Dynamic masses for the close PG1159 binary
SDSS J212531.92–010745.9

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Abstract. The evolutionary scenarios which are commonly accepted for PG1159 stars are mainly based on numerical simulations. These stellar evolution scenarios have to be tested and calibrated with real objects with known stellar parameters. One of the most crucial but also quite uncertain parameters is the stellar mass. PG1159 stars have masses between 0.5 and 0.8 solar masses, as derived from asteroseismic and spectroscopic determinations. Such mass determinations are, however, themselves model-dependent. Moreover, asteroseismologically and spectroscopically determined masses deviate systematically for PG 1159 stars by up to 10%. SDSS J212531.92–010745.9 is the first known PG 1159 star in a close binary with a late main sequence companion allowing a dynamical mass determination. The system shows flux variations with a peak-to-peak amplitude of about 0.7 mag and a period of about 6.96 h. In August 2007, 13 spectra of SDSS J212531.92–010745.9 covering the full orbital phase range were taken at the TWIN 3.5 m telescope at the Calar Alto Observatory (Almería, Spain). These confirm the typical PG 1159 features seen in the SDSS discovery spectrum, together with the Balmer series of hydrogen in emission (plus other emission lines), interpreted as signature of the companion’s irradiated side. A radial velocity curve was obtained for both components. Using co-added radial-velocity-corrected spectra, the spectral analysis of the PG 1159 star is being refined. The system’s lightcurve, obtained during three seasons of photometry with the Göttingen 50cm and Tübingen 80cm telescopes, was fitted with both the NIGHTFALL and PHOEBE binary simulation programs. An accurate mass determination of the PG 1159 component from the radial velocity measurements requires to first derive the inclination, which requires light curve modelling and yields further constraints on radii, effective temperature and separation of the system’s components. From the analysis of all data available so far, we present the possible mass range for the PG 1159 component of SDSS J212531.92–010745.9.

1. The SDSS J212531.92–010745.9 system: a close PG 1159 binary
1.1. Evolutionary scenarios and masses for PG 1159 stars
PG 1159 stars are hot hydrogen-deficient (pre-)white dwarfs with effective temperatures between 75 000 and 200 000 K, and \( \log (g/cm^2) = 5.5–8.0 \) (Werner 2001). They are in the transition between the asymptotic giant branch (AGB) and cooling white dwarfs. Spectra of PG 1159 stars are dominated by absorption lines of He II, C IV and O VI. Roughly half of them have a planetary nebula. Current theory suggests (e.g. Werner 2001) that they are the outcome of a late or very late helium-shell flash, a phenomenon that drives the currently observed fast evolutionary rates of three well-known objects (FG Sge, Sakurai’s object, V605 Aql). Flash-induced envelope
mixing produces a H-deficient stellar surface. The photospheric composition then essentially reflects that of the region between the H- and He-burning shells in the precursor AGB star. The He-shell flash forces the star back onto the AGB. The subsequent, second post-AGB evolution explains the existence of Wolf-Rayet central stars of planetary nebulae and their successors, the PG 1159 stars. These in turn are the progenitors of the helium rich WD sequence. Currently, 40 PG 1159 stars are known, Figure 1 shows their positions in a log $T_{\text{eff}}$-log $g$-diagram.

Recent evolutionary models for PG 1159 stars (Miller Bertolami & Althaus 2006b, Werner & Herwig 2006) lead to spectroscopic masses which still suffer from serious uncertainties concerning the efficiency of the overshooting process in the He-flash driven convection zone during the thermal pulse phase on the AGB. This efficiency is represented in the models with an a priori unknown free parameter. The other ingredient for the determination of spectroscopic masses, the stellar atmosphere models, have to deal with uncertainties in the line broadening theory, so lacking reliable physical input there makes the determination of log $g$ particularly difficult.

The overall resulting uncertainties in model masses manifest themselves as discrepancies between current asteroseismological masses and spectroscopic masses, as is evident from Table 3 in Werner & Herwig (2006: an updated version has been adopted as Table 1 in Schuh & Nagel 2007). The determination of a dynamical mass as an alternative method and test case for the models is currently restricted to only one suitable object: SDSS J212531.92−010745.9.

1.2. Discovery of one PG 1159 close binary among many SDSS white dwarf binaries

The important role of binaries containing white dwarfs, for dynamical mass and other parameter determinations, is evident from the number of publications devoted to the topic in these proceedings. The contributions by Heller et al. (2009), Rebassa-Mansergas et al. (2009), Schreiber et al. (2009), and further contributions on specific individual systems, reflect the remarkable increase in number of known white dwarfs with companions that the Sloan Digital Sky Survey (SDSS) has brought about. Among the PG 1159 stars, however, SDSS J212531.92−010745.9 is the only known close binary system (Nagel et al. 2006). Eisenstein et al. (2006) also list it as a spectroscopically confirmed white dwarf from the SDSS.

The spectrum of SDSS J212531.92−010745.9 shows significant features that are typical for PG 1159 stars, for example the strong C iv absorption lines at 4650−4700˚A and He ii at 4686˚A. Furthermore, the spectrum shows the Balmer series of hydrogen in emission. We have shown from our extensive follow-up photometry and modelling that this is due to a close cool companion which is heated up by irradiation from the hydrogen-deficient PG 1159 star. Thus, the radial velocities for both stars can be measured in this double-lined system.

Nagel et al. (2006) first reported a photometric period of 6.95573(5) h with an amplitude of 0.354(3) mag which represents the orbital period of the binary system. From an initial comparison of the SDSS archive spectrum (Data Release 4) with NLTE model spectra they derived, as preliminary results, an effective temperature of 90,000 K, log $(g/$cm s$^{-2}) \sim 7.60$ and the abundance ratio C/He $\sim 0.05$ for the PG 1159 component. They simulated the light curve of the binary system using NIGHTFALL, showing that in in addition to the constant contribution from the PG 1159, the irradiated side of the companion leads to a periodic brightening due to the reflection effect. For the inclination they obtained $(70 \pm 5)\text{°}$. The system is not eclipsing and has not been found to be pulsating. While their solution for a mean radius of $(0.4 \pm 0.1)$ R$_{\odot}$, a mass of $(0.4 \pm 0.1)$ M$_{\odot}$ and a temperature of the irradiated surface of about 8200 K for the companion was in good agreement with the observed light curve, a manifold of solutions remains equally plausible as long as we cannot reliably and independently fix the PG 1159 mass and radius.

We note that in the SDSS Data Release 6 catalogue Adelman-McCarthy et al. (2008) quote a proper motion of +5(3) mas yr$^{-1}$ in RA and +4(3) mas yr$^{-1}$ in DEC, a value for the redshift corresponding to 138(60) km s$^{-1}$, and Sloan colours of $u'=17.144(0.009)$ mag, $g'=17.538(0.005)$ mag, $r'=17.757(0.006)$ mag, $i'=17.794(0.008)$ mag, $z'=17.828(0.020)$ mag.
Figure 1. Positions of PG 1159 stars with known $T_{\text{eff}}$ and $\log g$ in the log $T_{\text{eff}}$-$\log g$-diagram. The current state-of-the-art post-AGB evolutionary tracks, first presented by Miller Bertolami et al. (2006a), as well as the positions of known PG1159 stars, are adopted from Figure 3 in Miller Bertolami & Althaus (2006b, dotted lines). The masses correspond to evolutionary sequences for 0.87, 0.664, 0.609, 0.584, 0.564, 0.542, 0.53, and 0.512 $M_\odot$ from left to right. We also give lines of constant radii for the theoretical tracks (dashed lines with annotations in $R_\odot$). The position of SDSS J212531.92$-010745.9$ found by Nagel et al. (2006) is shown as a circle; the position we find from our new spectral analysis (see section 2.2) is indicated by the error ellipse.

1.3. Orbit ephemeris from photometric observations
From time-series photometry of SDSS J212531.92$-010745.9$ performed in 2005, 2006 and 2007 with the Tübingen 80 cm and the Göttingen 50 cm telescopes, Schuh et al. (2008b) find the ephemeris of the predicted maxima times to be $HJD = 2454055^{d}2134(4) + 0^{d}289822(2) \cdot E$. Further multi-colour observations are available, which show that the photometric amplitude in the optical is roughly 35% smaller in the blue than in the red.

2. Analysis of the Calar Alto 3.5 m TWIN spectroscopic data
2.1. Observational data and stellar atmosphere model grid
In 2007 we obtained time-resolved spectra with the TWIN spectrograph at the 3.5 m telescope at Calar Alto. The observations have been described in Schuh et al. (2008a): in the double-lined spectrum both sets of lines vary as expected with the orbital phase. The series of phase-resolved spectra can be used to derive radial velocity curves on the one hand, and to refine the spectral analysis (originally done on one SDSS spectrum) on the other hand. In order to do a spectral analysis of the PG 1159 component, a suitable grid of stellar model atmospheres is being calculated using NGRT (see Figure 2 for details).
Figure 2. The model atmospheres were calculated with NGRT (Werner et al. 2003). Shown are the models calculated by end of October 2008 in the log $g - T_{\text{eff}}$-plane for six different C-abundances represented by different plot symbols (squares: C/He=0.01, triangles: C/He=0.03, diamonds: C/He=0.05, crosses: C/He=0.07, asterisks: C/He=0.10, plus signs: C/He=0.13). Other elemental abundances (all by number) are fixed at N/He=0.01 and O/He=0.01. The grid is still being completed: The whole range from $T_{\text{eff}} = 60 \ldots 100$ kK in steps of 5 kK and from log ($g/\text{cm s}^{-2}$) = 5.6 \ldots 8.0 in steps of 0.2 dex will be filled with models in all six C-abundances by December 2008. Model spectra were calculated from the atmosphere models using profile and were convolved with a gauss profile to match the spectral resolution of 1.2 $\text{A}$ of the Calar Alto TWIN Spectograph in the configuration used.

2.2. Spectral analysis of the PG 1159 component
The spectra were wavelength shifted according to the radial velocity solution shown in Figure 4 and co-added, however without correcting for the phase-variable continuum contribution by the irradiated side of the companion yet, for a spectral analysis with our model grid. The median spectrum of the PG 1159 component was normalised to the continuum and cross-correlated with each normalised spectrum of the model grid. This cross-correlation was restricted to wavelength ranges where at least one of the model spectra shows significant spectral features (minimum line depth is a free parameter of this restriction; usually 1% was chosen, 3%, however, yields similar results) and where the mean companion spectrum shows no significant spectral features (the maximum line height of emission lines is another free parameter for the restriction – possible red shift differences between the two components are taken into account). Different choices of the free parameters show a stable maximum in the cross-correlation values for the median spectrum at an effective temperature of about $(72500 \pm 5000)$ K, log ($g/\text{cm s}^{-2}$) of about $7.1 \pm 0.5$ and C/He of $0.07 \pm 0.03$. The error bars quoted are very preliminary by-eye values. Two spectra from the
Figure 3. Cross-correlating specific spectral features of the Calar Alto spectra radial velocities were deduced. The three panels show three distinctive PG1159 features in the median spectrum (solid black line) along with the two model spectra (grey lines), one of which (dotted line) belongs to the model atmosphere with \( \log \left( \frac{g}{\text{cm s}^{-2}} \right) = 7.60 \) and \( T_{\text{eff}} = 90000 \text{ K} \) and \( \text{C/He} = 0.05 \) and was found as first preliminary result by Nagel et al. (2006). The solid grey line is the model spectrum with the highest cross-correlation value found by the quantitative spectral analysis with the extended model grid (\( \log \left( \frac{g}{\text{cm s}^{-2}} \right) = 7.1, T_{\text{eff}} = 72500 \text{ K}, \text{C/He} = 0.07 \)). The lowermost panel shows the narrow \( \text{CIV} \) lines used for the radial velocity determination of the PG1159 star.

model grid are shown in comparison to three spectral regions containing lines of the PG 1159 component of SDSS J212531.92−010745.9 in Figure 3. Combining the quantitative with the by-eye spectral analysis, we currently constrain the stellar parameters of the PG 1159 component to the following cuboid in parameter space: \( T_{\text{eff}} = 65000 \text{ K} \ldots 90000 \text{ K}, \log \left( \frac{g}{\text{cm s}^{-2}} \right) = 6.50 \ldots 8.00, \text{C/He} = 0.04 \ldots 0.10 \). These preliminary values were obtained as part of the diploma thesis work by Beeck (2009) and will be finalised when the model grid has been completed and the quantitative spectral analysis has been optimised.

2.3. Radial velocity curves

The radial velocity curves derived by Beeck (2009) are shown in Figure 3. Due to the individual exposure times of 30 min the spectral lines are somewhat smeared by the orbital motion, adding to the uncertainties in the determination of the radial velocities. The ratio of projected semi-amplitudes yields \( k_1/k_2 \approx m_1/m_2 \approx 1.2 \), allowing a range of mass ratios \( 1.0 \ldots 1.5 \). Although we find a shift of the zero point of the PG 1159’s velocity curve with regard to the companion’s
Figure 4. Radial velocity curves for the PG 1159 star (triangles, light gray) and the companion (diamonds, black) determined from spectra obtained with TWIN at Calar Alto. The best fit sine curves yield semi-amplitudes of $k_1 = 94.3 \pm 15.0 \text{ km s}^{-1}$ for the PG 1159 (light gray sine curve) and $k_2 = 113.0 \pm 3.0 \text{ km s}^{-1}$ for the companion (black sine curve). The zero points of the two velocity curves are shown as dashed lines, the dotted lines indicate their uncertainties. The shift of the zero points relative to each other by about 11 km s$^{-1}$ could be explained by gravitational redshift of the PG 1159 star but is not significant.

3. Phase resolved light curve and spectral modelling

3.1. Light curve modelling with NIGHTFALL and PHOEBE

With the known orbital period $P$ and projected radial velocities $k_1$, $k_2$ measured from spectroscopy, in principle the only value the light curve modelling still needs to provide is the inclination $i$ to obtain the mass: $m_1 \sin^3 i = \frac{P}{2 \pi \sigma} \frac{(k_1 + k_2)^3}{1 + k_1 k_2}$ (similarly for $m_2$).

At an assumed value for the inclination of 40°, the photometric variation can be fit using PHOEBE as shown in Figure 5; further independent considerations to constrain the inclination are not overwhelmingly helpful (Figure 6). The best value will be determined from a comprehensive parameter study, including a comparison of results from NIGHTFALL and PHOEBE (Beeck 2009).
Figure 5. The observed light curve of all nights from 2005 to 2007 folded onto the orbital period and the simulated light curve of a binary system, consisting of a PG 1159 star and a heated M dwarf, calculated with PHOEBE for $m_1=0.55 M_\odot$, $\log (g/\text{cm s}^{-2})=7.1$, $R_1=0.035 R_\odot$ (black line).

3.2. Challenges in the modelling approach and additional constraints
All the light curve solutions are obtained under the simplifying assumptions of bound rotation and a circular orbit. Further complications arise from the choice of the albedo value in particular for the companion which is unknown and possibly larger than 1 in the relevant wavelength range due to redistribution, large uncertainties in the physical modelling of reflection effect, and a formal limitation inherent to PHOEBE where the maximum $T_{\text{eff}}$ currently available is 50 000 K.

Constraints for the many parameters governing a light curve simulation will come from the spectral analysis not only of the PG 1159, but also from irradiated spectra calculated using PHOENIX to model the hot side of the companion. A particularly strong additional constraint would come from a good determination of the gravitational redshift for the PG 1159 star.

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Figure 6. Using the photometric period and the mass ratio from the radial velocity amplitudes, the masses can be obtained as a function of the inclination. For the radial velocity curve solution in Figure 4, the \((m_1,m_2)\) pairs lie on the line (error range: dashed) shown above, with \(m_{1,\text{min}} = 0.15 \, M_{\odot}\) and \(m_{2,\text{min}} = 0.12 \, M_{\odot}\). The dark areas mark forbidden ranges of the inclination: \(m_1 < 1.44 \, M_{\odot}\) requires \(i > 20^\circ\), and the fact that the system is not eclipsing sets a limit of \(i < 80^\circ\), implying \(m_1 > 0.15 \, M_{\odot}\); more stringent constraints are clearly required. A comparison with the evolutionary tracks in Figure 1 (although these may not be appropriate for a presumed PCEB system) favours a higher inclination (lower masses) than assumed in Figure 5.

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