The VAST Survey – IV. A wide brown dwarf companion to the A3V star ζ Delphini

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ABSTRACT
We report the discovery of a wide comoving substellar companion to the nearby (D = 67.5 ± 1.1 pc) A3V star ζ Delphini based on imaging and follow-up spectroscopic observations obtained during the course of our Volume-limited A-Star (VAST) multiplicity survey. ζ Del was observed over a five-year baseline with adaptive optics, revealing the presence of a previously unresolved companion with a proper motion consistent with that of the A-type primary. The age of the ζ Del system was estimated as 525 ± 125 Myr based on the position of the primary on the colour–magnitude and temperature–luminosity diagrams. Using intermediate-resolution near-infrared spectroscopy, the spectrum of ζ Del B is shown to be consistent with a mid-L dwarf (L5 ± 2), at a temperature of 1650 ± 200 K. Combining the measured near-infrared magnitude of ζ Del B with the estimated temperature leads to a model-dependent mass estimate of 50 ± 15 M_Jup, corresponding to a mass ratio of q = 0.019 ± 0.006. At a projected separation of 910 ± 14 au, ζ Del B is among the most widely separated and extreme-mass ratio substellar companions to a main-sequence star resolved to date, providing a rare empirical constraint of the formation of low-mass ratio companions at extremely wide separations.

Key words: techniques: high angular resolution – techniques: spectroscopic – binaries: visual – brown dwarfs – stars: early-type – stars: individual: ζ Del.

1 INTRODUCTION
Since the discovery of the brown dwarf GJ 229 B (Nakajima et al. 1995), over a hundred examples of brown dwarf companions to main-sequence stars have been catalogued (e.g. Bird & Metchev 2010). Recent surveys designed to characterize the frequency of substellar companions to nearby stars have found a significant deficit of brown dwarf companions relative to both planetary-mass and stellar companions (Grether & Lineweaver 2006; Lafrenière et al. 2007; Vigan et al. 2012; Nielsen et al. 2013). The dearth of brown
dwarf companions is most striking when compared to known planet-hosting systems: an order of magnitude more planetary-mass companions have been discovered to date, despite being more technically challenging to detect. Understanding the frequency and properties of companions intermediate to stellar and planetary-mass companions, and determining the shape of the companion mass ratio distribution, will allow for the formation of such companions to be placed in the context of both binary star and planet formation theories (e.g. Chabrier et al. 2014).

At wide angular separations, typically greater than an arc-second, substellar companions are readily accessible to spectroscopic follow-up observations to characterize their atmospheres (e.g. Schultz et al. 1998; Leggett et al. 2008; Janson et al. 2010; Chilcote et al. 2014). These wide substellar companions represent important benchmark objects with which atmospheric and evolutionary models can be tested. By assuming coevality of the companion with the main-sequence primary, the observed degeneracies between age, mass, and luminosity for these objects can be broken (e.g. Dupuy, Liu & Ireland 2009; Kasper, Burrows & Brandner 2009; King et al. 2010; Deacon et al. 2012). Considerable effort has been made in identifying wide substellar companions to main-sequence stars, with studies utilizing both all-sky photometric surveys (e.g. Gizis et al. 2001; Pinfield et al. 2006; Faherty et al. 2010) and dedicated multi-epoch surveys (e.g. Deacon et al. 2014) discovering numerous examples, predominantly with field-age solar-type primaries.

In this paper, we report the astrometric and spectroscopic confirmation of a newly discovered wide substellar companion to the A3V star ζ Delphini (hereafter ζ Del), observed over a five-year baseline during the course of our Volume-limited A-Star (VAST) multiplicity survey (De Rosa et al. 2011, 2012, 2014). The companion to ζ Del joins the small list of known brown dwarf companions to early-type (<F0) stars: HR 7329 B (Lowrance et al. 2000), HD 100546 B (Acke & van den Ancker 2006; Mulders et al. 2013), HD 180777 B (Galland et al. 2006), HR 6037 B (Huelamo et al. 2010, discovered to be a binary brown dwarf by Nielsen et al. 2013), HIP 78530 B (Laflerrière et al. 2011), HD 1160 BaBb (Nielson et al. 2012), and κ Andromedae b (Carson et al. 2013; Bonnefoy et al. 2014a). The large majority of these substellar companions were discovered using direct-imaging techniques; precision radial velocity searches for low-mass companions to A-type stars are complicated by the limited number of metallic lines, and their broadening caused by rapid stellar rotation. With the relatively low yield of brown dwarf companions in recent large-scale surveys of nearby, young (<1 Gyr) stars, the detection of an individual companion still represents a significant advancement in our understanding of these objects.

2 PROPERTIES OF ζ DEL A

Observed as a part of our VAST multiplicity survey, ζ Del A is an A3V star (Slettebak 1954) located at a distance of 67.5 ± 1.1 pc from the Sun (van Leeuwen 2007), with $T_{\text{eff}} = 8336$ K, log (g) = 3.72 dex and a slightly subsolar metallicity of $[\text{Fe/H}] = -0.05$ (Table 2; Erspamer & North 2003). Previous speckle interferometry measurements, and the adaptive optics (AO) measurements presented here, exclude the presence of a bright ($\Delta V \lesssim 3$) stellar companion beyond 0.03 arcsec (2 au; Hartkopf & McAlister 1984), and any stellar companion to the bottom of the main sequence beyond ~0.9 arcsec (60 au). Eight substellar candidates were identified within the AO imaging presented in this study within a separation of ~15 arcsec from ζ Del A, as shown in Fig. 1. Searches for stellar companions beyond the field of view of the AO images have yielded a null result.

(Shaya & Olling 2010; De Rosa et al. 2014). ζ Del A is listed as having either a spectroscopic companion or radial velocity variations by Hartkopf & McAlister (1984), although no further spectroscopic observations could be found in the literature confirming or rejecting these variations. Hartkopf & McAlister (1984) also list the star as potentially being photometrically variable, though subsequent Hipparcos measurements exclude variability amplitudes greater than 0.01 mag (Adelman 2001). ζ Del A is not a known member of any stellar moving group or association, and is not well suited for age determination through either gyrochronology or chromospheric indicators due to the lack of surface convection zones and diminishing chromospheric activity observed for A-type stars (e.g. Barnes 2003; Mamajek & Hillenbrand 2008). An age can therefore only be estimated through a comparison of the observed and derived parameters with theoretical stellar evolution models. Two grids of models were used to estimate the age (Siess et al. 2000; Bressan et al. 2012). The position of the star on the temperature–gravity and the colour–magnitude diagrams (CMDs) was used to estimate the age, with the CMD shown in Fig. 2. The temperature and surface gravity of ζ Del A were estimated from high-resolution optical spectroscopy (Ersparmer & North 2003). Optical and near-infrared absolute magnitudes colours were computed from measurements within the Tycho2 (Høg et al. 2000) and 2MASS (Skrutskie et al. 2006) catalogues, respectively. The bolometric luminosity of ζ Del A is an A3V star (Slettebak 1954) located at a distance of 67.5 ± 1.1 pc from the Sun (van Leeuwen 2007), with $T_{\text{eff}} = 8336$ K, log (g) = 3.72 dex and a slightly subsolar metallicity of $[\text{Fe/H}] = -0.05$ (Table 2; Erspamer & North 2003). Previous speckle interferometry measurements, and the adaptive optics (AO) measurements presented here, exclude the presence of a bright ($\Delta V \lesssim 3$) stellar companion beyond 0.03 arcsec (2 au; Hartkopf & McAlister 1984), and any stellar companion to the bottom of the main sequence beyond ~0.9 arcsec (60 au). Eight substellar candidates were identified within the AO imaging presented in this study within a separation of ~15 arcsec from ζ Del A, as shown in Fig. 1. Searches for stellar companions beyond the field of view of the AO images have yielded a null result.

Figure 1. The Gemini/NIRI observation of the ζ Del system obtained on 2010 June 8 showing the location of the heavily saturated ζ Del A, the substellar companion ζ Del B (indicated) and the seven background objects used in the astrometric analysis (indicated by the arrows). The image has been processed through a median filter to reduce the significant amount of scattered light from ζ Del A. The orientation and angular scale are given for reference.
warm circumstellar material, consistent with the age estimated for ζ Del A relative to the bulk of debris disc-hosting early-type stars (Rieke et al. 2005; Su et al. 2006). No longer-wavelength Spitzer or Herschel measurements were found within the literature. The mass of ζ Del A was estimated as 2.5 ± 0.2 M⊙ based on the position of the primary on both the temperature–surface gravity and CMDs relative to mass tracks within each model grid.

3 AO IMAGING OBSERVATIONS AND RESULTS

3.1 Observations and data analysis

ζ Del was initially observed on 2008 September 8 using the NearInfraRed Imager and Spectrometer (NIRI; Hodapp et al. 2003) in combination with the ALTitude conjugate Adaptive optics for the InfraRed (ALTAIR; Herriot et al. 2000) system on the Gemini North telescope. The observing strategy consisted of a sequence of short integrations with the narrow-band Brγ filter in which the primary star remains unsaturated, followed by longer exposures in the wide-band K′ filter to achieve sensitivity to faint stellar and substellar companions. The unsaturated sequence consisted of images obtained at four dither positions on a 256 × 256 subarray of the NIRI detector, each consisting of 400 co-added frames of 0.021 s. The saturated sequence, using the full 1024 × 1024 array, also used a four-point dither pattern, at which two co-added frames of 25 s were obtained. The ALTAIR field lens was used to reduce the effect of isoplanatism.

In order to determine if any of the identified substellar companion candidates were physically bound, additional observations were obtained with Gemini/NIRI in similar configuration in 2010 and 2013. Fig. 1 shows the 2010 June 6 Gemini/NIRI observations in which the heavily saturated primary can be seen, in addition to eight candidate substellar companions. Observations were also obtained with the KIR instrument (Doyon et al. 1998) on the Canada–France–Hawaii Telescope (CFHT) in 2009 and with the Arizona Infrared Imager and Echelle Spectrograph (ARIES; McCarthy et al. 1998) on the MMT in 2013. For the CFHT/KIR observations on 2009 August 31, a sequence of 20 0.5 s exposures were taken using the narrow-band H2(ν = 1–0) filter in a four-point dither pattern on a 512 × 512 subarray of the KIR detector. This was followed by a saturated sequence of 27 60 s exposures taken using the wide-band K′ filter in a four-point dither pattern on the full 1024 × 1024 array. For the MMT/ARIES observations on 2013 September 18, a sequence of nine 0.9 s exposures were taken using the narrow-band Ks,2.99 filter, in combination with a neutral density filter, in a nine-point dither pattern. This was followed by a saturated sequence of nine 4.9 s exposures using the wide-band Ks filter in a nine-point dither pattern.

All of the images were processed through the standard near-infrared data reduction process consisting of the following steps: dark frame subtraction, division by a flat-field, bad pixel identification and removal, and sky subtraction. For the Gemini/NIRI observations, the field distortion was corrected based on the information provided on the Gemini website. The position of the primary in the unsaturated images was estimated from a Gaussian fit using the GCTRD IDL procedure, while in the saturated images the position was determined through a cross-correlation of the diffraction spikes caused by the secondary mirror supports (Lafreri et al. 2007).
For each set of observations, the images were shifted to a common centre using the measured position of the primary, and rotated such that north was up and east to the left based on the astrometric information encoded into the image headers.

3.2 Astrometry

Based on a visual inspection of the images obtained over the multiple epochs, one of the candidate substellar companions (hereafter ζ Del B) was observed to remain stationary with respect to the centroid of ζ Del A, with the remaining candidates moving with the magnitude and direction consistent with that of a background object. The relative pixel positions of each object within each of the observations were measured by comparing the centroid location of each object measured using the gCentred routine with the position of the saturated primary estimated previously. In order to convert the pixel position into an angular separation and position angle, the plate scale and orientation of each instrument were required. Comparing the pixel position of Trapezium cluster members in observations obtained in 2010 with both CFHT/KIR and Gemini/NIRI, and in 2013 with MMT/ARIES, with previous astrometric measurements (McCaughrean & Stauffer 1994), enabled a measurement of the plate scale and angle of true north for each instrument, given in Table 1.

The pixel scale and orientation of each instrument were used to convert the measured pixel offset between ζ Del A and B into an on-sky angular separation and position angle for each observation, which are listed in Table 1. This process was repeated for seven additional candidates resolved in the vicinity of ζ Del A. The astrometric motion of each candidate was measured relative to the position in the 2008 Gemini/NIRI data set. The relative change in the positions of eight candidate companions from the first epoch, plotted alongside the expected motion of a background objects based on the parallax and proper motion of ζ Del A, are shown in Fig. 3. Each subsequent measurement of ζ Del B was within the uncertainty of the original epoch, consistent with a physically bound companion. In contrast, the seven additional candidates followed the expected motion of a background object (Fig. 3). The changes in the separation and position angle of ζ Del B measured relative to the 2008 Gemini/NIRI data set are also inconsistent with the expected motion of a background objects, as shown in Fig. 4.

In order to quantify the significance of the astrometric confirmation, the χ² statistic is computed based on a comparison of the position of ζ Del B with that expected of a background object (χ²BG), and with that expected of a bound companion with no orbital motion (χ²CPM). Definitions for χ²BG and χ²CPM are given in Nielsen et al. (2012). Comparing the measured position of ζ Del B with the expected motion of a background object leads to a χ²BG = 39.38, corresponding to a reduced χ² = 6.56 with 6 degrees of freedom. The measurements are inconsistent with the hypothesis that ζ Del B is a stationary background object, with a probability derived from the χ² statistic of $P_{BG} \approx 10^{-6}$. Fitting the measurements to the expected constant separation and position angle of a bound companion yields a $\chi^2_{CPM} = 6.29$, corresponding to a reduced $\chi^2 = 1.05$. Based on the value of $\chi^2_{CPM}$, the hypothesis that ζ Del B has a fixed separation and position angle can only be accepted at a low confidence level ($P_{CPM} = 0.39$), due to the relatively small annular proper motion of ζ Del A. Whilst the confidence of the astrometric confirmation is relatively low, additional spectroscopic evidence was obtained to support the hypothesis that ζ Del B is a bound companion (Section 4).

3.3 Photometry

As the primary was saturated within all of the images in which ζ Del B was detected, it was not possible to measure a magnitude difference in an individual image. Instead, the flux from the primary was measured using aperture photometry within the short integrations.
Figure 4. The measured changes in the separation (top panel) and position angle (bottom panel) of ζ Del B relative to ζ Del A (filled points) are inconsistent with the expected change for a stationary background object (solid curve). As ζ Del A has a proper motion vector almost tangential to vector between ζ Del A and B, the expected motion of a stationary background object relative to ζ Del A at the location of ζ Del B is dominated by the change in the position angle (dθ/dt).

4 SPECTROSCOPIC OBSERVATIONS AND RESULTS

An intermediate-resolution (R ~ 1800) spectrum of ζ Del B was obtained with the Gemini Near Infrared Spectrograph (GNIRS; Elias et al. 2006) mounted on the Gemini North telescope on 2013 October 11 in order to confirm the substellar nature of the object, and reject the possibility of a background star with a similar proper motion to ζ Del A. GNIRS was operated in cross-dispersed mode, providing simultaneous coverage to wavelengths in the range 0.9-2.5 μm, using the short blue camera with the 32 lines mm⁻¹ grating and the 0.3 arcsec slit. ζ Del B was observed in an ABBA pattern, with 300 s per exposure, and a total on-source integration time of 1800 s. The slit was orientated at a position angle of 270 deg, with no contamination from ζ Del A seen within either the raw or reduced spectra. An argon lamp and a flat-field lamp were observed to measure the wavelength scale and variations in the detector response. Finally, a spectrum of the B3V star HIP 104320 (Teff = 19000 K; Cox 2000) was obtained, to correct for telluric absorption in the spectrum of ζ Del B.

The observations of ζ Del B, and the telluric calibrator, were reduced using the GNIRS-specific tools provided within the Gemini IRAF package. Cosmic rays were identified by comparing pairs of images at each dither position, and were removed by interpolating neighbouring pixels. The spectra were then divided by a flat-field, and sky-subtracted. The spectral trace was measured and corrected to straighten the spectra within the 2D images, and the wavelength solution was derived from the position of the lines within the argon lamp spectrum. The spectrum of ζ Del B, and the telluric calibrator, at each nod position was extracted using a nine pixel (1.35 arcsec) rectangular aperture extended perpendicular to the dispersion direction. An adjacent aperture was used to construct a sky spectrum to remove any residuals from the sky-subtraction caused by variations in the strength of the sky lines over the course of the observations. Both sets of observations were scaled by the exposure time, such that the spectra were expressed in units of ADU s⁻¹. The six individual spectra of ζ Del B were median-combined, divided by the telluric spectrum, and multiplied by a T eff = 19 000 K log (g) = 4.5 BT-SETTL model atmosphere (Allard, Homeier & Freytag 2012), scaled to the 2MASS Ks apparent magnitude HIP 104320. No residual spectral features intrinsic to the B3V telluric standard remained within the calibrated spectrum of ζ Del B, indicating a good match between the telluric calibrator and the BT-SETTL model atmosphere.

The final flux-calibrated spectrum of ζ Del B is shown in Fig. 5. From this spectrum, the apparent magnitudes in the 2MASS JHKs and MKO JHKs photometric systems were computed using the filter transmission curves given in Cohen, Wheaton & Megeath (2003) and Tokunaga et al. (2002), respectively. The MKO filter transmission curves were multiplied by the transmission of the atmosphere above Mauna Kea, assuming a precipitable water vapour column of 3 mm. The resulting MKO filter curves are overplotted on Fig. 5 for reference. The apparent magnitudes estimated from the flux-calibrated spectrum, and computed absolute magnitudes and corresponding near-infrared colours, are given in Table 2. The MKO Ks = 15.35 ± 0.17 of ζ Del B measured within the MMT/ARIES data set, assuming a negligible colour transformation between the 2MASS and MKO photometric systems for the A-type primary, is consistent with the magnitude derived from the flux-calibrated spectrum.
5 PROPERTIES OF \( \zeta \) DEL B

5.1 Spectral type, effective temperature, and surface gravity

The spectral type of \( \zeta \) Del B was estimated through a comparison with empirical spectra of field brown dwarfs within the SpeX Prism Spectral Library. The GNIRS spectrum of \( \zeta \) Del B and the SpeX spectra were smoothed by convolution with a 50 Å Gaussian, and interpolated to the same wavelength scale. For each object within the SpeX library, the spectrum was scaled to minimize the reduced \( \chi^2 \) when compared with \( \zeta \) Del B, calculated over the wavelength ranges 1.05–1.35 \( \mu \)m, 1.45–1.80 \( \mu \)m, and 1.98–2.40 \( \mu \)m. In this case, the \( \chi^2 \) statistic is equivalent to the \( G \) statistic, defined by Cushing et al. (2008), as the weightings are uniform across the entire wavelength range of the spectrum of \( \zeta \) Del B. Fig. 6 shows the spectrum of \( \zeta \) Del B compared with the M-, L-, and T-dwarf near-infrared spectral standards from Kirkpatrick et al. (2010) and Geißler et al. (2011), which are all available within the SpeX library. Fig. 7 shows the reduced \( \chi^2 \) as a function of spectral type for all of the objects within the SpeX library, with the spectral standards highlighted, from which a spectral type of L5 ± 2 was adopted for \( \zeta \) Del B. The mid-L spectral classification is consistent with the spectral type estimated from various spectral indices defined in the literature, given in Table 3 (McLean et al. 2003; Allers et al. 2007; Burgasser 2007). This range of spectral types corresponds to an effective temperature of 1550 ± 140 K, using the spectral type–temperature relations of Stephens et al. (2009) derived for field brown dwarfs. The spectrum of \( \zeta \) Del B was also compared with BT-SETTL synthetic spectra (Allard et al. 2012), with a best-fitting effective temperature of \( T_{\text{eff}} = 1650 \pm 200 \) K and surface gravity of \( \log(g) = 5.0^{+0.5}_{-1.0} \), based on a \( \chi^2 \) minimization of the observed and model spectra.

The observed spectrum does not exhibit the strong triangular shape of the H-band continuum seen in the lowest surface gravity brown dwarfs (e.g. Lucas et al. 2001; Allers et al. 2007), consistent with the higher surface gravity estimated for \( \zeta \) Del B from the comparison with the model spectra. The shape of the H-band peak can be quantified using the \( H \)-cont index defined by Allers & Liu (2013). While the \( H \)-cont index for \( \zeta \) Del B of 0.92 would suggest a lower surface gravity than field objects, Allers & Liu (2013) note that numerous older dusty field brown dwarfs also exhibit similar behaviour, and caution against using this index alone to diagnose low-surface gravity. The remaining Allers & Liu (2013) indices which could be measured using the GNIRS data, Fe H \( \lambda 1.25 \), and K I \( \lambda 1.22 \), are consistent with the field population, and suggest a high surface gravity for \( \zeta \) Del B.

Individual spectral features are also diagnostic of surface gravity. The strength of the sodium (Na I) line at 1.1396 \( \mu \)m and the potassium (K I) doublets at 1.174 and 1.248 \( \mu \)m, indicated in Fig. 5, are observed to depend strongly on the spectral type and surface gravity of an object (Gorlova et al. 2003), being significantly weaker within the spectra of the youngest objects of a given spectral type (Allers & Liu 2013). The equivalent widths of these lines, which were calculated using the method described in McLean et al. (2003), are given in Table 4. The strength of these lines within the spectrum of \( \zeta \) Del B suggest a surface gravity more similar to those found for field brown dwarfs (e.g. McLean et al. 2007), than found for younger objects (e.g. Bonnefoy et al. 2014b). The presence of a deep \( ^{13}\text{CO} \) 2–0 bandhead at 2.29 \( \mu \)m, indicated in Fig. 5, is a potential indicator of low surface gravity (e.g. Cushing, Rayner & Vacca 2005), based on the depth of the bandhead within the spectra of M-type giants relative to M-dwarfs of the same spectral type (Kleinmann & Hall 1986). Without an empirical relation between the strength of this absorption and surface gravity for a given brown dwarf spectral type, the significance of the deep absorption seen in the spectrum of \( \zeta \) Del B cannot be quantified.

5.2 Bolometric luminosity and mass

In order to determine the bolometric luminosity of \( \zeta \) Del B, a \( K \)-band bolometric correction of \( BC_{K} = 3.31 \pm 0.09 \) was estimated using the adopted spectral type and the spectral type–BC \( K \) relation for field brown dwarfs presented in Liu et al. (2010). Applying this correction to the measured \( K \)-band magnitude leads to a bolometric magnitude of \( M_{\text{bol}} = 14.59 \pm 0.12 \) and a bolometric luminosity of \( \log(L/L_\odot) = -3.94 \pm 0.05 \) for \( \zeta \) Del B, assuming \( M_{\text{bol}} \odot = 4.74 \).
Table 2. Properties of the ζ Del system.

<table>
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<th>Property</th>
<th>Value</th>
<th>Value</th>
<th>Unit</th>
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<td>ζ Del B</td>
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<td>Parallax</td>
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<td>Distance</td>
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<td>mas yr⁻¹</td>
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<td>48.63 ± 1.66h</td>
<td>0.00012 ± 0.00001h</td>
<td>L&lt;sub&gt;⊙&lt;/sub&gt;</td>
</tr>
<tr>
<td>log (L&lt;sub&gt; bol&lt;/sub&gt;/L&lt;sub&gt;⊙&lt;/sub&gt;)</td>
<td>1.687 ± 0.015</td>
<td>–3.94 ± 0.05</td>
<td>dex</td>
</tr>
<tr>
<td>Spectral type</td>
<td>A3V&lt;sup&gt;i&lt;/sup&gt;</td>
<td>L.7 ± 2&lt;sup&gt;i&lt;/sup&gt;</td>
<td>–</td>
</tr>
<tr>
<td>T&lt;sub&gt; eff&lt;/sub&gt;</td>
<td>8336&lt;sup&gt;i&lt;/sup&gt;</td>
<td>1550 ± 250&lt;sup&gt;i&lt;/sup&gt;</td>
<td>K</td>
</tr>
<tr>
<td>log (g)</td>
<td>3.72&lt;sup&gt;i&lt;/sup&gt;</td>
<td>5.0 ± 0.3&lt;sup&gt;i&lt;/sup&gt;</td>
<td>dex</td>
</tr>
<tr>
<td>[Fe/H]</td>
<td>−0.05&lt;sup&gt;i&lt;/sup&gt;</td>
<td>–</td>
<td>dex</td>
</tr>
<tr>
<td>Age</td>
<td>525 ± 125&lt;sup&gt;m&lt;/sup&gt;</td>
<td>Myr</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>2.5 ± 0.2&lt;sup&gt;n&lt;/sup&gt;</td>
<td>M&lt;sub&gt;⊙&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>–</td>
<td>55 ± 10&lt;sup&gt;o&lt;/sup&gt;</td>
<td>M&lt;sub&gt;sup&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>–</td>
<td>40 ± 15&lt;sup&gt;o&lt;/sup&gt;</td>
<td>M&lt;sub&gt;sup&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>Mass ratio</td>
<td>0.021 ± 0.004&lt;sup&gt;q&lt;/sup&gt;</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>ρ</td>
<td>0.015 ± 0.006&lt;sup&gt;q&lt;/sup&gt;</td>
<td>0.02&lt;sup&gt;q&lt;/sup&gt;</td>
<td>–</td>
</tr>
<tr>
<td>θ</td>
<td>135.35 ± 0.30&lt;sup&gt;o&lt;/sup&gt;</td>
<td>deg</td>
<td></td>
</tr>
<tr>
<td>a&lt;sub&gt;proj&lt;/sub&gt;</td>
<td>912 ± 15</td>
<td>au</td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>907 ± 723&lt;sup&gt;q&lt;/sup&gt;</td>
<td>256</td>
<td>au</td>
</tr>
<tr>
<td>P</td>
<td>~10&lt;sup&gt;–3&lt;/sup&gt; r</td>
<td>yr</td>
<td></td>
</tr>
</tbody>
</table>

Note: a van Leeuwen (2007), assumed to be equal for both components, bHög et al. 2000, cSkrutskie et al. (2006), destimated from the flux-calibrated GNIRS spectrum of ζ Del B, e negligible 2MASS–MKO colour transformation for an A3V star, f interpolated from B–V versus BC<sub>V</sub> table in Flower (1996), gestimated from spectral type–BC<sub>V</sub> relation in Liu, Dupuy & Leggett (2010), hcalculated from M<sub> bol</sub>, assuming M<sub> bo</sub> = 0.474 (Drilling & Landolt 2000), iCowley et al. (1996), jestimated from comparison with Spex library (Fig. 7), kErspamer & North (2003), lestimated from adopted spectral type and equation 3 of Stephens et al. (2009), mestimated from Siess et al. (2000) and Bressan et al. (2012) evolutionary models, nestimated from system age and absolute K<sub>5</sub> magnitude (Fig. 8, top panel), oestimated from system age and adopted temperature (Fig. 8, bottom panel), pphotometry measured in 2008 Gemini/NIRI observations, qcalculated using the probability density function for the factor a<sub>proj</sub> computed by Dupuy & Liu (2011), assuming a flat eccentricity distribution and no detection bias, rcalculated assuming a face-on, circular orbit.

Figure 6. The GNIRS spectrum of ζ Del B (black curve) is plotted against the M, L, and T-dwarf near-infrared spectral standards from Kirkpatrick et al. (2010) and Geißler et al. (2011, red curves). The spectral standards have been scaled relative to the spectrum of ζ Del B to minimize the reduced χ². The observed spectrum of ζ Del B is best fitted by the mid-L spectral standards.

(Drilling & Landolt 2000). Using evolutionary models at an age of 525 ± 125 Myr (Baraffe et al. 2002), this bolometric luminosity corresponds to an effective temperature of ~1950 ± 100 K, higher than the values estimated from both the adopted spectral type and the best-fitting model atmosphere. A similar discrepancy is also seen for the 800 Myr brown dwarf binary HD 130948 BC (Dupuy et al. 2009) and the 100 Myr brown dwarf CD-35 2722 B (Wahhaj et al. 2011), where the effective temperatures derived from the evolutionary models using the age and bolometric luminosity are ~100–300 K hotter than predicted from the spectral type.

The BT-SETTL atmospheric models (Allard et al. 2012) and the Baraffe et al. (2002) evolutionary models were used to provide an estimate of the mass of ζ Del B, exploiting the strong dependence...
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Models yield a mass of 55 ± 2 assuming an age of the system of 525 K, the primary given previously, the companion-to-primary mass ratio of 0.23 mas; van Leeuwen (2007).

Using the L5 dwarf temperature, the considerable spread in the ζ Del B is most similar to the mid L-dwarfs within the SpeX Library, and as such a spectral type of L5±2 is adopted (denoted by the vertical lines).

Table 3. Spectral type of ζ Del B derived from spectral indices.

<table>
<thead>
<tr>
<th>Index</th>
<th>Value</th>
<th>Spectral type</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2O A</td>
<td>0.55 ± 0.08</td>
<td>L3.6 ± 2.2</td>
<td>McLean et al. (2003)</td>
</tr>
<tr>
<td>H2O B</td>
<td>0.61 ± 0.14</td>
<td>L5.5 ± 3.3</td>
<td>McLean et al. (2003)</td>
</tr>
<tr>
<td>H2O C</td>
<td>0.66 ± 0.14</td>
<td>L3.1 ± 5.6</td>
<td>McLean et al. (2003)</td>
</tr>
<tr>
<td>H2O D</td>
<td>0.85 ± 0.10</td>
<td>L3.1 ± 2.6</td>
<td>McLean et al. (2003)</td>
</tr>
<tr>
<td>H2O J</td>
<td>1.35 ± 0.18</td>
<td>L4.6 ± 6.3</td>
<td>Allers et al. (2007)</td>
</tr>
<tr>
<td>H2O H</td>
<td>0.78 ± 0.13</td>
<td>L4.8 ± 3.9</td>
<td>Burgasser (2007)</td>
</tr>
<tr>
<td>CH3 K</td>
<td>0.72 ± 0.10</td>
<td>L5.7 ± 3.8</td>
<td>Burgasser (2007)</td>
</tr>
<tr>
<td>CH4 K</td>
<td>1.07 ± 0.08</td>
<td>L1.6 ± 3.9</td>
<td>Burgasser (2007)</td>
</tr>
</tbody>
</table>

on age of the mass of substellar objects of a given luminosity or temperature. Using the measured K-band magnitude for ζ Del B, and assuming an age of the system of 525 ± 125 Myr, the evolutionary models yield a mass of 55 ± 10 M_Jup (Fig. 8, top panel). Alternatively, using the effective temperature derived from the adopted spectral type leads to a lower mass estimate of 40.1±2 M_Jup (Fig. 8, bottom panel). Combining these mass estimates with the mass of the primary given previously, the companion-to-primary mass ratio of the ζ Del system was estimated to be between 0.023 ± 0.004 using the K-band magnitude and 0.015±0.006 using the adopted effective temperature.

5.3 Probability of chance superposition

Using the L5 ± 2 spectral type for ζ Del B and estimates for the surface density of mid-L dwarfs, an estimate of the probability of a chance superposition between ζ Del A and a unassociated foreground or background brown dwarf can be calculated. The surface density of L3–L7 brown dwarfs within a simulated magnitude-limited (K < 16) survey, assuming a lognormal mass distribution (Chabrier 2002), was estimated to be 1.42 × 10⁻² deg⁻² (Burgasser 2007). Assuming brown dwarfs are isotropically distributed throughout the sky, this surface density would correspond to a probability of detecting a brown dwarf of spectral type between L3 and L7 within a radius of 13.5 arcsec from a random location on the sky of P ≈ 2 × 10⁻³. This is an upper limit to the true probability as the surface density includes contributions from all L3 to L7 brown dwarfs along the line of sight until the magnitude limit of K < 16 is reached at D ≈ 100 pc. As the spectral type of ζ Del B provides a reasonable limit on its distance (25 < D[pc] < 110), the object can be constrained to a volume of space defined by a truncated cone with an inner and outer radii of 1.6 × 10⁻³ and 7.2 × 10⁻³ pc, respectively, and a height of 85 pc. Combining this volume with the number density of L3–L7 brown dwarfs, 3.87 × 10⁻³ pc⁻³ (Burgasser 2007), yields a probability of detecting an object like ζ Del B within a radius of 13.5 arcsec from a random location on the sky of P ≈ 2 × 10⁻⁵.

5.4 Semimajor axis and orbital period

The angular separation of 13.51 ± 0.08 arcsec between ζ Del A and B measured within the 2008 Gemini/NIRI data set was projected to a separation of 2723 ± 15 au using the Hipparcos parallax for ζ Del A (π = 14.82 ± 0.23 mas; van Leeuwen 2007). Due to the large number of orbital orientations and viewing geometries, the conversion between projected separation as seen on the sky into a semimajor axis (a) is non-trivial. Using the probability density function calculated for a/a_prox by Dupuy & Liu (2011), in the case of a flat eccentricity distribution with no discovery bias, the most probable semimajor axis of ζ Del B was estimated via a Monte Carlo method as 907 ± 230 au. An order-of-magnitude estimate of the orbital period of ~10⁶ yr was made using the most probable semimajor axis, assuming a face-on circular orbit, and the masses of each component given in Table 2.

5.5 Comparison with known substellar companions

The position of ζ Del B on an M_K versus J–K_S CMD, shown in Fig. 9, was compared to known intermediate-age (100–1000 Myr) substellar companions, Hyades brown dwarfs (Reid 1993; Bouvier et al. 2008; Hogan et al. 2008), and older field brown dwarfs (Dupuy & Liu 2012). The intermediate-age comparison sample of 100–1000 Myr substellar companions was drawn from the compilation of Zucker & Song (2009), complemented with the recent discovery of the ~100 Myr L4 dwarf CD-35 2722 B (Wahhaj et al. 2011). Several of the included objects do not have a parallax measurement within the literature – for G 196-3 a photometric distance of 11 ± 4 pc was used (Shkolnik et al. 2012), and for the Hyades brown dwarfs without distance estimates a value of 47.5 ± 3.6 pc was used (McArthur et al. 2011). For the three objects without

Table 4. Measured equivalent widths for ζ Del B.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Wavelength (Å)</th>
<th>Equivalent width (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na I</td>
<td>11 396</td>
<td>11.3 ± 0.5</td>
</tr>
<tr>
<td>K I</td>
<td>11 692</td>
<td>10.8 ± 0.4</td>
</tr>
<tr>
<td>K I</td>
<td>11 778</td>
<td>11.9 ± 0.4</td>
</tr>
<tr>
<td>K I</td>
<td>12 437</td>
<td>6.8 ± 0.4</td>
</tr>
<tr>
<td>K I</td>
<td>12 529</td>
<td>9.4 ± 0.7</td>
</tr>
</tbody>
</table>
stated photometric uncertainties, a value of $\sigma_{m} = 0.2$ mag was assumed. $\zeta$ Del B is at a similar location on the CMD to each of the components of the binary brown dwarfs Gl 417 BC (80–300 Myr, L4.5+L6; Zuckerman & Song 2009) and HD 130948 BC (800 Myr, L4.5+L4; Dupuy et al. 2009), and has a similar colour to the recently discovered companion to CD-35 2722 (100 Myr, L4; Wahhaj et al. 2011). The position of $\zeta$ Del B on the CMD is also consistent with the predicted location of an $\sim 50$ $M_{\text{up}}$ object at 500 Myr within the AMES-DUSTY model grid, intermediate to the two mass estimates for $\zeta$ Del B given in Table 2.

The spectrum of $\zeta$ Del B is compared in Fig. 10 with the most analogous objects for which similar-resolution spectra were available: CD-35 2722 B (Wahhaj et al. 2011), 2MASS J22244381-0158521 (2MASS J2224-0158; Cushing et al. 2005), and the blended spectrum of the brown dwarf binary Gl 417 BC (Bonnefoy et al. 2014b). While a good match is seen between these three objects and $\zeta$ Del B when each bandpass is fitted independently, $\zeta$ Del B appears redder than CD-35 2722 B and bluer than 2MASS J2224-0158 when the full flux-calibrated $JHK$ spectra are compared, consistent with their relative positions on the CMD (Fig. 9).

Figure 8. Atmospheric/evolutionary models showing the decline in absolute 2MASS $K_s$ magnitude (top panel) and temperature (bottom panel) as a function of age for substellar objects between 10 and 70 $M_{\text{up}}$ (Allard et al. 2012). Using the age of $\zeta$ Del A and the absolute magnitude of $\zeta$ Del B of $M_{K_s} = 11.14 \pm 0.17$, we estimate a mass of $55 \pm 10$ $M_{\text{up}}$ (top panel). Using the adopted temperature of 1550$^{+250}_{-100}$ K, derived from the spectral type–temperature relations given in Stephens et al. (2009), yields a lower mass estimate of $40^{+15}_{-5}$ $M_{\text{up}}$ (bottom panel).

The spectrum of $\zeta$ Del B is compared in Fig. 10 with the most analogous objects for which similar-resolution spectra were available: CD-35 2722 B (Wahhaj et al. 2011), 2MASS J22244381-0158521 (2MASS J2224-0158; Cushing et al. 2005), and the blended spectrum of the brown dwarf binary Gl 417 BC (Bonnefoy et al. 2014b). While a good match is seen between these three objects and $\zeta$ Del B when each bandpass is fitted independently, $\zeta$ Del B appears redder than CD-35 2722 B and bluer than 2MASS J2224-0158 when the full flux-calibrated $JHK$ spectra are compared, consistent with their relative positions on the CMD (Fig. 9).

Figure 9. CMD in the 2MASS photometric system (Skrutskie et al. 2006) showing the location of $\zeta$ Del B (blue open star) relative to field brown dwarfs (light grey circles; Dupuy & Liu 2012) and known Hyades brown dwarfs (filled circles; Reid 1993; Bouvier et al. 2008; Hogan et al. 2008). Known substellar companions with ages of 100–1000 Myr drawn from the compilation of Zuckerman & Song (2009), and the recently discovered companion CD-35 2722 B (Wahhaj et al. 2011) are plotted for reference (open black symbols). The dusty field L4.5 dwarf 2MASS J22244381-0158521 (Cushing et al. 2005) is also highlighted (open red square). The literature $J$- and $K$-band photometry for CD-35 2722 B and HD 130948 BC, and $J$-band photometry for HD 203030 B, were measured in the MKO photometric system; no 2MASS magnitudes for these objects were found within the literature. For mid L-dwarfs, the colour correction between these photometric systems is expected to be $\Delta J - K_s \leq 0.2$ mag (e.g. Stephens & Leggett 2004). Theoretical 500 Myr isochrones from the BT-SETTL (black solid curve; Allard et al. 2012), AMES-COND (blue dot–dashed curve; Baraffe et al. 2003), and AMES-DUSTY (red dashed curve; Chabrier et al. 2000) model grids are shown for comparison.

6 WIDE SUBSTELLAR COMPANION FORMATION

$\zeta$ Del B is among the most widely separated and lowest mass ratio companions resolved around a main-sequence star to date, as shown in Fig. 11. Significant uncertainty exists in the formation history of such objects. Intermediate to the lowest mass stars and massive directly imaged planetary-mass companions, a number of formation theories have been suggested for these objects, ranging from formation in a large circumstellar disc, or through the fragmentation of a pre-stellar core, to the gravitational capture by the massive primary within a dynamical star-forming environment. While disc fragmentation models predict the formation of substellar companions around A-type primaries (e.g. Kratter, Murray-Clay & Youdin 2010), the formation of $\zeta$ Del B in situ would require an unusually massive circumstellar disc for sufficient mass to be available at such separations. The time-scale for formation through core accretion is also prohibitively long at large separations (e.g. Pollack et al. 1996), requiring the core to form before the gas disc dissipates. These formation scenarios cannot be excluded; however, as $\zeta$ Del B may have migrated outward prior to the dissipation of the disc (e.g. Vorobyov 2013), or dynamical interaction with unseen interior companion may have dynamically scattered it (e.g. Jiang, Laughlin & Lin 2004; Stamatellos & Whitworth 2009) on to a potentially unstable orbit (e.g. Veras, Crepp & Ford 2009).

Formation through the fragmentation of a pre-stellar core is predicted to form companions with separations of the order of 10$^4$ au (Bate, Bonnell & Price 1995), with mass ratios ranging from the stellar to substellar regimes (Bonnell & Bastien 1992). Large-scale simulations of star formation within clusters are able to produce low-mass ratio companions at wide separations, although such models are limited in terms of the overall size of the cluster and, by extension, the number of high-mass stars produced (Bate 2009, 2012). An alternative scenario is that $\zeta$ Del B formed independent of $\zeta$ Del A, and was dynamically captured, either through a three-body interaction in which a natal companion was ejected (e.g. Bonnell 2001),

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7 SUMMARY

We have presented the discovery of a wide substellar companion to the A3V star ζ Delphini, augmenting the small number of examples of such companions to early-type stars currently reported within the literature. Based on our AO images obtained in 2008, ζ Del B is at a projected separation of \( a_{proj} = 912 \pm 15 \) au from ζ Del A, with a most probable semimajor axis of \( a = 907^{+723}_{-236} \) au, assuming a flat eccentricity distribution (Dupuy & Liu 2011). Based on the position of ζ Del A on the temperature–surface gravity and CMDs, we estimate a system age of 525 \( \pm 125 \) Myr. Comparing ζ Del B with evolutionary models, we estimate a mass of \( 55 \pm 10 \, M_{Jup} \) using bolometric luminosity estimated from the \( K_S \) magnitude, and \( 40^{+15}_{-5} \, M_{Jup} \) using the adopted spectral type and empirical spectral type–temperature relations, corresponding to a companion mass ratio of \( q = 0.02 \pm 0.01 \). Future spectroscopic measurements of the C/O ratio of ζ Del B, and other wide substellar companions, may provide an observational diagnostic of their formation mechanism (e.g. Konopacky et al. 2013). The continuation of large-scale surveys for such objects (e.g. Faherty et al. 2010; Deacon et al. 2014; Naud et al. 2014) is essential to develop empirical comparisons for theoretical formation models. The frequency and properties of such objects at wide separations (\( \sim 10^3 \) au) will also provide important context for the expected yield of substellar companions resolved in upcoming extreme-AO systems such as GPI (Macintosh et al. 2014) and SPHERE (Beuzit et al. 2008) at separations of between 1 and 100 au to nearby main-sequence stars.

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