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 HeI 6678Å spectral lines vary sinusoidally with the same period (2$h^{17}m$) as the ellipsoidal variability seen by Billères et al. (2000). The amplitude of the orbital motion (349.3±2.7 km s$^{-1}$) combined with the canonical mass for sdB stars (0.5$M_\odot$) implies a total mass for the binary of 1.47±0.01$M_\odot$. The unseen companion star is almost certainly a white dwarf star. The binary will merge within ∼200 million years due to gravitational wave radiation. The accretion of helium and other elements heavier than hydrogen onto the white dwarf which then exceeds the Chandrasekhar mass (1.4$M_\odot$) is a viable model for the cause of Type Ia supernovae. KPD 1930+2752 is the first star to be discovered which is a good candidate for the progenitor of a Type Ia supernova of this type which will merge on an astrophysically interesting timescale.

Key words: stars: subdwarfs – binaries: spectroscopic – stars: individual: KPD 1930+2752 – 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∼1) so they can be used to measure cosmological parameters, e.g., the cosmological constant, Λ (Perlmutter et al. 1999). However, the peak optical brightnesses of SNe Ia are not uniform, they are correlated with the shape of the lightcurve and vary by about one magnitude. 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<0.5 being about 0.3 magnitudes too bright compared to a non-accelerating (Λ=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$M_\odot$) 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 super-soft sources and double degenerates.

Super-soft sources are white dwarfs which 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 a 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 & Livio 2000; Yungelson et al. 1995).

The double degenerate model posits two white dwarfs with an orbital period of a few hours which merge due to 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 have both a sufficiently short orbital period and a total mass in excess
of 1.4\textit{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 \textit{BVRI} 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 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 they have lost a substantial fraction of their mass, perhaps due to 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 due to the orbital motion (Saffer, Livio & Yongelson 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 which 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 \textit{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 14th EC 14026 star known. The photometry also showed variability with a period of 2\textperiodcentered17m with an amplitude of 1.4 percent. This is much longer than the pulsation periods of EC 14026 stars. The lightcurve 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 due to the rotation of a star distorted by the presence of a companion star.

In this paper we present spectroscopy of the the Ho and Hε6678Å spectral lines which confirms that KPD 1930+2752 is a binary star with an orbital period of 2\textperiodcentered17m. 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 which will explode due to the accretion of helium and other elements heavier than hydrogen onto a white dwarf on an astrophysically interesting timescale.

3 THE SPECTROSCOPIC ORBIT

Visual inspection of the Ho and Hε6678Å spectral lines shows clearly the Doppler motion expected from a binary star with an orbital period of 2\textperiodcentered17m with a semi-amplitude of \textasciitilde350 km s\textsuperscript{-1}, confirming the interpretation of Billères et al. To obtain a more accurate value of the semi-amplitude of the orbit, we created a model of the spectrum composed of three Gaussian profiles for the Ho line and a single Gaussian profile for the Hε6678Å 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 normalised prior to fitting using a quadratic fit to the continuum either side of the Ho and Hε6678Å spectral lines. Only data in the range 6500–6675Å 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 + \textit{K} \sin((\textit{T} - \textit{T}_0)/\textit{P}), where \gamma is the systemic velocity, \textit{K} is the projected orbital speed, \textit{T} is the time of mid-exposure of the spectrum and \textit{P} is the orbital period. We fixed the value of \textit{P} at the value given by Billères et al. (8217.8s = 0.005111d) since this value is much more accurately determined by their photometry than can be done from our spectroscopy. The time \textit{T}_0 corresponds to the point in the orbit when the sdB star is closest to the observer. The smearing of the spectra due to the motion during

2 OBSERVATIONS AND REDUCTIONS

Observations were obtain with the Isaac Newton Telescope at the Observatorio Roque de los Muchachos on the Island of La Palma. We used the Intermediate Dispersion Spectrograph with the 500mm camera, a 1200 lines/mm grating and a TEK charged-coupled device detector to obtain 25 spectra of KPD 1930+2752 covering 400Å around the Ho line with a dispersion of 0.39Å per pixel. The resolution measured from the full-width at maximum of the arc lines is 0.9Å. All the spectra were obtained in a single run of observations of just over 2 hours on the morning of 17 April 2000. The slit width used was 0.97 arcsec, which was well matched to 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 minutes in-between. The exposure time used for all the spectra was 300s.

Extraction of the spectra from the images was performed automatically using optimal extraction to maximize the signal-to-noise 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 due to 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 8 spectra lines was typically 0.09Å. 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 (<0.1Å) due to flexure of the instrument. Statistical errors on every data point calculated from photon statistics are rigorously propagated through every stage of the data reduction.
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\AA prior to fitting to account for the instrumental resolution. Parameters shown in bold type are fixed quantities in the fitting process.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ (H\alpha) (km s$^{-1}$)</td>
<td>$-13.9 \pm 2.2$</td>
</tr>
<tr>
<td>$\gamma$ (HeI 6678\AA) (km s$^{-1}$)</td>
<td>$-12.2 \pm 3.7$</td>
</tr>
<tr>
<td>$K$ (km s$^{-1}$)</td>
<td>$349.3 \pm 2.7$</td>
</tr>
<tr>
<td>HJD($T_0$)</td>
<td>$2451651.6466 \pm 0.0001$</td>
</tr>
<tr>
<td>$P$ (days)</td>
<td>$0.095111$</td>
</tr>
<tr>
<td>Gaussian 1 Rest wavelength (\AA)</td>
<td>$6562.76$</td>
</tr>
<tr>
<td>Gaussian 1 FWHM(\AA)</td>
<td>$4.2 \pm 0.3$</td>
</tr>
<tr>
<td>Gaussian 1 Depth</td>
<td>$0.141 \pm 0.007$</td>
</tr>
<tr>
<td>Gaussian 2 Rest wavelength (\AA)</td>
<td>$6562.76$</td>
</tr>
<tr>
<td>Gaussian 2 FWHM(\AA)</td>
<td>$16.1 \pm 0.5$</td>
</tr>
<tr>
<td>Gaussian 2 Depth</td>
<td>$0.161 \pm 0.006$</td>
</tr>
<tr>
<td>Gaussian 3 Rest wavelength (\AA)</td>
<td>$6678.149$</td>
</tr>
<tr>
<td>Gaussian 3 FWHM(\AA)</td>
<td>$3.0 \pm 0.2$</td>
</tr>
<tr>
<td>Gaussian 3 Depth</td>
<td>$0.115 \pm 0.007$</td>
</tr>
<tr>
<td>No. of data points</td>
<td>$14473$</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>$14067.65$</td>
</tr>
</tbody>
</table>

Figure 1. Measured radial velocities for KPD 1930+2752 from the H\alpha line (circles) and the HeI 6678\AA (squares) line. 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.

4 PHYSICAL PROPERTIES OF THE BINARY

The projected orbital speed, $K = 349.3 \pm 2.7$ km s$^{-1}$, and orbital period, $2^{17^m}$, 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 1930+2752 ($T_{\text{eff}}=33000 K$, $\log g = 5.61$) is typical for sdB stars and places it squarely in the region of the $T_{\text{eff}}-\log g$ 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$\pm 0.01 M_\odot$. The lightcurve of KPD 1930+2752 observed by Billères et al. after removal of the signal due to 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 lightcurve using the physical parameters derived above and assuming that the orbital inclination is 90$^\circ$. The radius of the sdB star implied by the surface gravity and canonical mass is $0.18 \pm 0.01 R_\odot$ and the separation of the stars is $0.98 R_\odot$. The orbit is far too small to contain a normal star of $0.97 \pm 0.01 M_\odot$ 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 lightcurve 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 $\log g = 5$, $T_{\text{eff}}=33000$ 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 lightcurve. An additional effect included in the model is the Doppler boosting due to the high orbital velocity. This effect increases the total flux by a factor $\left(1 - v(t)/c\right)^2$ 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 $\left(1 - v(t)/c\right)^2$ for observations on the Rayleigh-Jeans tail of a black-body 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 lightcurve asymmetric. This is shown in Fig. 2 by plotting a model lightcurves both with and without Doppler boosting. The agreement between either model and the observed lightcurve is excellent. Note that there has been no attempt made to optimize the parameters of the model, the lightcurve 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$^\circ$. 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 $0.01/0.18 = 0.3$ percent. There is a hint of just such a feature at the correct phase (0.5) in the lightcurve, but improved photometry will be required to confirm this feature.
5 DISCUSSION

KPD 1930+2752 is very similar to the star KPD0422+5421, which is an sdB–white dwarf binary with an orbital period of 2.16h and an projected orbital speed of 237±18 km s$^{-1}$ (Orosz & Wade 2000). The ellipsoidal variation in KPD0422+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 lightcurves.

Of course, the larger orbital velocity of KPD 1930+2752 implies a larger total mass for this binary than KPD0422+5421. The total mass of KPD 1930+2752 assuming that the sdB star has a mass of 0.5$M_\odot$ is at least 1.47±0.01$M_\odot$. The significance of this result is that the total mass exceeds the Chandrasekhar limit for white dwarfs (1.40$M_\odot$, Hamada & Salpeter 1961). KPD 1930+2752 will merge within about 200 million years due 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 which is a good candidate for the progenitor of a Type Ia supernova.

6 CONCLUSION

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

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