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On the inclination and binarity of the pulsating pre-white dwarf PG 2131 +066 ⋆

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Abstract. We report on new spectroscopic data as well as recent results from a temporal analysis of PG 2131 +066 WET time series, yielding a new interpretation of the binarity nature for PG 2131 +066. The newly discovered Hα emission features, the estimated low inclination and the found 3.9 h period, support the picture of a close binary system, composed of the nonradial oscillating white dwarf with a cool red dwarf companion. Since the spin and the orbital period are not yet synchronized and because PG 2131 +066 has no X–ray counterpart, we classify it as a progenitor of a cataclysmic variable.

Key words: stars: binaries: close – oscillations – white dwarfs – individual: PG 2131+066

1. Introduction

PG 2131 +066 (PG 2131 hereafter) is a member of the PG 1159 spectral class. These hot and luminous pre-white dwarfs are in the transition between the asymptotic giant branch and cooling white dwarfs. So far, pulsation (nonradial g-modes, Kawaler & Bradley 1994) was found in 8 among 27 members of this group. With the tools of asteroseismology an estimation of masses, luminosities and the internal structure is possible, helping to understand the late stages of stellar evolution.

Binarity of PG 2131 was already reported by Wesemael et al. (1985) on the basis of an apparent red excess in its optical spectrum. Since an HST-image showed a faint field star at 0.3″ distance, it was identified as the unknown distant companion (Schultz et al. 1996). We present new spectroscopic data (see Sect. 3) for PG 2131 resulting in a new interpretation of the binarity.

Furthermore, we have reanalyzed the photometric data of a previous WET campaign for PG 2131 published by Kawaler et al. (1995, Kaw95 hereafter) in order to understand the reported unequal amplitudes of the different triplet peaks in the frequency spectrum.

Kaw95 have analyzed photometric data of a WET campaign resulting in five frequency triplets identified as ($\ell = 1$) high overtone g-modes with a determined rotational splitting into three components resulting from the dissolution of the m-degeneracy. The noticed unequal amplitudes for the ($m = \pm 1$) peaks for each triplet can be interpreted as an effect of a possible magnetic field (Unno et al. 1989). Furthermore, all triplets show a strong suppression of the central ($m = 0$) peak, which we have used to derive an inclination of less than 10° for PG 2131 (see Sect. 4). We have examined the data (kindly provided by Dr. Kawaler) using standard time series analysis methods resulting in a, so far, unknown periodicity which additionally modulates the known stellar oscillations. This result gives further evidence that PG 2131 is part of a very close eclipsing binary system.

2. Observations

The spectroscopic observations were obtained in the nights of 07/08 and 08/09.11.1989 with the 3.5m telescope at Calar Alto, Spain. Using the TWIN spectrograph resulted in a resolution of 3.5 Å pixel^{-1} (72 Å mm^{-1}). The RCA#15 CCD (1024x640, 15μ pixel) for the blue and the GEC#17 CCD (1155x768, 22.5μ pixel) for the red channel were used. All standard reduction steps (bias subtracting, flat field correction, etc.) were done within MIDAS.

3. Binary nature of PG 2131

PG 2131 is a faint (V = 16.6 mag) pre-white dwarf. Dreizler et al. (1995) derived an effective temperature of 80 000 $\pm$ 10 000 K and a surface gravity of 7.0 $\pm$ 0.5. Wesemael et al. (1985) reported the binary nature for this star. The secondary component was later believed to be found at a separation of 0.3″ and an approximate spectral type of K7 was estimated from the red excess. This approximation can only be taken as a first estimation

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⋆ Based on observations obtained at the German-Spanish Astronomical Center, Calar Alto, operated by the Max Planck Institut für Astronomie Heidelberg jointly with the Spanish National Commission for Astronomy.

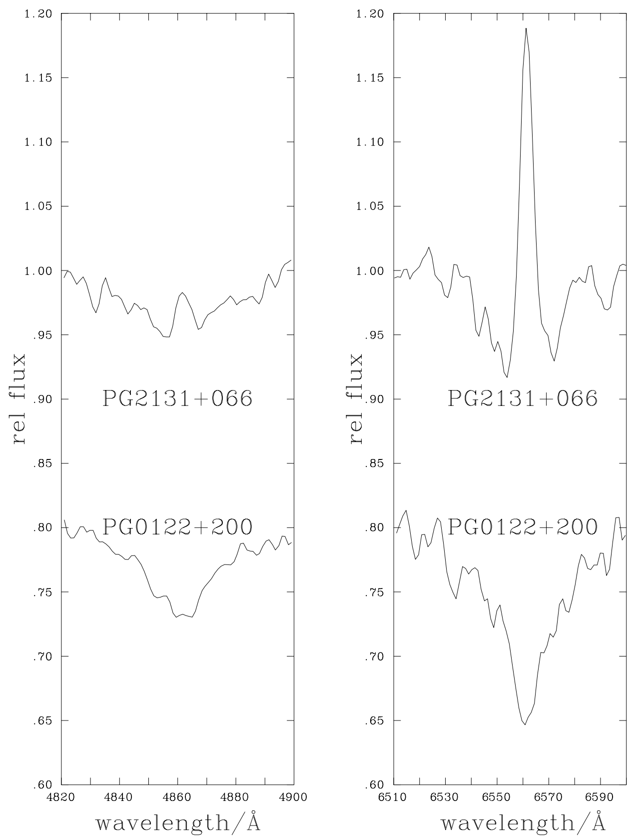

Fig. 1. He II/Hβ and He II/Hα line of PG 2131. An emission component is clearly visible in the He II/Hα line and weakly detectable also in He II/Hβ. Due to the known binarity nature of PG 2131 and the absence of a Planetary Nebula we interpret this as a re-processing line originating from the illuminated atmosphere of the cool companion. For comparison we included the same lines of a single PG 1159 stars (shifted downwards for clarity) with nearly identical stellar parameters.

of the relevant spectral region for the companion. Due to the used method, the possible error is rather large. With an asteroseismological distance (derived from the pulsation model and the apparent visual magnitude) of 470^{+180}_{-130} pc the given angular separation would correspond to 140^{+195}_{-100} AU. From the faintness of the secondary component, we estimate a spectral type of K7 V ($M_V \approx 8$, but M_V(K7 III) $\approx$ –0.3). But no proof can be given, if this star is really related to PG 2131.

On the other hand, the optical spectrum of PG 2131 indicates that it is a close binary system (Fig. 1). This becomes obvious if we compare the binary PG 2131 with the single star PG 0122+200, a PG 1159 star with very similar stellar parameters. The He II/Hα and (weaker) the He II/Hβ line show an emission component in the line profile which is absent in PG 0122+200. It seems unlikely that this is due to a Planetary Nebula since no other Nebula lines (e.g. [O III] 5007 Å) is visible in the spectrum. It can, however, be explained if we have a close binary system and the emission is due to re-processing in the illuminated atmosphere of the cool companion. The emission peak is not symmetrically embedded in the absorption profile which is partly due to the effect that the line profile of the PG 1159 star is mostly He II while the re-processing line would be pure hydrogen. We therefore expect the emission peak shifted by 2.7 Å to the red compared to the line center of the absorption profile. The separation is however only 1.3 Å which would result in a velocity shift of –65 kms^{-1}. This is well within the maximum possible orbital velocity (400 kms^{-1}) for the later derived parameters.

A wide range period search (Sect. 4) of previous published WET data reveals strong periodic modulation with 3.9 h which cannot be explained by a beat frequency of the triplet periodicities or by any combination with the spin period (Fig. 2). We are aware that the WET data are not differential and therefore optimized for timescales of about 10 minutes (Kaw95). The periodogram exhibits two "bumps" of spectral power in the frequency range of $2 \ldots 3 \cdot 10^{-4}$ Hz and $5 \ldots 6 \cdot 10^{-5}$ Hz, respectively. The first bump is due to the bundle of beat frequencies of different triplet's periods, the second one results from the beat frequencies of the ($m = 1$) and ($m = -1$) triplet period for each triplet. The autocorrelation function shows this additional modulation as a strong periodic component (Fig. 3). Since different observatories provided data for PG 2131, no strict phase correlation for the atmospheric low–frequency variations could exist. These variations are therefore completely uncorrelated resulting in a low–frequency noise component, but not in any periodic contribution, as clearly seen in the autocorrelation function (Fig. 3). In order to test our conclusions, we have checked the reliability of the low–frequency part of the periodogram by comparing it with other WET periodograms and have also found beat frequency bumps. But we have not found any prominent low– frequency peaks in the other WET periodograms which is due to the binarity nature of PG 2131.

The estimated periods from a Fourier analysis and an epoch folding (assuming ($\ell = 1$) modes as suggested by Kaw95) are $14\,188 \pm 237$ s and $14\,177 \pm 51$ s, respectively. We interpret this additional periodicity to originate from an eclipsing binary system with PG 2131 as the compact object and a close late type companion. Starting from the estimated orbital period of about 14 200 s, a PG 2131 mass of 0.65 $M_\odot$ (Kaw95), and assuming a main sequence star, we have determined upper values for the companions mass and radius of 0.36 $M_\odot$ and 0.42 $R_\odot$, respectively (Warner 1995). These values are typical for cool dwarfs (spectral type K8 to M2), which is consistent with the found red excess. The corresponding semi major axis of the binary system is given by 3 secondary radii or 107 white dwarf radii, with a maximum orbital plane inclination of about 20° for eclipses by the companion. These values are in good agreement with the parameters of cataclysmic variables (Patterson 1984). Since there is no X-ray counterpart identification for PG 2131 (ROSAT database, one degree search radius), we conclude that no interaction (mass flow, etc.) between these two stars takes place which makes this system to a possible progenitor of a cataclysmic variable. This conclusion is also supported by the observed 20% difference of the nonsynchronized spin and the orbital period which results, together with the estimated low

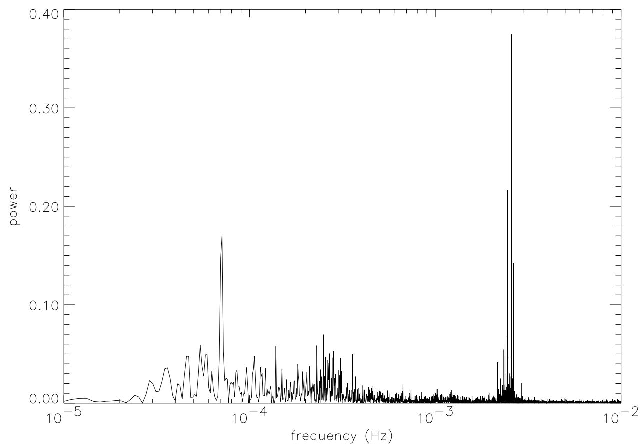

Fig. 2. Power spectrum for the PG 2131 WET data. The power in the frequency range of 2 - 3·10^{-3} Hz originates from the nonradial oscillations.

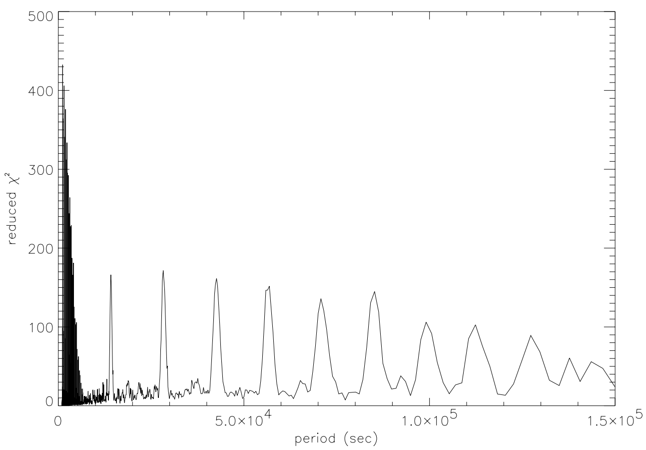

Fig. 3. Epoch folding of the autocorrelation function for the PG 2131 WET data. The long term correlations are dominated by the 3.9 h modulation. Combining the first 5 peaks, the period can be estimated as 14 177 ± 51 s.

magnetic field of PG 2131 (Kaw95), in a typical scenario for nonmagnetic cataclysmic variables (Cropper 1990).

In order to check this hypothesis we have modified the model atmosphere code of Dreizler & Werner (1993) to account for reflection effects according to the ideas of Vaz & Nordlund (1985). The K star model is constructed as a simple hydrogen model with incident radiation from the hot white dwarf taken from the non–LTE model best fitting the optical spectrum. The emergent spectrum of the cool companion is calculated under the assumption that only the irradiated hemisphere is visible. This produces the maximum possible re–processing effect for a given incident radiation. We have to emphasize that our model is quite simple and is only meant to check the consistency of our assumptions. We compared the calculated equivalent widths of the re–processing emission peak of Hα with the observed one taking into account that the white dwarf contributes nearly twice the flux of the K star in the Hα region (Wesemael et al. 1985). According to our model the maximum distance of the white dwarf to the K star is 150 white dwarf radii to account for the observed emission. This is in excellent agreement with the 107 white dwarf radii determined from the orbital period. It also clearly rules out that the companion in 140 AU can be the origin of the emission in Hα since it disappears already at irradiation over 1000 white dwarf radii.

Table 1. Estimated triplet parameters

triplet no.	$P_{(m=0)}{}^{a}$ (s)	$P_{(m=\pm1)}{}^{b}$ (s)	$\Omega_0{}^{c}$ (s)	$\chi^2_{\rm red}{}^{d}$
1	341.45	344.71, 338.61	18051	6.1
2	384.27	388.25, 380.30	18587	68.1
3	403.94	408.63, 399.95	18797	43.2
4	426.37	431.22, 421.41	18552	8.9
(5)	450.27*	456.15, 444.54	17151	5.2
(6)	456.25*	462.40, 450.26	17476	10.9

*estimated due to the rotational splitting and *not* observed directly
[a] central triplet period derived from the ($m = \pm 1$) peaks
[b] determined period for the ($m = \pm 1$) peaks
[c] rotational period estimated from the peak separation
[d] mean $\chi^2_{\rm red}$ value for the ($m = \pm 1$) triplet peaks

4. Temporal analysis

The used WET dataset includes 705525 seconds over 9.6 days (duty cycle of about 42 %) of observations from ten different observatories. We have applied both, a Fourier transform and an epoch folding (a method which is based on binning the data after they were folded modulo a trial period and testing the resulting lightcurve for uniformity; Leahy et al. 1983) for the time series analysis. Both result in the same periodicities as reported by Kaw95 (Fig. 4). Our interpretation differs slightly in classifying the periodicities for the found triplets (see Tab. 1). Kaw95 lists two incomplete triplets (represented by a single peak) for the period range of 450 – 462 s, whereas our classification yields complete triplets. The triplet peaks ($m = 0$, triplet no. 5) and ($m = 0$, triplet no. 6) are *not* observed directly because they are obscured by the (much stronger) corresponding ($m = \pm 1$) peaks. Each of these triplets shows a strong suppression of the central ($m = 0$) peak and the limiting ($m = \pm 1$) peaks exhibit different amplitudes. The interpretation of triplet no. 5 and 6 as ($\ell = 1$) overtone modes with different n radial order seems problematic since both ($m = 0$) modes are too close in spacing (6 s). Kaw95 discusses this issue in more detail (also the possibility of the identification as ($\ell = 2$) modes). Both ($m = 0$) modes would fit (within the error bars) into the found frequency spacing. Only further observations could lead to a solution of this problem. The observed rotational splitting of the triplets leads to a rotational period estimate of Ω_0 = 18 102 ± 665 s which is in good agreement with the value of 18 252 ± 792 s given in Kaw95.

The absence of the triplets central peaks can be used to probe the inclination of PG 2131. This sensitive method is based

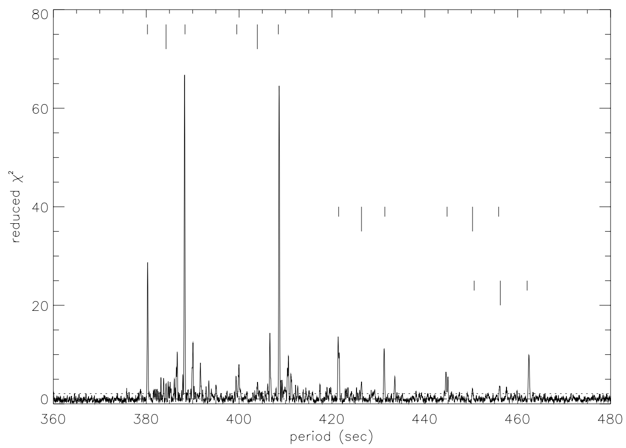

Fig. 4. Results of an epoch folding analysis for PG 2131 (five triplets with $m = -1, 0, +1$ are indicated, for clarity reasons the first triplet is not displayed). The small peaks in the vicinity of the prominent peaks are due to the $1\mathrm{d}^{-1}$ sidelobes in the period search algorithm.

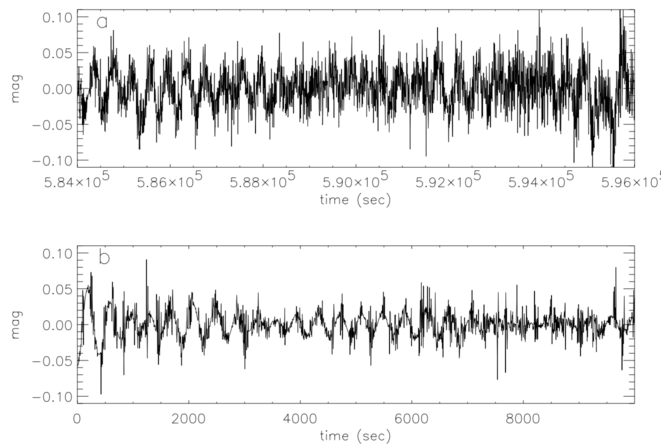

Fig. 5. a Observed and **b** simulated lightcurve for PG 2131. We have used the main triplets with an inclination of one degree and a noise level which has been adapted to the entire WET data variance. Please note that the simulation is not in phase with the observed lightcurve, but gives a good impression of the lightcurves dynamics.

on the different dependence on inclination for the ($m = 0$) and ($m = \pm 1$) contributions to the nonradial stellar oscillation. The ($\ell = 1$) oscillation mode can be described as a linear combination of the spherical surface harmonics $Y_l^m(\theta, \phi)$ for ($\ell = 1$) given by

$$Y_1^0(\theta,\phi) = \sqrt{\frac{3}{4\pi}}\cos(\theta),$$
$$Y_1^{\pm1}(\theta,\phi) = \sqrt{\frac{3}{8\pi}}\sin(\theta)\cos(\phi).$$

As we want to derive the time dependent magnitude $m(t)$ of the oscillating white dwarf, we integrate over the visible half of the stars surface. The inclination i is added to the trigonometric argument in both contributing spherical harmonics yielding the amplitude of the oscillation. The corresponding frequency of the oscillation mode ω completes the analytic description. Furthermore, the stars rotational frequency Ω_0 modifies the ϕ values with a periodicity $\Omega = \Omega_0\, \ell(\ell+1)$ which depends on the multiplicity of the oscillation mode:

$$m(t) = \sqrt{\frac{3}{4\pi}} \int_{\theta=0}^{\pi}\int_{\phi=0}^{\pi} \Big(\cos(\theta - \mathrm{i}) + \sqrt{\frac{1}{2}}\sin(\theta - \mathrm{i})\cos(\phi + \Omega \mathrm{t})\Big)\sin(\omega \mathrm{t})\sin(\theta)\,\mathrm{d}\theta\,\mathrm{d}\phi$$
$$= \sqrt{\frac{3}{4\pi}}\Big(\frac{\pi^2}{2}\sin(\mathrm{i})\sin(\omega \mathrm{t}) + \frac{\pi}{\sqrt{2}}\cos(\mathrm{i})\sin(\omega \mathrm{t})\cos(\Omega \mathrm{t})\Big).$$

The resulting temporal function $m(t)$ can be interpreted as the lightcurve of the oscillating star. Positive and negative amplitudes correspond to a temporarily dark and bright stellar surface, respectively. The resulting lightcurve (derived by the above analytic integration) can be simplified by trigonometric addition theorems yielding different frequencies ω and $\omega \pm \Omega$. They are caused by the rotational splitting of the m–degenerated oscillation mode. Their contribution is weighted by the inclination according to:

$$m(t) = \sqrt{\frac{3}{4\pi}}\Big(\frac{\pi^2}{2}\sin(\mathrm{i})\sin(\omega \mathrm{t}) + \frac{\pi}{\sqrt{8}}\cos(\mathrm{i})\{\sin(\omega \mathrm{t} + \Omega \mathrm{t}) + \sin(\omega \mathrm{t} - \Omega \mathrm{t})\}\Big)$$

Table 2. Dependence on the inclination for the triplet amplitudes

amplitude ratio[a]	inclination
1.0	24.0°
0.5	8.1°
0.1	5.7°
0.01	2.6°

[a] theoretical (m=0)/(m=±1) peak ratio

This last equation reveals the strong functional dependence ot the amplitude of the central peak on the stars inclination. Due to the larger amplitude of the first term of the sum, even a small inclination would give a dominant central peak contribution to the stellar oscillation (see Tab. 2). Since the central peak candidates in the major triplets (no. 2, 3, 4 in Tab.1) never exceed 10% of the ($m = \pm 1$) peaks power, we deduce an inclination of less than 10° for PG 2131 (the corresponding amplitude ratio is less than 64%). In order to get an impression on the dynamics of this equator–on seen oscillator, we have simulated a lightcurve which is composed by the main triplets. As found in the observed lightcurve, the simulation exhibits short episodes with an absence of any periodic behaviour (Fig. 5) which only appears in the case of small inclination angles.

5. Conclusion

From new spectroscopic data (Hα emission features of the companion) and after a careful temporal reanalysis (found 3.9 h period, probably caused by eclipses) of photometric data for the pre-white dwarf PG 2131, we are able to present a new interpretation of the binary nature for this star, as well as an estimate of the upper limit of the inclination (10°). Furthermore, the results of Kaw95 are confirmed although there are still problems with the identification of different ($\ell = 1$) mode triplets.

We conclude that PG 2131 is part of a close binary system, composed of the nonradial oscillating white dwarf with a cool red dwarf companion. This interpretation is inconsistent with the former proposed scenario of a visual component (found on a HST image) at $0.3''$ distance. Since no proof (e.g. by photometric or spectroscopic observations) has been given in the literature that this visual component is related to PG 2131, we strongly suggest to consider it as an effect caused by the line-of-sight.

The absence of a detectable X–ray flux (thus no interaction) for this binary system together with the probably low magnetic field of PG 2131 further strengthens the possibility of an interpration as a progenitor for a cataclysmic variable. Taking into account the differences between the nonsynchronized spin and orbital periods, similarities to the scenario of a nonmagnetic cataclysmic variable are evident supporting our results.

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