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The Subdwarf B + White Dwarf Binary KPD 1930 + 2752, a Supernova Type Ia Progenitor Candidate

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Abstract. The nature of the progenitors of type Ia supernovae is still under controversial debate. KPD 1930+2752 is one of the best SN Ia progenitor candidates known today. The object is a double degenerate system consisting of a subluminous B (sdB) star and a massive white dwarf. Maxted, Marsh, & North (2000) conclude that the system mass exceeds the Chandrasekhar mass. This conclusion rests on the assumption that the sdB mass is $0.5\,M_\odot$. However, recent binary population synthesis calculations suggest that the mass of an sdB star may range from $0.3\,M_\odot$ to more than $0.7\,M_\odot$. It is therefore important to measure the mass of the sdB star simultaneously with that of the white dwarf. Since the rotation of the sdB star is tidally locked to the orbit the inclination of the system can be constrained. An analysis of the ellipsoidal variations in the light curve allows to tighten the constraints derived from spectroscopy. We derive the mass–radius relation for the sdB star from a quantitative spectral analysis. The projected rotational velocity is determined for the first time from high-resolution spectra. In addition a reanalysis of the published light curve is performed. The atmospheric and orbital parameters are measured with unprecedented accuracy. In particular the projected rotational velocity $v_{\rm rot}\sin i = 92.3 \pm 1.5\ {\rm km\,s^{-1}}$ is determined. The mass of the sdB is limited between $0.45\ M_\odot$ and $0.52\ M_\odot$. The total mass of the system ranges from $1.36\ M_\odot$ to $1.48\ M_\odot$ and hence is likely to exceed the Chandrasekhar mass. So KPD 1930 + 2752 qualifies as an excellent double degenerate supernova Ia progenitor candidate.

1. Introduction

Supernovae of type Ia (SN Ia) play an important role in the study of cosmic evolution. They are regarded as the best standard candles for the determination of the cosmological parameters. The nature of their progenitors is still under debate. There is general consensus that only the thermonuclear explosion of a white dwarf (WD) is compatible with the observed features of SN Ia. A white dwarf has to accrete mass from a close companion to reach the Chandrasekhar limit of $1.4\,M_\odot$. Two main scenarios of mass transfer are currently under discussion. In the so-called single degenerate (SD) scenario (Whelan & Iben 1973), the mass donating component is a red giant/subgiant, which fills its Roche lobe and is continually transferring mass to the white dwarf. According to the so-called double degenerate (DD) scenario (Iben & Tutukov 1984) the mass donating companion is a white dwarf, which eventually merges with the primary due to orbital shrinkage caused by gravitational wave radiation. KPD 1930 + 2752 was identified as a pulsating subdwarf B star (sdBV). Multiperiodic variations with short periods and low amplitudes were detected. In addition to these pulsations a strong variation at a much longer period of about 4100 s was found. This variation could be identified as an ellipsoidal deformation of the sdB star most likely caused by a massive companion. Billères et al. (2000) predicted the period of the binary to be two times the period of this brightness variation. This was proven by Maxted et al. (2000), who measured a radial velocity curve of KPD 1930 + 2752 which matched the proper period. The radial velocity amplitude combined with an assumption of the canonical mass for sdB stars $M_{\rm sdB} = 0.5\,M_\odot$ led to a lower limit for the mass of the system derived from the mass function. This lower limit $M \geq 1.47\,M_\odot$ exceeded the Chandrasekhar mass of $1.4\,M_\odot$. The system is considered to become double degenerate when the subdwarf eventually evolves to a white dwarf. Orbital shrinkage caused by gravitational wave radiation will lead to a merger of the binary. Maxted et al. concluded that KPD 1930 + 2752 could be a good candidate for the progenitor of a type Ia supernova.

This conclusion rests on the assumption that the mass of the primary is $0.5\,M_\odot$. SdB stars have been identified as core helium burning stars at the blue end of the horizontal branch. According to canonical stellar evolution the mass is fixed by the onset of the core helium flash to about half a solar mass (Heber 1986). However, binary population synthesis calculations (Han et al. 2003) suggest, that the mass range for sdB stars is much wider, ranging from $0.3\,M_\odot$ to more than $0.7\,M_\odot$. Therefore we aim at measuring the mass of the sdB star simultaneously with that of the white dwarf. Since the rotation of the sdB star is tidally locked to the orbit the inclination of the system can be constrained, if the sdB radius and the projected rotational velocity can be measured with high precision. An analysis of the ellipsoidal variations in the light curve allows to tighten the constraints derived from spectroscopy. We derive the mass–radius relation for the sdB star from a quantitative spectral analysis. The projected rotational velocity is determined for the first time from high-resolution spectra. In addition a reanalysis of the published light curve is performed.

2. Observations and Data Analysis

With the 10 m Keck I Telescope at the Mauna Kea Observatory two hundred high-resolution spectra were obtained using the High Resolution Echelle Spectrometer (HIRES). Two spectra were taken with the ESO Very Large Telescope UT2 (Kueyen) equipped with the UV-Visual Echelle Spectrograph (UVES). Additional 150 low-resolution spectra were obtained with the 2.2 m Telescope at the Calar Alto Observatory using the Calar Alto Faint Object Spectrograph (CAFOS). The data was reduced using the ESO–MIDAS package. The radial velocities were obtained by cross correlation with a model spectrum at rest wavelength. Combining with data from literature we derive: $K = 341 \pm 1\,{\rm km\,s^{-1}}$, $P = 0.0950933 \pm 0.0000015$ d.

For the analysis of the spectra of KPD 1930+2752 we used LTE model grids for 10 times solar metallicity. As the surface gravity is of utmost importance for our analysis we also calculated new grids of models and synthetic spectra to account for NLTE effects and metal line blanketing simultaneously. The mean parameter values from the model atmosphere fits are: $T_{\rm eff} = 35\,200 \pm 500\,{\rm K}$ and $\log g = 5.61 \pm 0.06\,{\rm dex}$.

The primary aim of the high-resolution time-series spectroscopy was to measure the projected rotational velocity of KPD $1930 + 2752$ as accurately as possible. For this purpose the spectra obtained with HIRES and UVES were used. The projected rotational velocity was measured by convolving a synthetic spectrum calculated from the best fit model atmosphere with a rotational broadening ellipse for appropriate $v_{\rm rot} \sin i$ (see Figure 1). The result is very accurate: $v_{\rm rot} \sin i = 92.3 \pm 1.5\,{\rm km\,s^{-1}}$.

3. Mass and Inclination

KPD $1930 + 2752$ is obviously affected by the gravitational forces of the companion, demonstrated by its ellipsoidal deformation. Since the period of the photometric variations is exactly half the period of the radial velocity variations the rotation of the sdB star is tidally locked to the orbit. Having determined the gravity and projected rotational velocity, we have three equations at hand that constrain the system, with the sdB mass $M_{\rm sdB}$ being the only free parameter. Besides the mass function

$$f(M_{\rm sdB}, M_{\rm comp}) = \frac{M_{\rm comp}^3 (\sin i)^3}{(M_{\rm sdB} + M_{\rm comp})^2} = \frac{K_{\rm sdB}^2 P}{2\pi G} \qquad (1)$$

these are

$$\sin i = \frac{v_{\rm rotsini} P}{2\pi R} \qquad (2)$$

$$R = \sqrt{\frac{M_{\rm sdB} G}{g}} \qquad (3)$$

With log g obtained from the model atmosphere analysis, the radius of the star R was calculated using the standard mass–radius relation (Eq. 3). Together with the orbital period of the system P and the projected rotational velocity $v_{\rm rotsini} = v_{\rm rot} \sin i$ the inclination of the system $\sin i$ was derived for different values of the sdB mass. Because the rotation is tidally locked to the orbit, the rotational period of the sdB equals the orbital period of the system. Therefore the absolute value of the rotational velocity could be calculated. From the measured projected rotational velocity the inclination of the system follows (Eq. 2). With the sdB mass as a free parameter, the measured radial velocity semi-amplitude $K_{\rm sdB}$ and orbital period P the mass function was solved numerically (Eq. 1) to derive the mass of the companion $M_{\rm comp}$ and calculate the total mass of the binary. The fact that $\sin i$ cannot exceed unity gave a lower limit for the mass of the sdB $M_{\rm sdB} \geq 0.45\,M_\odot$. The total mass of the system exceeds the Chandrasekhar limit for almost all assumptions of $M_{\rm sdB}$. The inclination angle of the system is close to 90° implying that KPD $1930 + 2752$ may be an eclipsing binary.

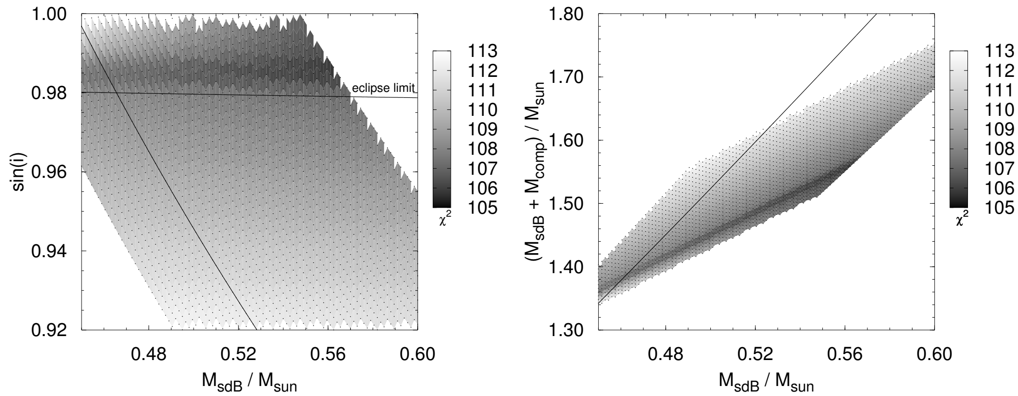

Figure 1. The left figure shows the $\sin i$ as a function of sdB mass. The full drawn line marks the solution derived from spectroscopy, the dashed lines the associated errors in $\sin i$. Each dot denotes the location of a parameter set for which a light curve has been calculated. The background shading corresponds to the quality of the fit – darker shading implying better χ^2. The similar figure in the right shows the secondary mass as a function of the sdB mass.

4. Constraints by Photometry

The light curve obtained by Billères et al. (2000) shows ellipsoidal variations. We used this information to further constrain the parameters of the KPD 1930+2752 system. We employed the light curve synthesis and solution code MORO which is based on the model by Wilson & Devinney (1971). A very fine grid of synthetic light curves was constructed, containing more than 76000 parameter combinations. Indeed, a significant overlap between the spectroscopically determined parameter range and a set of very good light curve fits could be found. Most notable is the coincidence of the best fits with the region of eclipse ($i \approx 80°$) (see Figure 1). If we combine the results of the photometric analysis with the mass–inclination relation derived from spectroscopy, the sdB mass is constrained to a very narrow range of $M_{\rm sdB} = 0.45 - 0.52\,M_\odot$, corresponding to a total mass of $1.36 - 1.48\,M_\odot$ (cf. Figure 1).

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