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Variable central stars of young Planetary Nebulae

A photometric study of the central star of M 2–54*

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Abstract. We acquired 63.8 hours of time-series photometry of the variable central star of the young Planetary Nebula M 2−54. This object exhibits light variations with a peak-to-peak amplitude of up to 0.3 mag in Johnson V. 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 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.

Key words: stars: variables — planetary nebulae: individual: M 2−54 — stars: oscillations — stars: mass loss

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 min or longer (e.g. Handler et al. 1998). 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 are 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, hereafter Paper I, 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 the two hypotheses, Handler (1998) carried out a survey for photometric variability among bright Northern Hemisphere CSPN. He observed 25 objects and found that more than 30% of CSPN with effective temperatures of 25 000 − 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 M 2–54 (we will use the name of the nebula for the central star throughout the remainder of this paper). M 2–54 is also known as PK 104 − 06 1 or PN G 104.8 − 06.7 (see Acker et al. 1992) and its variability was discovered by Handler (1996, 1998). It is the highest amplitude variable of the latter

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* Table 2 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

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Table 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

group found 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 M 2–54 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 M 2–54 was also detected in HIPPARCOS photometry (ESA 1997). These measurements are analysed as well.

2. Observations and reductions

Photoelectric time-series photometry of M 2–54 was acquired with the 0.9 m telescope at McDonald Observatory, Ft. Davis, Texas, U.S.A. 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 M 2–54) 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 awarded three weeks of observing time, and an overview of the acquired measurements is given in Table 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 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 s on the comparison stars, while we measured the brightness of M 2–54 for 100 s (since it is much fainter than the comparison stars). This yielded a mean separation of 6.5 min 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 observation 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 peak higher than 0.7 mmag. 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 M 2–54: 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 M 2–54 are given in Table 2 (available only at CDS) and displayed in Fig. 1.

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 (≈ 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. 1 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 (Paper I).

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 zero-points. 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 than

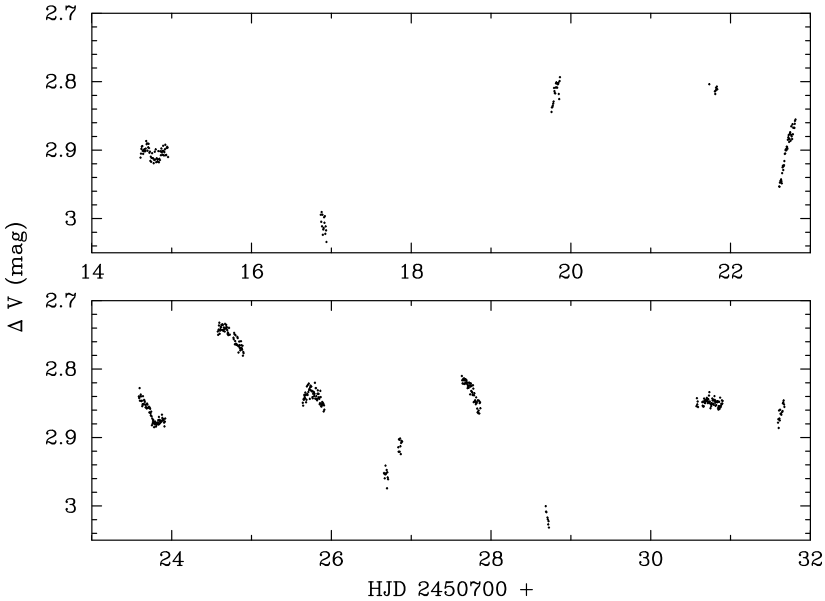

Fig. 1. The light curve of M 2–54 during our observations. Magnitudes are relative to those of the brighter comparison star (HD 235981). Variability with a total amplitude of 0.3 mag is obvious

an observing night will be suppressed. We refer to Paper I 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. 1, we never covered a full cycle during a single observing night. Therefore, the time scale must be longer than 8 hours.

Keeping the limitations explained above in mind, we set all nightly mean magnitudes to zero and calculated an amplitude spectrum of these data. This is shown in Fig. 2. 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. 2, suggesting that the zeropoint adjustments of the short runs have negligible influence on our results.

What is the underlying time scale of the short-term variations? Three peaks in Fig. 2 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. 2. This can be due to two reasons:

– The variations are not strictly periodic.

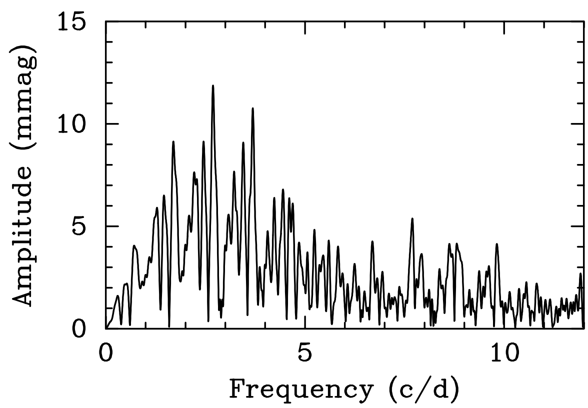

Fig. 2. The amplitude spectrum of the M 2–54 data after adjusting the nightly zeropoints

– The long-term variability could not be completely removed from the data. Therefore, remaining trends can affect the analysis. This may also result in different amplitudes for different cycles - which is apparent in Fig. 1.

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.

The most interesting feature in Fig. 3 clearly is that the phase diagram relative to the 2.69 c/d frequency is much smoother. This also suggests that this frequency is

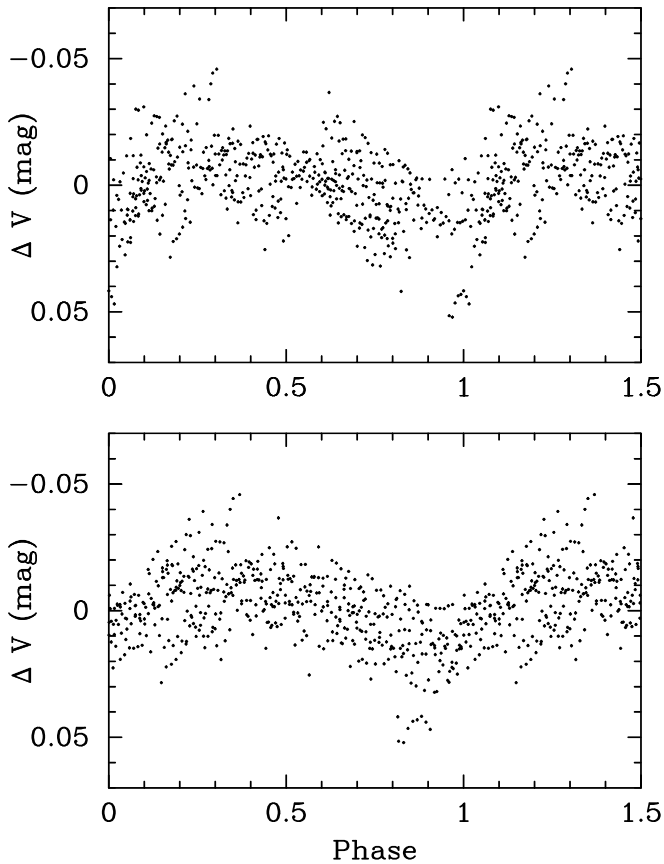

Fig. 3. Upper panel: a phase plot of the adjusted M 2–54 data relative to a frequency of 1.68 c/d. Lower panel: the same, but relative to the 2.69 c/d frequency

more likely to correspond to the correct time scale of the short-term light variations of M 2–54.

To summarize the results of our light-curve analysis, the variability of M 2–54 is quite similar to that of HD 35914 (Paper I). 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.

4. HIPPARCOS photometry

M 2–54 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 analysing 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. 4.

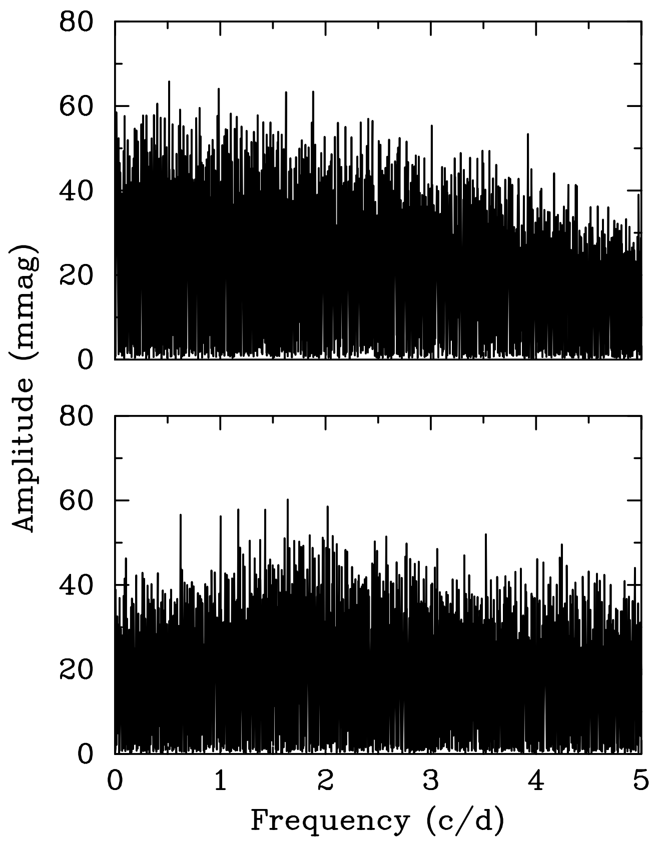

Fig. 4. Upper panel: the amplitude spectrum of the HIPPARCOS photometric data of M 2–54. Lower panel: an amplitude spectrum of a random data set, sampled exactly as the HIPPARCOS data and having the same standard deviation

The amplitude spectra shown in Fig. 4 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 M 2–54. 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.

5. Discussion

To examine the physical reason of the variability of M 2–54 (following the discussion in Paper I), 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 M 2–54 is around 30 000 K. 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 M 2–54. 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 ± 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 M 2–54 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

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

where $R_{\rm eq}$ is the equatorial radius of the star ($R_{\rm eq} = 1.5\,R_*$), becomes 39^{+30}_{-24} hours for M 2–54. Only by assuming an 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 unlikely. 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 than 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 M 2–54 (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 Paper I 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 M 2–54.

6. Summary and conclusions

We carried out a time-series photometric study of the variable central star of the young Planetary Nebula M 2–54. 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 M 2–54 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 M 2–54. 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 M 2–54 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) is 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.

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