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Abell 43, a second pulsating "hybrid-PG 1159" star★

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Abstract. We report observations of the planetary nebula nucleus Abell 43, obtained at the 2.5 m Nordic Optical Telescope, which show that it is a pulsator. Abell 43, a "hybrid-PG 1159" type star, is the second pulsator of this class, after HS 2324+3944. From the limited data set acquired, we find that Abell 43 exhibits at least two periods of 2600 s and 3035 s, the longest ones observed up to now in PG 1159 and "hybrid-PG 1159" pulsators. This strongly suggests that the variations are due to non-radial g-mode pulsations and cannot be a consequence of binarity. This discovery raises puzzling questions regarding the excitation mechanism in this H rich, C and O poor "hybrid-PG 1159" since the C and O abundances are too low to trigger the instability through the κ-mechanism induced by the partial ionization of C and O, a mechanism invoked to explain the instability in the PG 1159 stars and in the previously known "hybrid-PG 1159" pulsator HS 2324+3944.

Key words. stars: white dwarfs – stars: individual: hybrid-PG 1159 – ISM: planetary nebulae: individual: Abell 43 – stars: oscillations

1. Introduction

The instability mechanism for the pulsating PG 1159 stars (or GW Vir stars), named after the prototype of this class PG 1159-035, has been identified as the κ-mechanism related to the partially ionized carbon and oxygen by Starrfield et al. (1984, 1985). While it was subsequently claimed that a small admixture of hydrogen would inhibit the instability (Stanghellini et al. 1991), Saio (1996) found that the stability of the g-modes was not affected by a 3% admixture of hydrogen by mass in the otherwise characteristic composition of PG 1159 stars. In the mean time, Napiwotzki & Schönberner (1991) discovered a new class of PG 1159 stars showing strong Balmer lines, which they called "hybrid-PG 1159" stars. Werner (1992) classified them as lgEH in his classification scheme.

Silvotti (1996) found the first pulsating "hybrid-PG 1159" star: HS 2324+3944. The pulsation spectrum was dominated by a 2140 s period. This was later confirmed by Silvotti et al. (1999) who found HS 2324+3944 to be a rich multiperiodic pulsator with at least 7 frequencies between 391 μHz (2553 s) and 961 μHz (1039 s). While Bradley & Dziembowski (1996) and Cox (2003) require a different composition in the driving zone, compared to the composition observed at the surface, Gautschy (1997) was able to reproduce the instability strip for the PG 1159 pulsators and the observed range of periods for the then unique "hybrid-PG 1159" HS 2324+3944, with a uniform composition in agreement with the observed composition. More recently, Quirion et al. (2004), reanalyzing the stability problem of the PG 1159 stars, confirm that the instability strip of the PG 1159 stars is well reproduced by models having a uniform composition similar to the observed one for each PG 1159 pulsator. They also reproduce satisfactorily the periods observed in HS 2324+3944, with a model including 10% of hydrogen mass fraction, and find unstable modes in a period range 1355 s-3013 s, slightly wider than the observed one. They also show that small differences in He/C/O composition and metallicity from star to star account for the puzzling coexistence of pulsators and non-pulsators with identical atmospheric parameters.

In this context, it is worthwhile to wonder whether HS 2324+3944 is a unique case of pulsating "hybrid-PG 1159" star, and if more such stars do exist, were are the boundaries of the corresponding instability strip. Ciardullo & Bond (1996) conducted a large survey to search for pulsating nuclei of planetary nebulae. Included in this survey were 3 of the "hybrid-PG 1159" stars known by the time: Abell 43, NGC 7094 and Sh 2-68. None of them were found to pulsate and their Table 2 lists them as non-pulsators. However, in the case of Abell 43, they noted that the FT of their light curve did show one peak at ≈404 μHz with an amplitude of 3.5 mmag, which was just below their adopted detection limit. For this reason, they did not consider Abell 43 as a pulsator. In the case of NGC 7094, they did not detect any significant peak in the power spectrum

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above 300 μHz, but they comment that their light curve shows quasi-sinusoidal variations on a time scale of 2 h and with an amplitude of 20 mmag. More recently, González Pérez (2004) reobserved both Abell 43 and NGC 7094 and did not detect any variations. For Abell 43, the maximum amplitude of its power spectrum was ≤3 mma (where mma, the milli-modulation amplitude, is the fractional amplitude in the Fourier Transform in units of 10^{-3}), while it would have required an amplitude of 6 mma for a peak in the power spectrum to have a False Alarm Probability (FAP) of only 1/20 to be due to noise and be considered as possibly significant. In the case of NGC 7094, for wich he obtained better quality data, the maximum amplitude in the power spectrum was ≤0.7 mma while for the same FAP it would have required an amplitude of 0.9 mma to be significant at the same level of confidence. However, from his data set on NGC 7094, one cannot check whether the 2 h time scale variability suspected by Ciardullo & Bond (1996) is present since the run is shorter.

In the present letter, we report new observations of Abell 43 showing that it is indeed a pulsator, the second one among the class of the "hybrid-PG 1159" stars. In Sect. 2 we describe our observations. We discuss the results in the context of the instability mechanism in Sect. 3.

2. Observations and analysis

We used the Nordic Optical Telescope (NOT) with the Andalucia Faint Object Spectrograph and Camera (ALFOSC) equipped with a thinned 2048 × 2048 E2V CCD 42-40 chip, operated in multi-windowed fast photometry mode (Østensen 2000). We used a filter centered on 550 nm with a *FWHM* of 275 nm, in order to increase the contrast with the sky background. Flat field measurements were performed at the beginning of each observing night, and the bias level was determined from overscan obtained for each windowed frame. The light curves have been corrected for atmospheric extinction by using a coefficient proportional to the airmass. The coefficient is adjusted so as to flatten the light curve as much as possible.

We first observed Abell 43 on June 24th, 2004 (start time 22:25:28 UT) together with 6 comparison stars and 2 sky background fields. The observing cycle was choosen as 20 s, which, with a total readout time of 7.4 s for the 9 windows, results in an exposure time of 12.2 s for each frame. The average seeing was 0.9 arcsec (*FWHM*) so that the S/N ratio was optimized with a 12 pixels aperture, which corresponds to an aperture diameter of 4.6 arcsec at the ALFOSC pixel scale (0.19 arcsec/pixel). We obtained a 6000 s light curve, showing unambiguously that the star is variable. The light curve of the target and one of the comparison stars is shown in Fig. 1, together with their Fourier transform, plotted in amplitude terms. Two cycles are clearly visible in the light curve. The FT shows an unresolved peak of 2.5 mma amplitude, while the average noise level is about 0.3 mma. We observed Abell 43 again on June 27th, 2004 (start time 23:15:26 UT) for a confirmation run. We used 3 comparison stars and 2 sky background fields. The cycle time was 30 s, which, with a total readout time of 5 s for the 6 windows, results in an exposure time of 24.7 s for each frame. The average seeing was 1.5 arcsec (*FWHM*). The best S/N ratio was obtained with an aperture of 17 pixels, i.e. 6.5 arcsec. We obtained a longer light curve of 13 500 s, shown in Fig. 2, together with its Fourier transform. On this light curve, one clearly sees that the variation cycles are irregular in length, suggesting that the star is multiperiodic or that a frequency change occured during the run. The average noise level in the FT is $\sigma = 0.2$ mma. The peak at 340 μHz with an amplitude of 2.5 mma, is at 12.5σ.

In spite of the fact that these two observing runs are three days apart, we combined the two light curves to perform a FT with a better resolution, shown in Fig. 3 together with the corresponding window function. Both are shown on an enlarged scale encompassing the frequency interval which shows power, i.e. between 0 and 1000 μHz. The FT shows at least two

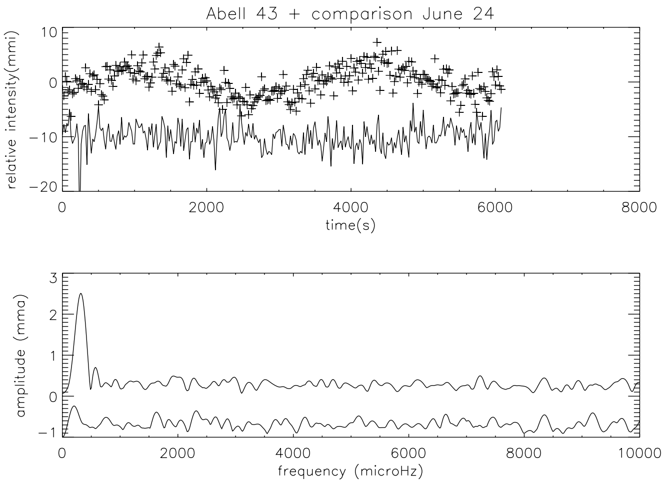

Fig. 1. *The upper panel* shows the normalized light curve of Abell 43 obtained on June 24th, 2004. The relative intensity in units of milli-modulation intensity (mmi), which is the fractional modulation intensity in units of 10^{-3}, is plotted as a function of time in seconds. The Abell 43 light curve (crosses) is shown together with the average light curve for one of the comparison stars (full line) relative to the average of the remaining comparison stars. The comparison star light curve is displaced 10 mmi downwards for clarity. The lower panel shows the FT of these light curves, plotted in units of milli-modulation amplitude (mma) as a function of frequency in μHz. The FT for the comparison star light curve is displaced downwards by 1 mma for clarity.

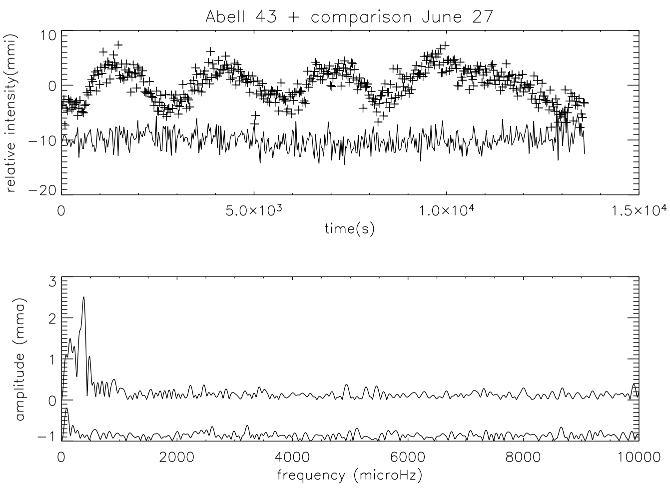

Fig. 2. As in Fig. 1 for the run on June 27th, 2004.

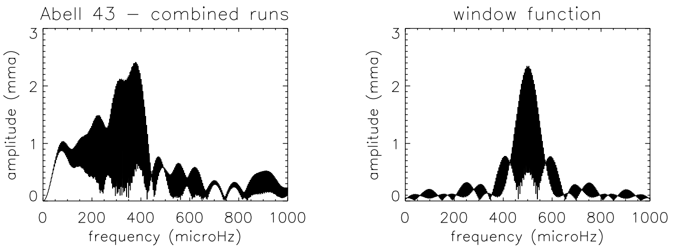

Fig. 3. *The left panel* shows the FT of the combined light curves (June 24th + 27th). The amplitude in units of milli-modulation amplitude (mma) is plotted as a function of frequency in μHz. The FT is shown on the restricted frequency range 0–1000 μHz. The right panel shows the window function on the same scale.

significant peaks at 329 μHz (3035 s period), with a 2.1 mma amplitude, and at 384 μHz (2600 s period), with a 2.4 mma amplitude.

A third run was obtained on July 15th, 2004 in similar conditions than the two previous ones, except that the aperture was 10 pixels, i.e. 3.8 arcsec, and the cycle time was 30 s with an integration time of 25 s. The light curve, ≈7500 s long, and its FT are shown in Fig. 4. This third run shows variations with an amplitude significantly larger since the peak in the FT is at 4.7 mma.

Previous observations did not detect the Abell 43 variations because 1) they have long periods and 2) their amplitudes are small and variable.

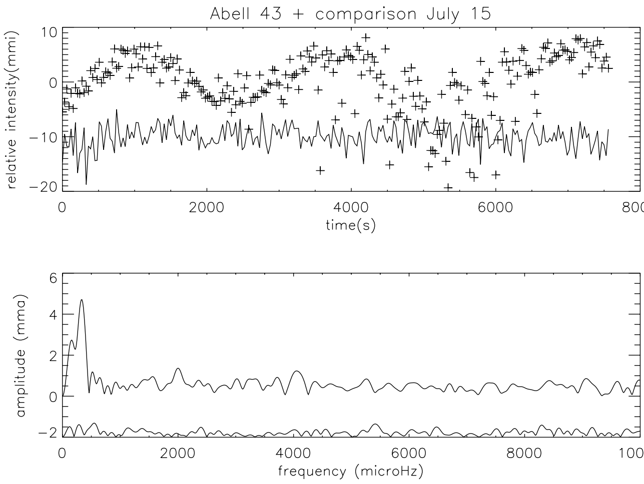

Fig. 4. As in Fig. 1 for the run on July 15th, 2004. The FT for the comparison star light curve is displaced downwards by 2 mma for clarity. Comparison with Figs. 1 and 2 clearly shows the amplitude variations.

3. Discussion

Are the variations observed in Abell 43 due to pulsations? A number of planetary nebulae nuclei are binary sytems. Some reflection effects may happen if the companion is a hot star close enough to the planetary nebula nucleus and/or the nucleus itself may take a non spheroidal shape because of the tidal interaction induced by the companion. Both effects would produce a light variation in phase with the rotation period of the nucleus. In a search for companions of planetary nebula nuclei, Ciardullo et al. (1999) did not find any evidence for such a companion close to Abell 43 nor to NGC 7094. However, their method would have detected only visual companions, too far from the planetary nebula nucleus to produce any reflection effect. This does not preclude the possibility for Abell 43 and NGC 7094 to have a close companion. Such a close binary system would be detectable through radial velocity measurements. We are not aware of any such radial velocity study on those two stars. But the multiperiodicity or the frequency variation found in the FT of the Abell 43 light curve excludes that the observed variations could be due to such an effect in that star. We do conclude that the variations in Abell 43 are due to non-radial g-mode pulsations. With periods of 2600 s and 3000 s, Abell 43 shows the longest periods observed in PG 1159 and "hybrid-PG 1159" stars. In the case of NGC 7094, we clearly need more data to check the reality of the 2 h variability suspected by Ciardullo & Bond (1996).

The discovery of pulsations in Abell 43 is puzzling and raises interesting questions regarding the excitation mechanism and the evolutionay status. Both Abell 43 and NGC 7094 occupy the same location in the log g–$T_{\rm eff}$ diagram (Dreizler et al. 1995). In this diagram, they seem to lie on the same evolutionary track as HS 2324+3944, between for instance the evolutionary tracks of Schönberner (1983) for 0.565 $M_\odot$ and 0.605 $M_\odot$. With $T_{\rm eff}$ = 110 kK and log g = 5.7, they are clearly less evolved than HS 2324+3944 at $T_{\rm eff}$ = 130 kK and log g = 6.2 (Dreizler et al. 1996). Both Abell 43 and NGC 7094 have still a surrounding nebula while none is seen around HS 2324+3944. Most interestingly, their composition strongly differs from HS 2324+3944 and PG 1159 composition, being H-rich (42% by mass), with similarly a high abundance of He (51% by mass), and poor in C (5% by mass) while N and O are below detection limit (Dreizler et al. 1995). By comparison, HS 2324+3944 has the same relative C/He abundance as the PG 1159 stars but a much smaller H abundance of 18% by mass, with 37% of He, 44% of C and less than 1% of N and O, by mass (Dreizler et al. 1995). A mass-loss rate has been measured in NGC 7094, of $\log \dot{M} = -7.3\ M_\odot\ {\rm yr}^{-1}$ from CIV line or of $\log \dot{M} = -7.7\ M_\odot\ {\rm yr}^{-1}$ from OVI line (Koesterke et al. 1998a,b). While no such mass-loss rate determination exists for Abell 43, Dreizler (1998) reports that both Abell 43 and NGC 7094 show a P Cygni profile in the O V line at 1371 Å. This strongly suggests that Abell 43 is also losing mass. This gives a coherent picture of an evolutionary link between Abell 43, NGC 7094 and HS 2324+3944, consistent with the fact that HS 2324+3944 has less hydrogen left than Abell 43 and NGC 7094 as a consequence of the mass-loss, and with the fact that HS 2324+3944 had the time to disperse its nebula while Abell 43 and NGC 7094 kept their nebulae. Finally, among those two stars, Abell 43 is a pulsator while for NGC 7094 we can only say that we do not know yet.

The model explaining the instability in the PG 1159 stars and in the "hybrid-PG 1159" HS 2324+3944 does not seem applicable to Abell 43. Both Abell 43 and NGC 7094 have a very low abundance of C and O. Even if one considers that the preliminary abundance analysis of Dreizler et al. (1995) does not take into account the influence of the stellar wind on the atmospheric modeling, it is difficult to imagine that taking this effect into account could increase the C and O abundances so much as to reach the values derived for HS 2324+3944. If the composition of Abell 43 is uniform from the surface to the potential driving zone, as expected if mass-loss precludes any gravitational settling, it is difficult to invoke an instability due to the κ-mechanism induced by the C and O partial ionization with such a low abundance of C and O. As in the case of the PG 1159 pulsators, one may have also to explain the coexistence of pulsators and non pulsators with identical atmospheric parameters among the "hybrid-PG 1159" stars if NGC 7094 is confirmed to be a non pulsator.

A first alternative would be to postulate that the still unknown mass-loss rate in Abell 43 is too low to inhibit the gravitational settling of C and O. The composition in the driving zone would not reflect the abundances observed at the surface. The C and O abundances in the driving zone could be enhanced such as to trigger the pulsations through the κ-mechanism. However, if the gravitational settling takes place, it should also affect He relative to H abundance. The observed He and H abundance in Abell 43 does not fit with this scheme. In addition, it is expected that the mass-loss rate in Abell 43 should be higher than in HS 2324+3944, or at least similar to the one measured in NGC 7094, if it is related to the luminosity. If this is the case, the gravitational settling should not occur in Abell 43 if it does not occur in HS 2324+3944. Furthermore, if there is no mass loss in Abell 43 there cannot be any evolutionary link with stars like HS 2324+3944 and PG 1159 stars which are hydrogen deficient.

Another possibility to trigger the instability, through the ϵ-mechanism induced by remnant nuclear shell burning during the planetary nebula and pre-white dwarf evolutionary phases, was suggested by Kawaler et al. (1986). One may wonder whether the Abell 43 variability could be due to this mechanism. However, it would make only the low order g-modes unstable, which have periods much shorter than the observed periods in Abell 43. None of the surveys of planetary nebulae nuclei conducted by Grauer et al. (1987), Hine & Nather (1987) and more recently by Ciardullo & Bond (1996) found any short period variability which could be identified with g-modes triggered by the ϵ-mechanism. The same conclusion was reached by Vauclair et al. (2002) in their analysis of the PG 1159 central star of the planetary nebula RX J2117+3412.

A third alternative would be to give up the idea that the pulsations in Abell 43 are due to the κ-mechanism related to the partial ionization of C and O or to the ϵ-mechanism. We suggest that episodic mass loss could excite the pulsations (by stochastic excitation). The same mechanism could also be at work in NGC 7094, where a mass-loss is observed and measured. This model predicts that NGC 7094 could also pulsate. In this context, it is worth pointing out the sudden change in the pulse length observed in Abell 43 during the June 27th run (see Fig. 2). Similar changes on a short timescale have also been detected in the other pulsating planetary nebula nucleus NGC 246 (González Pérez 2004). Such behaviours cannot be related to beating phenomena. They are real changes on short time scales which deserve longer observations to be investigated. This suggestion could be tested by observations. It would require simultaneous spectroscopic and photometric observations to check whether 1) there is evidence of time dependent mass-loss in Abell 43 and 2) there is a correlation between the pulsation amplitudes and the mass-loss episodes. Alternatively, the life time of the pulsation modes, if excited by episodic mass-loss events, should be short compared to the life time of modes excited by the κ-mechanism. This could be checked by measuring the line width in the power spectrum. Long enough multisite campaigns may provide the necessary frequency resolution to check the life time of the modes. A wavelet analysis may be more appropriate to reveal those modes whose lifetime could be short relative to the length of the observing campains. It is also urgently needed to check whether NGC 7094 could also be a pulsator, possibly with longer periods than the one which could have been determined from previous observations.

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