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KPD 1930+2752: a candidate Type Ia supernova progenitor

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ABSTRACT

We present spectra of the pulsating sdB star KPD 1930 + 2752 which confirm that this star is a binary. The radial velocities measured from the Hα and He I 6678-Å spectral lines vary sinusoidally with the same period (2 h 17 min) as the ellipsoidal variability seen by Billères et al. The amplitude of the orbital motion ($349.3 \pm 2.7\,\mathrm{km\,s^{-1}}$) combined with the canonical mass for sdB stars ($0.5\,\mathrm{M_{\odot}}$) implies a total mass for the binary of $1.47 \pm 0.01\,\mathrm{M_{\odot}}$. The unseen companion star is almost certainly a white dwarf star. The binary will merge within ~200 million years because of gravitational wave radiation. The accretion of helium and other elements heavier than hydrogen on to the white dwarf, which then exceeds the Chandrasekhar mass ($1.4\,\mathrm{M_{\odot}}$), is a viable model for the cause of Type Ia supernovae. KPD 1930 + 2752 is the first star to be discovered that is a good candidate for the progenitor of a Type Ia supernova of this type, which will merge on an astrophysically interesting time-scale.

Key words: binaries: spectroscopic – stars: individual: KPD 1930 + 2752 – subdwarfs – supernovae: general.

1 INTRODUCTION

Type Ia supernovae (SNe Ia) are one of the most important tools for observational cosmology because there appears to be a relatively small spread in their peak optical brightness around $M_V = -19.6$ and they can be seen out to cosmological distances ($z \sim 1$) so they can be used to measure cosmological parameters, e.g. the cosmological constant Λ (Riess et al. 1998; Perlmutter et al. 1999). However, the peak optical brightnesses of SNe Ia are not uniform; they are correlated with the shape of the light curve and vary by about 1 mag. Meaningful measurements of cosmological parameters require this variation to be calibrated, e.g. the non-zero value of Λ measured by Perlmutter et al. is required by supernovae at $z \sim 0.5$ being about 0.3 mag too bright compared with the case of a non-accelerating ($\Lambda = 0$) universe. The corrections to peak brightnesses have to be empirical because it is still not yet clear what causes SNe Ia.

Type Ia supernovae near maximum light show no hydrogen or helium lines but do show strong silicon lines. The absence in the spectrum of the two most common elements in the Universe dramatically reduces the number of potential progenitors, as does their appearance in old stellar populations, e.g. elliptical galaxies. All the most likely models for progenitors feature an accreting white dwarf (Leibundgut 2000; Branch et al. 1995) which ignites carbon in its core either because it has reached the Chandrasekhar mass ($1.4\,\mathrm{M_{\odot}}$) or because ignition of accumulated helium causes compression of the core and a so-called 'edge-lit detonation'. This explains the fast rise times for SNe Ia, the lack of hydrogen and helium and the fairly uniform peak brightness. To initiate the explosion, the white dwarf must accrete material from a companion star. Two models for the companion star which have gained popularity in recent times are supersoft sources and double degenerates.

Supersoft sources are white dwarfs that accrete hydrogen from a non-degenerate star at a rate just sufficient to support steady nuclear burning on the surface of the white dwarf (Kahabka & van den Heuvel 1997). This leads to an accumulation of material on the white dwarf, but it is not clear whether or not the accretion rate stays within the required range sufficiently long for an SNe Ia explosion to result, or that there are a sufficient number of these binaries to explain the observed rate of SNe Ia. Neither is it clear that these binaries have a sufficiently long lifetime to be observed in elliptical galaxies (Yungelson et al. 1995; Yungelson & Livio 2000).

The double degenerate model posits two white dwarfs with an orbital period of a few hours which merge because of the loss of gravitational wave radiation. Two drawbacks with this model have been a poor understanding of how such a detonation might be initiated and the lack of observed progenitors. There are now many double degenerates known (Marsh, Dhillon & Duck 1995; Moran, Marsh & Bragaglia 1997; Moran, Maxted & Marsh 2000) but none has both a sufficiently short orbital period and a total mass in excess of $1.4\,\mathrm{M_{\odot}}$. However, at least one good candidate for the progenitor of an edge-lit detonation is known (WD 1704 + 481.2; Maxted et al. 2000).

KPD 1930 + 2752 was identified as a subdwarf-B (sdB) star in the Kitt Peak–Downes survey of UV excess objects near the Galactic plane (Downes 1986). Photometry in the Cousins *BVRI*

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system by Allard et al. (1994) and Strömgren photometry by Wesemael et al. (1992) revealed nothing exceptional about this star other than that it has a low reddening and that there is no evidence for a companion to this star. Of the 100 subdwarfs in the study of Allard et al. 31 show evidence for a companion, which, when some estimate of the selection effects is made, suggests that more than half of these stars are binaries.

The binary fraction of sdB stars is a matter of some interest because the properties of these stars suggest that they have lost a substantial fraction of their mass, perhaps because of interactions with a companion star (Heber 1986; Saffer et al. 1994; Iben & Livio 1993). In addition to the composite spectrum binaries identified by Allard et al. several binary sdB stars have been identified from the Doppler shift of the spectral lines resulting from the orbital motion (Saffer, Livio & Yungelson 1998). This technique has the advantage of being sensitive to the companion star whatever its type, and can detect sdB stars with white dwarf companions that would be missed by almost any photometric technique. Direct evidence for white dwarf companions to sdB stars is seen in the eclipsing sdB–white dwarf binary KPD 0422 + 5421 (Orosz & Wade 2000).

Other clues to the properties of sdB stars comes from the EC 14026 stars – sdB stars showing p-mode pulsations with periods of a few minutes (Koen et al. 1998; Fontaine et al. 1998; O'Donoghue et al. 1999). High-speed photometry by Billères et al. (2000) identified KPD 1930 + 2752 as the fourteenth EC 14026 star known. The photometry also showed variability with a period of 2 h 17 min with an amplitude of 1.4 per cent. This is much longer than the pulsation periods of EC 14026 stars. The light curve folded on this period shows an almost sinusoidal variation with two minima per cycle, but with one minimum being slightly deeper than the other. This was interpreted as being the ellipsoidal variation arising from the rotation of a star distorted by the presence of a companion star.

In this paper we present spectroscopy of the the Hα and He I 6678-Å spectral lines which confirms that KPD 1930 + 2752 is a binary star with an orbital period of 2 h 17 min. We also show that the total mass of the binary exceeds the Chandrasekhar mass and conclude that KPD 1930 + 2752 is the first good candidate Type Ia supernova progenitor that will explode because of the accretion of helium and other elements heavier than hydrogen on to a white dwarf on an astrophysically interesting time-scale.

2 OBSERVATIONS AND REDUCTIONS

Observations were obtain with the Isaac Newton Telescope at the Observatario Roque de los Muchachos on the Island of La Palma. We used the Intermediate Dispersion Spectrograph with the 500-mm camera, a 1200 line mm^{-1} grating and a TEK charge-coupled device detector to obtain 25 spectra of KPD 1930 + 2752 covering 400 Å around the Hα line with a dispersion of 0.39 Å pixel^{-1}. The resolution measured from the full width at half maximum of the arc lines is 0.9 Å. All the spectra were obtained in a single run of observations of just over 2 h on the morning of 2000 April 17. The slit width used was 0.97 arcsec, which was well matched to the seeing estimated from the spatial profile of the spectra of around 1.3 arcsec. Observations of a CuNe arc were obtained before and after the run of observations and every 25 min in between. The exposure time used for all the spectra was 300 s.

Extraction of the spectra from the images was performed automatically using optimal extraction to maximize the signal-to-noise ratio of the resulting spectra (Horne 1986). The arcs associated with each stellar spectrum were extracted using the same weighting determined for the stellar image to avoid possible systematic errors caused by tilted spectra. The wavelength scale was determined from a fourth-order polynomial fit to measured arc-line positions. The standard deviation of the fit to the eight spectral lines was typically 0.09 Å. The wavelength scale for an individual spectrum was determined by interpolation to the time of mid-exposure from the fits to arcs taken before and after the spectrum to account for the small amount of drift in the wavelength scale (<0.1 Å) caused by flexure of the instrument. Statistical errors on every data point calculated from photon statistics are rigorously propagated through every stage of the data reduction.

3 THE SPECTROSCOPIC ORBIT

Visual inspection of the Hα and He I 6678-Å spectral lines shows clearly the Doppler motion expected from a binary star with an orbital period of 2 h 17 min with a semi-amplitude of $\sim$350 km s^{-1}, confirming the interpretation of Billères et al. To obtain a more accurate value of for the semi-amplitude of the orbit, we created a model of the spectrum composed of three Gaussian profiles for the Hα line and a single Gaussian profile for the He I 6678 Å line. We used a least-squares fit to the first spectrum to obtain an initial estimate of the shape of the model spectrum. We then fixed the shape of the model spectrum and varied only the position of the lines in a least-squares fit to each of the spectra to obtain an initial estimate of the radial velocity from each spectrum. These radial velocities are shown in Fig. 1. The spectra were normalized prior to fitting using a quadratic fit to the continuum either side of the Hα and He I 6678-Å spectral lines. Only data in the range 6500–6675 Å were included in the fit.

We then used a simultaneous least-squares fit to all the spectra to determine the best profile shape and to determine the spectroscopic orbit simultaneously. The position of the model profile varies from spectrum to spectrum according to the radial velocity predicted by $\gamma + K \sin[(T - T_0)/P]$, where γ is the systemic velocity, K is the projected orbital speed, T is the time of mid-exposure of the spectrum and P is the orbital period. We fixed the value of P at the value given by Billères et al. (8217.8 s = 0.095111 d) because this value is much more accurately determined by their photometry than can be done from our spectroscopy. The time T_0 corresponds to the point in the orbit when the sdB star is closest to the observer. The smearing of the spectra resulting from the motion during the exposure is incorporated into the model. We used independent values of γ for the Hα and He I 6678-Å spectral lines to allow for any difference arising from pressure shifts. There are many free parameters in this fit, so we first varied the parameters in the spectroscopic orbit while holding the model profile fixed and then vice versa so all the parameters were near their optimum values. We then varied all the parameters to find the solution given in Table 1. The fit to the data is very good, judged both by the value of χ^2 and visual inspection of the residuals.

4 PHYSICAL PROPERTIES OF THE BINARY

The projected orbital speed, $K = 349.3 \pm 2.7$ km s^{-1}, and orbital period, 2 h 17 min, immediately imply a minimum mass for the unseen companion star of $0.42 \pm 0.01\,M_{\odot}$. More realistically, the measured effective temperature and surface gravity of KPD

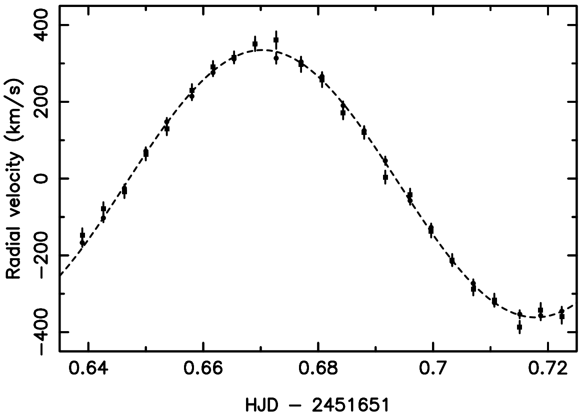

Figure 1. Measured radial velocities for KPD 1930 + 2752 from the Hα line (circles) and the He I 6678-Å line (squares). Also shown is the sinusoidal fit (dashed line) used to find good estimates of the amplitude and systemic velocity for the simultaneous fit to all the spectra.

1930 + 2752 ($T_{\rm eff} = 33\,000$ K, $\log g = 5.61$) is typical for sdB stars and places it squarely in the region of the $T_{\rm eff}$–$\log g$ plane occupied by models of core helium-burning stars with masses of 0.5 M$_\odot$ and very thin hydrogen envelopes (<0.02 M$_\odot$, Saffer et al. 1994), in which case the mass of the companion star is at least 0.97 ± 0.01 M$_\odot$. The light curve of KPD 1930 + 2752 observed by Billères et al. after removal of the signal resulting from pulsations is shown in Fig. 2. The quasi-sinusoidal signal with unequal minima characteristic of a star distorted by a close companion is apparent. We can produce a model light curve using the physical parameters derived above and assuming that the orbital inclination is 90°. The radius of the sdB star implied by the surface gravity and canonical mass is 0.18 ± 0.01 R$_\odot$ and the separation of the stars is 0.98 R$_\odot$. The orbit is far too small to contain a normal star of 0.97 ± 0.01 M$_\odot$ or more, so we assume that the unseen companion is a white dwarf star. Other parameters of the model are the gravity-darkening exponent of the sdB star, for which we assume the standard value appropriate for radiative stars, and the limb-darkening. The light curve was obtained with a blue-sensitive detector, so we use a linear limb-darkening coefficient of 0.29, which is the mean of the values for *U* and *B* filters for a $\log g = 5$, $T_{\rm eff} = 33\,000$ model atmosphere given by Diaz-Cordoves, Claret & Gimenez (1995). The precise value of the limb-darkening or gravity-darkening exponent used has very little effect on the light curve. An additional effect included in the model is the Doppler boosting arising from the high orbital velocity. This effect increases the total flux by a factor $[1 - v(t)/c]^3$, where v is the radial velocity at time t and c is the speed of light. This effect is counteracted by the Doppler shift, which reduces the effect by a factor $[1 - v(t)/c]^2$ for observations on the Rayleigh–Jeans tail of a blackbody spectrum, which is a good approximation to the spectrum of KPD 1930 + 2752 in the optical region. The overall effect is to make the maxima of the light curve asymmetric. This is shown in Fig. 2 by plotting a model light curve both with and without Doppler boosting. The agreement between either model and the observed light curve is excellent. Note that that there has been no attempt made to optimize the parameters of the model; the light curve is prediction based purely on the measured surface gravity, effective temperature and orbital velocity together with the assumption that the mass of the sdB star is 0.5 M$_\odot$ and that the inclination is 90°. One effect excluded from our model is the transit of the companion star across the face of the sdB star. If the companion is a white dwarf star, its radius will be approximately 0.01 R$_\odot$ so the eclipse depth will be about $(0.01/0.18)^2 = 0.3$ per cent. There is a hint of just such a feature at the correct phase (0.5) in the light curve, but improved photometry will be required to confirm this feature.

Table 1. Results of the simultaneous fit to all the spectra for the model spectrum and the spectroscopic orbit. Note that the model profile is convolved with a Gaussian of width 0.9 Å prior to fitting to account for the instrumental resolution. Parameters shown in bold type are fixed quantities in the fitting process.

γ (Hα) (km s^{-1})	−13.9±2.2
γ (He I 6678 Å) (km s^{-1})	−12.2±3.7
K (km s^{-1})	349.3±2.7
HJD (T_0)	245 1651.6466±0.0001
P (d)	**0.095111**
Gaussian 1	
Rest wavelength (Å)	**6562.76**
FWHM (Å)	4.2±0.3
Depth	0.141±0.007
Gaussian 2	
Rest wavelength (Å)	**6562.76**
FWHM (Å)	16.1±0.5
Depth	0.161±0.006
Gaussian 3	
Rest wavelength (Å)	**6562.76**
FWHM (Å)	148±13
Depth	0.077±0.013
Gaussian 4	
Rest wavelength (Å)	**6678.149**
FWHM (Å)	3.0±0.2
Depth	0.115±0.007
No. of data points	14 473
χ^2	14 067.65

5 DISCUSSION

KPD 1930 + 2752 is very similar to the star KPD 0422 + 5421,

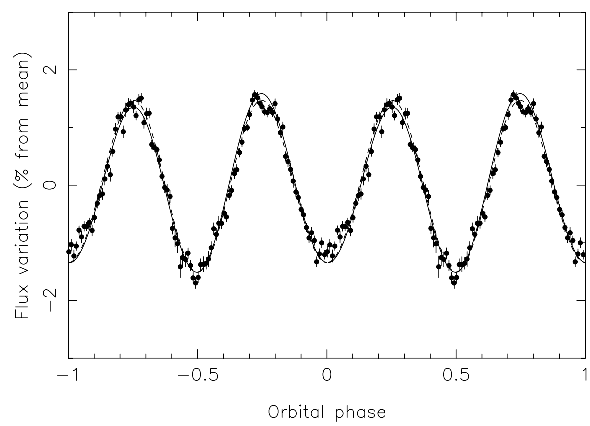

Figure 2. The light curve of KPD 1930 + 2752 after removal of the signal arising from pulsations from Billères et al. (2000) with a model light curve (solid line) for the ellipsoidal variability, assuming an inclination of 90°. The model light curve excluding Doppler boosting is shown as a dashed line.

which is an sdB–white dwarf binary with an orbital period of 2.16 h and projected orbital speed of $237 \pm 18\,\mathrm{km\,s^{-1}}$ (Orosz & Wade 2000). The ellipsoidal variation in KPD 0422 + 5421 has almost exactly the same amplitude as that seen KPD 1930 + 2752 and the transit of the white dwarf across the face of the sdB star is seen in high-quality light curves.

Of course, the larger orbital velocity of KPD 1930 + 2752 implies a larger total mass for this binary than KPD 0422 + 5421. The total mass of KPD 1930 + 2752 assuming that the sdB star has a mass of $0.5\,\mathrm{M_\odot}$ is at least $1.47 \pm 0.01\,\mathrm{M_\odot}$. The significance of this result is that the total mass exceeds the Chandrasekhar limit for white dwarfs ($1.40\,\mathrm{M_\odot}$; Hamada & Salpeter 1961). KPD 1930 + 2752 will merge within about 200 million years owing to a combination of orbital shrinkage through gravitational wave radiation and the evolutionary expansion of the sdB star. Thus, KPD 1930 + 2752 is the first star to be discovered that is a good candidate for the progenitor of a Type Ia supernova arising from accretion of helium and other elements heavier than hydrogen on to the white dwarf, which then exceeds the Chandrasekhar mass.

6 CONCLUSION

We have confirmed the conclusion of Billères et al. that KPD 1930 + 2752 is a binary star in which the sdB star shows ellipsoidal variability and the orbital period is 2 h 17 min. The amplitude of the orbital motion ($349.3 \pm 2.7\,\mathrm{km\,s^{-1}}$) combined with the canonical mass for sdB stars ($0.5\,\mathrm{M_\odot}$) implies a total mass for the binary of $1.47 \pm 0.01\,\mathrm{M_\odot}$. The unseen companion star is almost certainly a white dwarf star. The binary will merge within ~200 million years because of gravitational wave radiation. The accretion of helium and other elements heavier than hydrogen on to the white dwarf, which then exceeds the Chandrasekhar mass ($1.4\,\mathrm{M_\odot}$), is a viable model for the cause of Type Ia supernovae. KPD 1930 + 2752 is the first star to be discovered that is a good candidate for the progenitor of a Type Ia supernova of this type, which may explode on an astrophysically interesting time-scale.

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