations. However, such a period is a factor of 3–4 larger than the periods of GW Vir pulsators.

There is a second possibility to explain the light variations of HS 2324+3944: binarity. The AM CVn stars (see Provencal (1994) and Warner (1995) for detailed discussions) are helium-transferring double-degenerate binaries with orbital periods of the same order as the time scale of the variations of HS 2324+3944 reported by Silvotti (1995, 1996). Hence, it should not be ruled out without further scrutiny that HS 2324+3944 be a related object, although spectroscopic observations (Dreizler et

Table 6.1: Journal of the observations

| Telescope | Observer(s) | Detector | Date (UT) | Start (UT) | Length (hrs) |
|---|---|---|---|---|---|
| McD 2.1 m | GH | PMT | 13 Dec 95 | 2:18:28 | 1.90 |
| McD 2.1 m | GH | PMT | 15 Dec 95 | 1:11:44 | 2.71 |
| McD 0.9 m | GH, AK, MHM | CCD | 16 Dec 95 | 2:29:02 | 3.60 |
| McD 0.9 m | GH, AK, MHM | CCD | 17 Dec 95 | 2:38:05 | 3.05 |
| McD 0.9 m | GH | CCD | 20 Dec 95 | 1:05:06 | 1.08 |
| McD 0.9 m | GH | CCD | 21 Dec 95 | 3:13:18 | 0.50 |
| McD 0.9 m | GH | PMT | 27 Dec 95 | 1:22:54 | 1.64 |
| McD 0.9 m | GH | PMT | 28 Dec 95 | 1:24:33 | 2.88 |
| | | | | Total | 17.36 |

Observers: GH = G. Handler, AK = A. Kanaan, MHM = M. H. Montgomery

al. 1996) did not show evidence of mass transfer.

Earlier observations of ours (of a quality too low to publish) confirmed the unusual variability. Therefore, and because Silvotti's data set was too small to determine whether the variations are multiperiodic or not, we carried out a more extensive photometric study of HS 2324+3944.

### 6.1.2 Data acquisition and reduction

In December 1995, we acquired eight time-series photometric runs of HS 2324+3944 during a time span of 15 days. Three different telescope/instrument combinations at McDonald Observatory were used: the 2.1 m telescope with a two-channel photoelectric photometer (no filter), the 0.9 m telescope with a CCD (B filter) and the 0.9 m telescope with the two-channel photometer (no filter). This choice of the filters ensures measurements at approximately the same effective wavelength for both the photoelectric and CCD data. An observing log is given in Table 6.1.

#### CCD observations

For our CCD observations we used a Tektronics $2048 \times 2048$ CCD with 27$\mu$m pixels binned $2 \times 2$. The full width at half maximum through most of the measurements was about $3\farcs0$. Each observation consisted of a 60 second exposure; we attempted to observe as many comparison stars on the same frame together with HS 2324+3944. By reading out only part of the chip we decreased the readout time as far as possible. In this way, we acquired one observation each 70 seconds.

The frames were corrected for bias and flat field effects using the standard IRAF procedures. Photometric reductions were then accomplished using the IRAF AP-

PHOT task. We extracted the magnitudes of HS 2324+3944 plus 7 or 8 comparison stars and selected the aperture size giving the lowest scatter for the comparison star data. We double-checked the constancy of the comparison stars by calculating amplitude spectra of their magnitudes relative to the brightest comparison star and relative to the mean of all comparison stars. No evidence for variability of any of these objects was found within the 4 nights of CCD observation. 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 from the measurements of HS 2324+3944 on a point-by-point basis and a correction for differential extinction was applied (since HS 2324+3944 is much blueer than its comparison stars). Finally, all the times of measurement were converted into Heliocentric Julian Date (HJD) and the data were subjected to further analysis.

We also note that the nightly mean magnitudes of HS 2324+3944 relative to the comparison stars did not change during the observations.

#### Photoelectric observations

Since the variability of the target object occurs on time scales at which slow variations in sky transparency can occur, we checked the quality of the nights by means of the Channel 2 comparison star. The latter was assumed to be photometrically constant, since it was also one of the comparison stars used during the CCD measurements and not found to be variable in these data. Since we had only two channels available and could thus not check the stability of the sky background, we chose a Channel 2 star with star/sky count ratio similar to that of the variable. In this way, we could roughly test for possible sky background variations (and did not find any during our measurements).

We started the reductions with discarding bad data. Consequently, we performed sky subtraction by a piecewise linear or spline fit to our sky measurements (which were obtained by interrupting the target light curves each 20 – 30 minutes). Then we corrected the data for extinction. The mean magnitude of each run was set to zero. If some systematic trends in the data not attributable to intrinsic variatons of HS 2324+3944 remained, we removed them by fitting a straight line to the data. Finally, we summed the photoelectric measurements in 70-second bins to give them equal weight to the CCD data, and we calculated the HJD of each observation. Figure 6.1 shows our reduced light curves together with a four-frequency fit to be derived in Sect. 6.1.3, where we will further comment on this plot.

### 6.1.3 Frequency analysis

Our final time series was analysed with a period-finding package (Breger 1990), using single-frequency Fourier and multiple least-squares sine wave fitting methods.

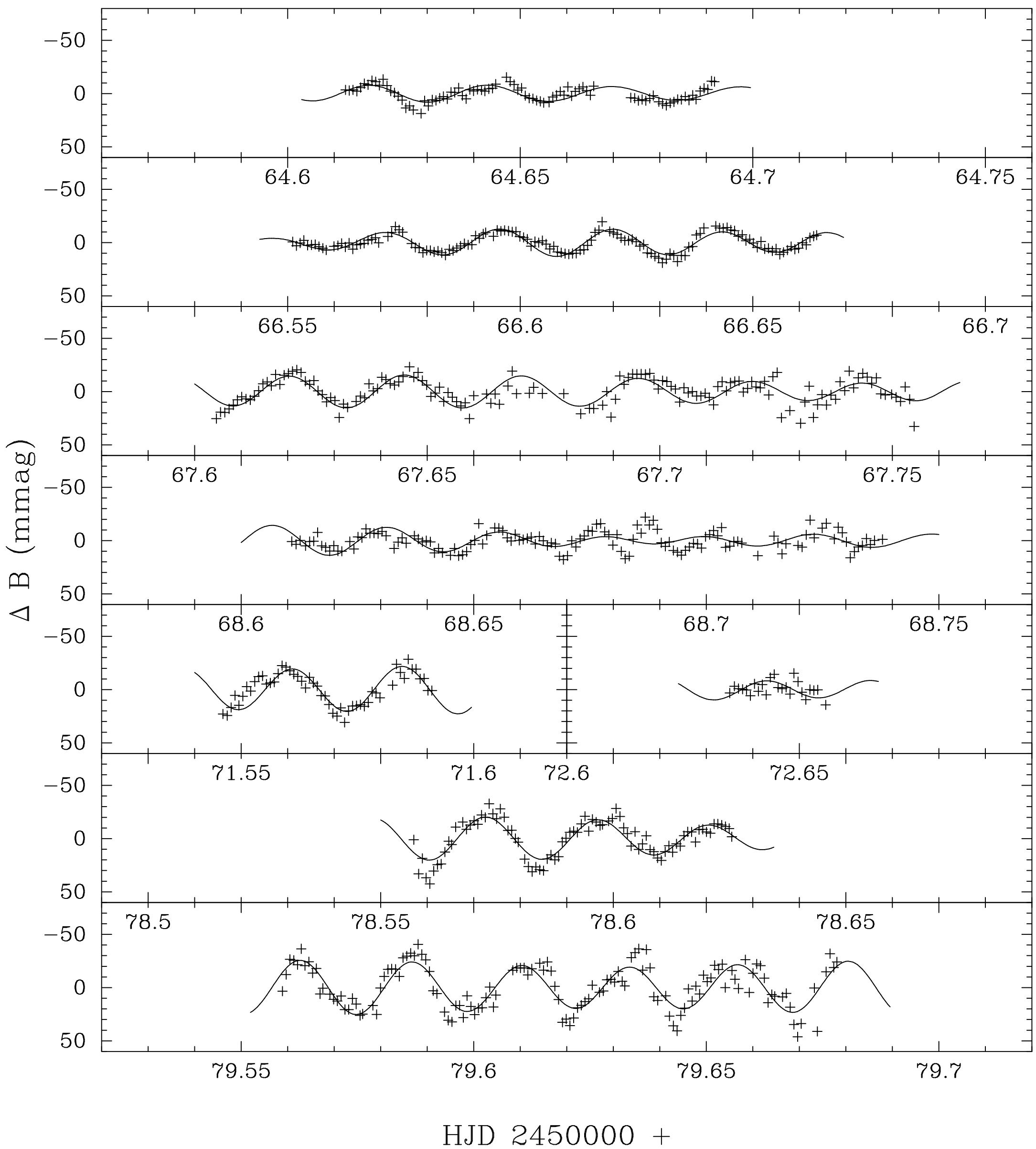


Figure 6.1: B-light curves and the corresponding 4-frequency fit (derived in Sect. 6.1.3) for our data of HS 2324+3944

These programs allow us to search for promising peaks and prewhiten the data by calculating simultaneous n-frequency fits[1].

In this way three frequencies can easily be revealed in the light variations of the program star (Fig. 6.2). As can be seen in the third lowest panel of Fig. 6.2, there may still be more periodicities hidden in the data. However, special care must be taken when trying to identify them. Therefore, we estimated a detection threshold for intrinsic variations by analysing high-speed photometric observations of constant stars, reduced and sampled in the same way as our data of HS 2324+3944. The nightly scatter was scaled to the same level as the residuals between the program star's light curve and our fit. Using this method we concluded that we may detect signals with an amplitude of about 3 mmag at frequencies around 200 $\mu$Hz, and 2.5 mmag signals around 1000 $\mu$Hz. We note that in the presence of strong aliasing like in our data the adoption of signal-to-noise criteria or false alarm tests is less safe.

The next promising frequency to consider is near 408.8 $\mu$Hz. Its amplitude is almost 4 mmag, and by dividing our data in different subsets (e.g. using the three different telescope/detector combinations), we found out that this signal has constant amplitude and phase throughout the whole data set. On the other hand, adopting the daily alias of this frequency (which is stable throughout the data set as well) at 420.4 $\mu$Hz for a four-frequency fit, the residual scatter of the light curve is only 0.03% larger. Hence, we cannot decide which of the two peaks is real, and we must consider both as a possible solution.

Including this fourth frequency in our fit and removing the improved fit from our data, a further signal at 368.6 $\mu$Hz (or 379.3 $\mu$Hz, when the 420.4 $\mu$Hz frequency is assumed) becomes conspicuous (second lowest panel of Fig. 6.2). This signal is present in the whole data set with constant amplitude and phase as well, but its low amplitude of about 2.5 mmag prevents us from suggesting it is intrinsic to the star.

There is further power between 750 and 950 $\mu$Hz (lowest panel of Fig. 6.2), which exceeds our detection threshold as estimated above. However, when testing these variations for amplitude and phase stability, they are very prominent in only a few of the nights (mostly December 17 and 27, see below for more). Moreover, the dominating peaks in this frequency region do not correspond to linear combinations or harmonics of the already detected frequencies (Fig. 6.3). Hence we cannot reliably include them in our frequency solution and we are left with four secure frequencies in the light curves of HS 2324+3944. These are summarized in Table 6.2. The errors in frequencies, amplitudes and phases as listed in Table 6.2 are formal errors determined following Kovacs (1981) and should be taken only as estimates.

Of course, due to the aliasing present and despite our great care, the frequency

[1] During our prewhitening process we do not necessarily choose the highest peak in our successive power spectra as the next frequency to be included in our solution. Because of the aliasing present we rather select the frequency combination yielding the lowest residuals between the observed light curves and the calculated fit. We consider this approach to be more reliable.

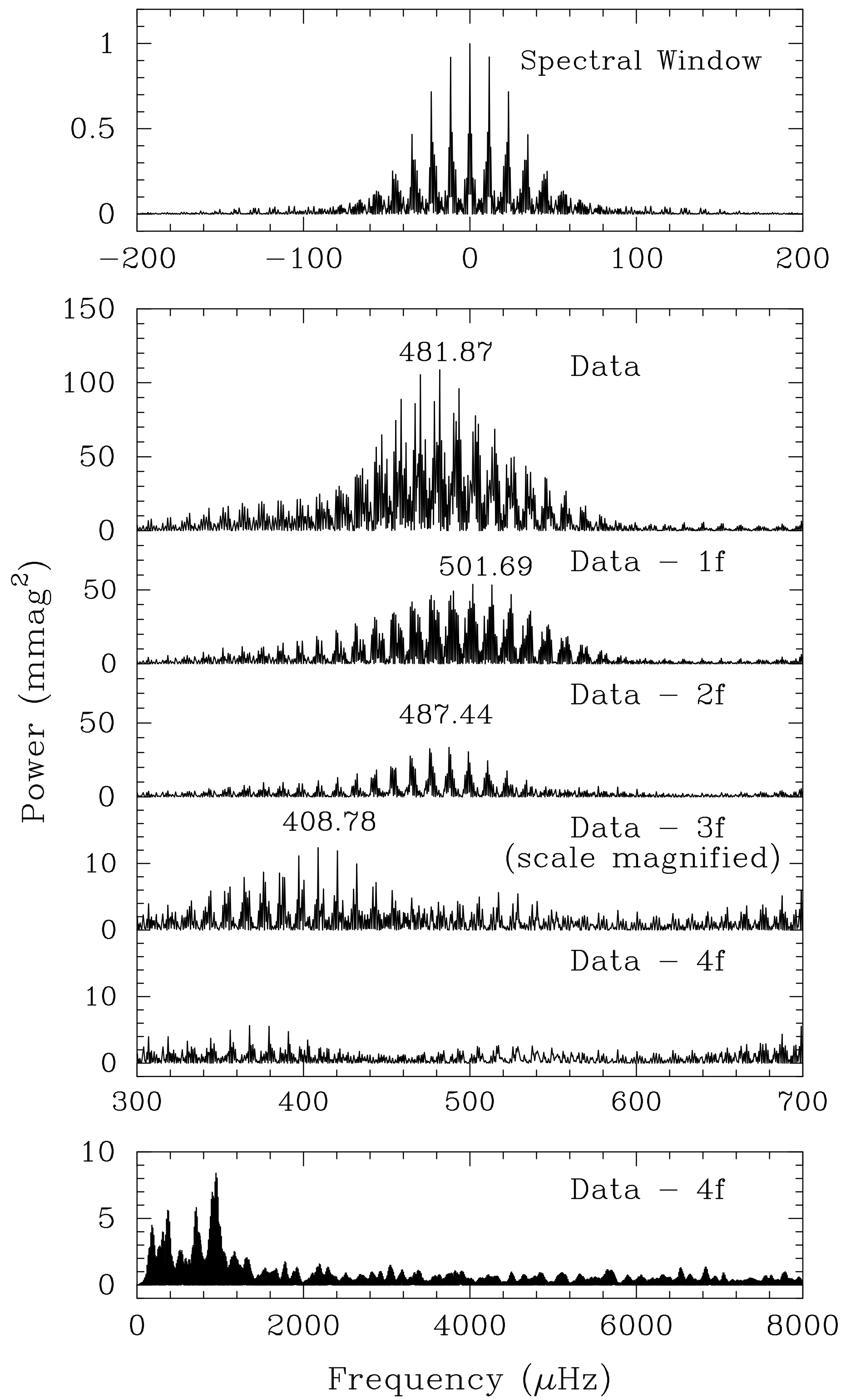


Figure 6.2: Power spectra of HS 2324+3944. Four frequencies are detected in the star's light variations

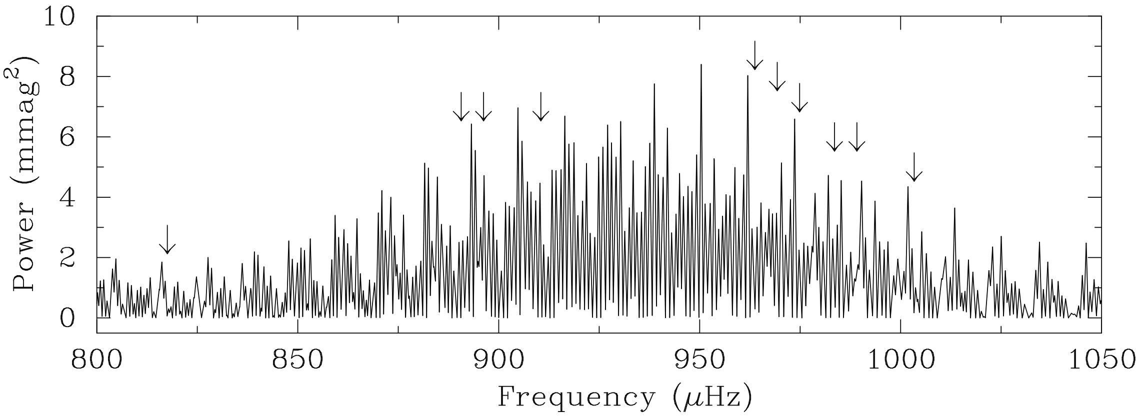


Figure 6.3: Power spectra of HS 2324+3944 in the range where linear combinations or harmonics of the four detected frequencies may be present. The ten possible combinations are indicated with arrows. No agreements with the dominating peaks are visible.

Table 6.2: The 4-parameter fit calculated for our light curves of HS 2324+3944

| | Frequency ($\mu$Hz) | Amplitude (mmag) | Epoch (HJD 2450000 +) |
|---|---|---|---|
| $f_1$ | 481.87 ± 0.01 | 11.6 ± 0.5 | 64.5726 ± 0.0002 |
| $f_2$ | 501.69 ± 0.02 | 6.8 ± 0.5 | 64.5911 ± 0.0003 |
| $f_3$ | 487.44 ± 0.03 | 6.9 ± 0.5 | 64.5822 ± 0.0004 |
| $f_4$ | 408.78 ± 0.04 | 3.8 ± 0.5 | 64.5855 ± 0.0008 |
| ($f_{4a}$) | (420.41 ± 0.04) | (3.8 ± 0.5) | (64.5873 ± 0.0008) |

values are not definite. They may differ from the values in Table 6.2 by their daily aliases. It may be suspected that $f_2$ and $f_4$ ($f_{4a}$, respectively) are aliases of each other. However, when calculating residual power spectra of our light curves after removing the variations due to $f_1$ and $f_3$, both $f_2$ and $f_4$ ($f_{4a}$) are present, and no alias of either of these frequencies can account for the presence of both maxima in our power spectra.

Our synthetic light curves calculated with the parameters in Table 6.2 fit the light curves well, except the second half of the run obtained on HJD 2450068. It seems that in this night the variability of the star suddenly switched to a faster time scale. We do not think that this is a sign of inaccurate measurements, since our comparison star data for that night did not show any suspicious behavior. It rather seems likely that further presently undetected frequencies are active in HS 2324+3944.

On the other hand, we are unable to fit these variations when including some promising frequencies near 900 $\mu$Hz. We are careful to note that the excess power

near 900 $\mu$Hz is present (but it is less strong) when we exclude the Dec 17 run from the analysis; hence it cannot originate from this night only. Its cause remains unexplained.

Since we used three different telescope/detector combinations during our observations, it is interesting to compare the accuracy of these measurements. We find that the photoelectric observations with the 2.1 m telescope show a residual scatter between light curve and fit of less than 5 mmag per 70-second integration, while the 0.9 m CCD measurements are accurate to about 8 mmag per integration and the 0.9 m photoelectric observations have an rms error of about 10 mmag. This may suggest that CCD observations are to be preferred for a star of a magnitude and time scale of light variation similar to HS 2324+3944 ($V = 14.8$). We note, however, that the 0.9 m photoelectric data had a large contribution of moonlight, and thus their quality suffered from this influence.

### 6.1.4 Discussion

Our analysis shows that HS 2324+3944 is very likely a multiperiodic variable. In principle, this can be explained by both a pulsation and a binary hypothesis. Before we start discussing these two possibilities, let us note that Ciardullo & Bond (1996) - during their survey for variability among O VI central stars of Planetary Nebulae - observed the three other "hybrid" PG 1159 stars and reported suspected variations of two of those objects (A 43 and NGC 7094) with periods near 40 minutes and 2 hours, respectively. For the fourth, much fainter "hybrid" (Sh 2-68), their data was not conclusive.

Considering a binary hypothesis, it has to be pointed out that AM CVn stars may show complicated power spectra. These usually contain two independent frequencies (believed to be the orbital frequency and the rotational period of the accretor), which are different by only a few percent. Furthermore, linear combinations and harmonics of these frequencies may be present, as well as sidebands to the fundamental and harmonic periods (the frequency difference of these sidebands to the central frequency is believed to be the inverse precession period of the necessarily elliptical accretion disc). Comparing these features to our frequency solution, it is easy to see that the three close frequencies near 500 $\mu$Hz we found in our data of HS 2324+3944 can be explained by such a binary hypothesis. However, the presence of the fourth frequency near 410 $\mu$Hz does not fit into this scheme and argues against a binary origin of all the different periodicities.

Moreover, there is no spectroscopic correspondence between AM CVn stars and "hybrid" PG 1159-type stars. AM CVn stars have no hydrogen in their spectra; those of HS 2324+3944 show no evidence for mass transfer.

Consequently, the explanation of the variability of HS 2324+3944 in terms of high-order g-mode pulsations becomes attractive. The (nearly) sinusoidal light curves, the photometric amplitudes of the variations and the multiperiodicity point

towards the excitation of pulsations.

Another interesting speculation can be made on the possible presence of two "magic numbers" in our frequencies. Firstly, the pulsating PG 1159 central star of NGC 1501 (Bond et al. 1996) shows frequency ratios very close to $\sqrt{3}/2$. These are interpreted in terms of trapped modes (see the paper cited above for more information). Interestingly, the ratio of our frequency $f_{4a}$ to $f_2$ is within 1% of $\sqrt{3}/2$ as well as the ratio of the suspected signal at 368.6 $\mu$Hz and $f_{4a}$. Secondly, mean period spacings of 20–23 seconds (used to determine the masses) are present in the $\ell = 1$ modes of several GW Vir pulsators. The period difference of the two closest frequencies we determined for HS 2324+3944 is 23.7 seconds.

As mentioned in the Introduction, the efficiency of the driving mechanism for GW Vir pulsators has originally been found to be very sensitive to the chemical composition of the driving region of the models used. However, recent theoretical investigations provided several clues to resolve this difficulty:

In their detailed investigation of pulsation driving in GW Vir models, Bradley & Dziembowski (1996) could only duplicate the observed frequency range with oxygen-rich compositions in the driving region. Furthermore, the surface abundances of some pulsating and nonpulsating PG 1159 stars are so identical, that they are sometimes called "spectroscopic twins". Consequently, Bradley & Dziembowski (1996) suggested that no GW Vir star has a driving region with photospheric abundances. This can of course also be taken as a reason why a "hybrid" PG 1159 star may pulsate.

The periods we found for HS 2324+3944 are between 1990 and 2450 seconds. Bradley & Dziembowski (1996) could only match the maximum unstable periods for the hotter GW Vir stars (e.g. about 1000 seconds for PG 1159-035 itself[2]) by using models with a combination of oxygen-rich driving regions and artificially increased radii. This implies that Bradley & Dziembowski models used to fit the periods of HS 2324+3944 would require even larger radii.

Saio (1996) presented model calculations for pulsations of hydrogen-deficient stars by using new OPAL opacities. These models suggested that the sensitivity of the driving mechanism to the chemical composition in the driving region of pre-white dwarfs is not as strong as previously assumed.

Gautschy (1997) computed envelope models for GW Vir stars and HS 2324+3944. His results disagreed with those of Bradley & Dziembowski (1996). Gautschy's instability domains matched the observed frequency distributions of GW Vir stars well, except for the short period modes. He did not need to postulate chemical compositions in the driving region differing from the photospheric compositions and he did not require artificially increased radii for a good match to the observed frequency ranges.

Another result of Gautschy's (1997) explorations is that the existence of hydro-

[2]This may be an observational long-period cutoff because of the observing and analysis techniques used by Winget et al. (1991).

gen in the driving zone does not necessarily influence the pulsational instability of HS 2324-like envelope models. He obtained unstable modes even with a hydrogen admixture of 20% in mass and he suggested that the differences between his results and those of Bradley & Dziembowski (1996) may simply be a consequence of differences in the numerical treatment of the nonadiabatic oscillations.

Anyway, theoretical approaches to possible pulsations of HS 2324+3944 still need refinement. A larger observational database to improve our knowledge of the variability of "hybrid" PG 1159 stars is also required. To this end, a multisite campaign of HS 2324+3944 was planned for 1997.

## 6.2 Multisite photometry of HS 2324+3944

### Summary

We review past efforts to unravel the nature of the light variations of the "hybrid" PG 1159 star HS 2324+3944 and we present preliminary results of a recent multisite campaign devoted to this interesting object. From the on-line frequency analysis of our measurements we can safely conclude that this star is a multimode pulsating variable. Some suggestions for further investigations are given.

### 6.2.1 The Past

HS 2324+3944 has been spectroscopically classified as a low gravity (log $g$=6.2) peculiar (H-rich) PG 1159 star by Dreizler et al. (1996). It is therefore a post-AGB star at the hot end of the white dwarf cooling sequence, and one of only four known "hybrid" PG 1159 stars.

About 30% of the PG 1159 stars are multiperiodic nonradial g-mode pulsators (the GW Vir stars). Driving of these pulsations is believed to be caused by the $\kappa$-$\gamma$-mechanism in the region of partial ionisation of carbon and oxygen (Starrfield et al. 1985). According to model calculations, the efficiency of the above $\kappa$-$\gamma$-mechanism seems to be very sensitive to the chemical composition in the driving region, which is located very close to the stellar surface. In particular, the presence of hydrogen in the driving zone was believed to inhibit pulsations (Stanghellini et al. 1991).

The spectroscopic analysis by Dreizler et al. (1996) places HS 2324+3944 in the GW Vir instability strip. To test Stanghellini et al.'s (1991) results, Silvotti (1996) obtained two nights of time-series photometric data of HS 2324+3944. He discovered the star to be variable with a period of about 35 minutes and suggested this is due to high-order g-mode pulsations. The time scale of these light variations is a factor of 3–4 larger than the typical periods of GW Vir pulsators.

Handler et al. (1997, Sect. 6.1) acquired 8 nights of time-series photometric observations of HS 2324+3944 and detected the presence of 4 independent frequencies in the object's light variations with good evidence for more. They gave arguments

that the variability of HS 2324+3944 is not likely to be caused by binarity: there is no spectroscopic correspondence between AM CVn stars and "hybrid" PG 1159-type stars and all obtained light curves were (nearly) sinusoidal. Moreover, the photometric amplitudes of the variations and the distribution of the detected frequencies point towards the excitation of pulsations.

Handler & Silvotti (1997) re-analysed all previous time-series photometry of HS 2324+3944 and found no common frequency solution for the complete data set. This suggests that the light variations are quite complicated.

Switching back to theory, the efficiency of the driving mechanism for GW Vir pulsators has, as mentioned above, originally been found to be very sensitive to the chemical composition of the driving region of the models used (for a detailed discussion see Dreizler 1997).

Gautschy (1997) computed envelope models for HS 2324+3944. He showed that the existence of hydrogen in the driving zone does not necessarily influence the pulsational instability of HS 2324-like models. He obtained unstable modes even with a hydrogen admixture of 20% in mass.

However, models with a more sophisticated evolutionary history (e.g. by Bradley & Dziembowski 1996) would require an oxygen-enriched driving region and artificially increased radii to match the observed frequency range of GW Vir pulsators: otherwise the unstable periods would be much shorter than the observed ones. The long periods of HS 2324+3944 are therefore even more challenging.

### 6.2.2 The Present

To solve the mystery of the variability of HS 2324+3944, we undertook a photometric multisite campaign from August 25 – September 8, 1997. A total of about 150 hours of measurement were acquired at the Beijing, Loiano, Calar Alto and McDonald observatories and are summarized in Table 6. 3. We performed on-line reductions and analyses of the data and we report preliminary results below. A portion of the acquired light curves during the central part of the campaign, when all four observatories were on line, is shown in Fig. 6.4.

We performed a preliminary frequency analysis of the data and show the obtained power spectra in Fig. 6.5. From Fig. 6.5 it is obvious that the light variations of HS 2324+3944 are quite complicated. Frequency analysis suggests the presence of at least 10 frequencies concentrated between 370 – 395 and 450 – 500 $\mu$Hz, respectively. There is further power between 920 – 970 $\mu$Hz, which could be due to harmonics and linear combination frequencies of the lower frequency variations.

However, we found evidence that the power spectrum is not completely resolved yet: several peaks with double maxima or deformations are present. The peaks near 950 $\mu$Hz show such features as well, and we cannot find many agreements between frequency combinations of the low-frequency variations and the higher frequency peaks.

Table 6.3: Journal of the observations

| Telescope | Detector | Observer | Date (UT) | Time (UT) | Run Length (hours) |
|---|---|---|---|---|---|
| McDonald 2.1 m | PMT | GH | 26 Aug 1997 | 07:31:20 | 3.55 |
| McDonald 2.1 m | PMT | GH | 27 Aug 1997 | 04:45:00 | 6.33 |
| Loiano 1.5 m | PMT | RS | 27 Aug 1997 | 20:19:16 | 3.54 |
| McDonald 2.1 m | PMT | GH | 28 Aug 1997 | 03:16:00 | 7.66 |
| McDonald 2.1 m | PMT | GH | 29 Aug 1997 | 03:10:30 | 7.59 |
| Loiano 1.5 m | PMT | RS | 29 Aug 1997 | 23:32:57 | 1.00 |
| Loiano 1.5 m | PMT | RS | 30 Aug 1997 | 21:57:57 | 4.84 |
| McDonald 0.9 m | PMT | GH | 31 Aug 1997 | 03:49:30 | 0.58 |
| Loiano 1.5 m | PMT | RS | 31 Aug 1997 | 22:01:01 | 5.00 |
| Beijing 0.85 m | PMT | JX | 01 Sep 1997 | 16:17:20 | 1.03 |
| Calar Alto 2.2 m | CCD | SD | 01 Sep 1997 | 19:58:51 | 8.98 |
| Loiano 1.5 m | PMT | RS | 01 Sep 1997 | 21:30:01 | 5.49 |
| Beijing 0.85 m | PMT | JX | 02 Sep 1997 | 11:59:40 | 8.39 |
| Loiano 1.5 m | PMT | RS | 02 Sep 1997 | 20:05:19 | 4.29 |
| Calar Alto 2.2 m | CCD | SD | 02 Sep 1997 | 22:16:23 | 6.20 |
| McDonald 0.9 m | PMT | GH | 03 Sep 1997 | 02:39:40 | 8.73 |
| Beijing 0.85 m | PMT | JX | 03 Sep 1997 | 12:04:20 | 8.27 |
| Calar Alto 2.2 m | CCD | SD | 03 Sep 1997 | 20:30:41 | 8.29 |
| Beijing 0.85 m | PMT | JX | 04 Sep 1997 | 16:03:30 | 4.10 |
| Loiano 1.5 m | PMT | RS | 04 Sep 1997 | 19:23:35 | 5.77 |
| Calar Alto 2.2 m | CCD | SD | 04 Sep 1997 | 19:32:06 | 9.28 |
| McDonald 0.9 m | PMT | GH | 05 Sep 1997 | 05:31:30 | 1.76 |
| Calar Alto 2.2 m | CCD | SD | 05 Sep 1997 | 19:32:18 | 8.82 |
| McDonald 0.9 m | PMT | GH | 06 Sep 1997 | 02:39:10 | 8.77 |
| McDonald 0.9 m | PMT | GH | 07 Sep 1997 | 06:05:00 | 5.38 |
| McDonald 0.9 m | PMT | GH | 08 Sep 1997 | 02:25:40 | 9.10 |

Observers: GH: G. Handler; RS: R. Silvotti; JX: Jiang Xiao-jun; SD: S. Dreizler

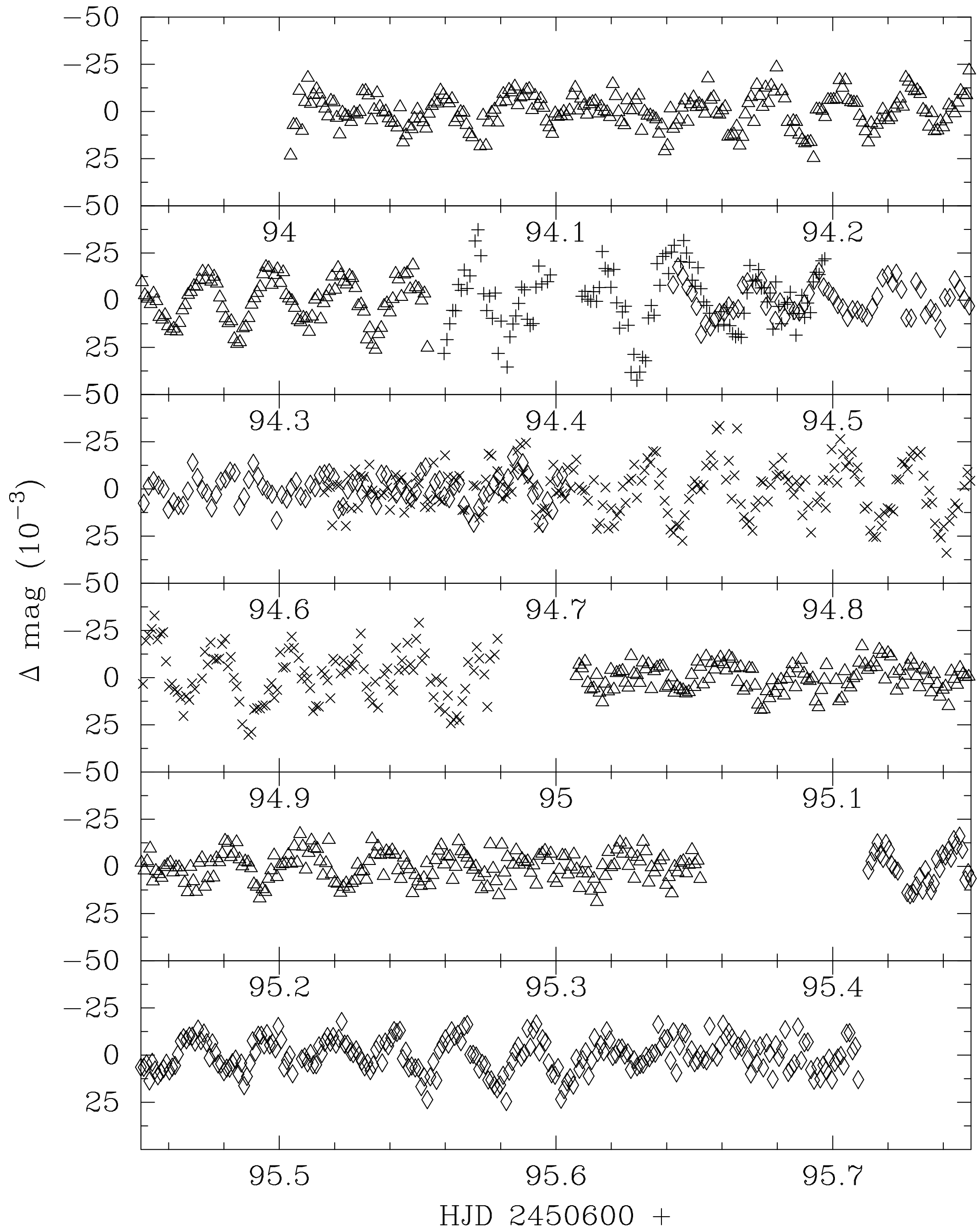


Figure 6.4: On-line reduced light curves of the 1997 observations of HS 2324+3944 during the central part of the multisite campaign. Open triangles: Beijing data, plus signs: Loiano observations, diamonds: Calar Alto measurements, crosses: McDonald photometry. Several overlaps are visible. Good agreement between the different observatories is found. The light curves strongly suggest multiperiodic variations of the target star.

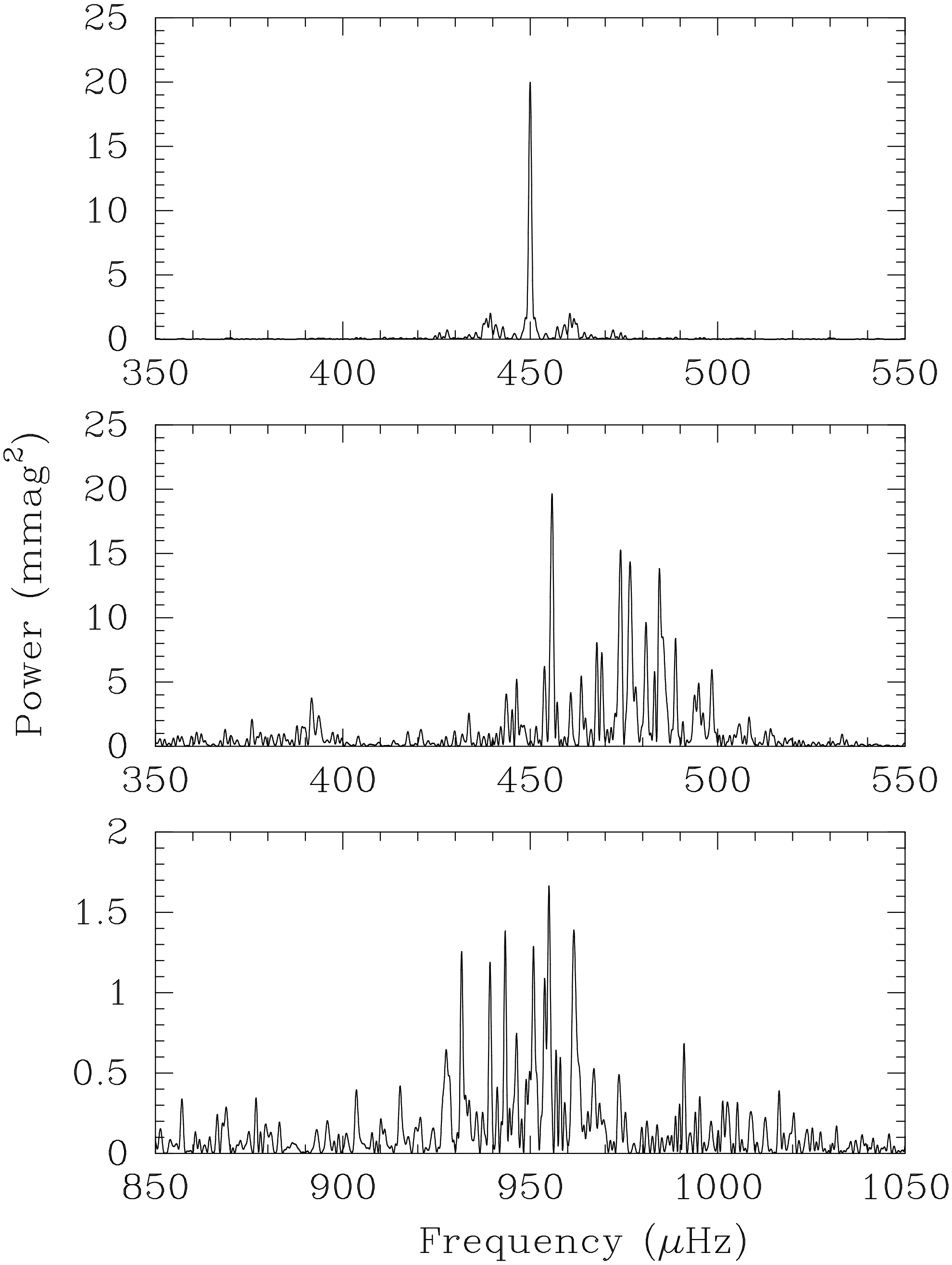


Figure 6.5: Power spectra of the on-line analysed 1997 multisite observations of HS 2324+3944. Upper panel: spectral window, middle panel: power spectrum of the data, lower panel: power spectrum in the frequency region where linear combination frequencies can be expected. Power spectra are consistent with noise in frequency regions not displayed. Note the excellent spectral window and the complicated power spectrum of the data.

Although the conclusion above is somewhat disappointing, our frequency analysis allows one definite important statement:

**The "hybrid" PG 1159 star HS 2324+3944 is a multiperiod g-mode pulsator.**

### 6.2.3 The Future

At this point, our data are not sufficient for detailed asteroseismological modeling of HS 2324+3944, but one theoretical study can be suggested. At this point it would be of great interest to calculate a grid of "hybrid" PG 1159 models with a detailed post-AGB evolutionary history and to attempt a match of pulsationally unstable model frequencies with the frequency region excited in the star.

To suggest further observational programs for "hybrid" PG 1159 stars, we start with HS 2324+3944 itself. Since we believe that our power spectrum is not completely resolved, a longer campaign would be necessary. One possible idea would be multisite measurements covering darktime of three consecutive months. Both photomultipliers and CCD's can be used. To reduce monthly aliases which may interfere with intrinsic pulsation frequencies, CCD observations should also be scheduled close to bright time. If a sufficient number of pulsation frequencies is unambiguously detected, mode identification will be possible with the help of Fourier transforms of both Fourier and period transforms of the data. We note that such large campaigns are not impossible (see Handler 1997) and will be undertaken.

It should also be pointed out that Ciardullo & Bond (1996) suspected light variability of the "hybrid" PG 1159 central stars of NGC 7094 and A 43, respectively. While the variations of NGC 7094 seem to occur on time scales of 2 hours, which will make a seismological analysis (if the star pulsates) practically impossible, A 43 appears to vary on a time scale similar to HS 2324+3944. It is therefore an interesting target for more intensive time-series CCD photometry.

Final results of this campaign are published elsewhere (Silvotti et al. 1999).

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- Über 300 Beobachtungsnächte, in denen mehr als 1200 Stunden an photoelektrischer und CCD-Photometrie sowie CCD-Spektroskopie an mehreren internationalen Observatorien gewonnen wurden
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| **Gastaufenthalte an internationalen Universitäten** | März 1995: | • 2 Wochen SAAO und Universität Kapstadt, Südafrika |
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| | Februar 1995: | • IAU Colloquium No. 155 in Kapstadt, Südafrika (Poster) |
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| | Jänner 1996: | • 187th meeting of the American Astronomical Society, San Antonio, Texas |
| | Juni 1996: | • EUROWET workshop in Skibotn, Norwegen (Vortrag) |
| | August 1996: | • IAU Symposium No. 180 in Groningen, Holland (2 Poster) |
| | Juni 1997: | • "A Half Century of Stellar Pulsation Interpretations", Los Alamos, USA (2 Poster) |
| | Juli 1997: | • 4th Whole Earth Telescope workshop in Koninki, Polen (Vortrag und Poster) |
| | September 1998: | • "Variable Stars as Important Astrophysical Tools" in Cesme, Türkei (Übersichtsvortrag) |
| | August 1999: | • IAU Colloquium No. 176 in Budapest, Ungarn (eingeladener Übersichtsvortrag) |

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# List of Publications

## Refereed journals

1. Chromospheric activity in G and K giants and their rotation-activity relation
K. G. Strassmeier, G. Handler, E. Paunzen, M. Rauth, 1994, A&A 281, 855

2. The $\delta$ Scuti star FG Vir. I. Multiple pulsation frequencies determined with a combined DSN/WET campaign
M. Breger, G. Handler, R. E. Nather, et al., 1995, A&A 297, 473

3. Nonradial pulsation of the unevolved hot $\delta$ Scuti star CD-24 7599 discovered with the Whole Earth Telescope
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5. Variable central stars of young Planetary Nebulae I. Photometric multisite observations of IC 418
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6. New Whole Earth Telescope observations of CD-24 7599: steps towards $\delta$ Scuti star seismology
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7. Frequency variability in the rapidly oscillating Ap star HR 3831: Three more years of monitoring
D. W. Kurtz, F. van Wyk, G. Roberts, F. Marang, G. Handler, R. Medupe, D. Kilkenny, 1997, MNRAS 287, 69

8. Nonvariability among $\lambda$ Bootis stars
E. Paunzen, R. Kuschnig, G. Handler, M. Gelbmann, W. W. Weiss, 1997, A&AS 124, 23

9. The variability of a newly discovered $\gamma$ Doradus star, HD 108100
M. Breger, G. Handler, R. Garrido, et al., 1997, A&A 324, 566

10. Complex light variations of the "hybrid" PG 1159 star HS 2324+3944
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11. On the frequency and amplitude variations of the $\delta$ Scuti star CD-24 7599 (=XX Pyx)
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13. The $\delta$ Scuti star FG Vir: III. 24 pulsation frequencies discovered with the 1995 multisite campaign
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16. A search for pulsations among low-mass DAO white dwarfs
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17. The pulsating $\lambda$ Bootis star HD 105759
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18. A search for rapid oscillations in chemically peculiar A-type stars
G. Handler, E. Paunzen, 1999, A&AS, in press

19. The photometric behaviour of the peculiar PG 1159 star HS 2324+3944 at high frequency resolution
R. Silvotti, S. Dreizler, G. Handler, X-j. Jiang, 1999, A&A, in press

20. Variable central stars of young Planetary Nebulae. A photometric study of the central star of M2-54
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## International journals, newsletters, proceedings

1. CD-24 7599, a new $\delta$ Scuti star discovered with the Whole Earth Telescope
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2. Extending the Whole Earth Telescope technique to lower frequencies
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3. GM Com, a new slowly variable early F star? or: collecting the pieces of the puzzle
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4. Nichtradiale Pulsationen des unentwickelten heißen $\delta$ Scuti Sterns CD-24 7599
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5. Multi-periodicity of HD 210111 and possible variability of HD 210049
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6. Detection of 13 pulsation modes for CD-24 7599 by WET observations
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7. New Whole Earth Telescope observations of the $\delta$ Scuti star CD-24 7599: amplitude variability and discovery of 13 pulsation modes
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24. Observations Versus Theory: The $\delta$ Scuti Star CD-24 7599
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