Observations of the pulsation of the Cepheid $\ell$ Car with the Sydney University Stellar Interferometer

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Accepted 2008 December 22. Received 2008 December 19; in original form 2008 November 6

ABSTRACT

Observations of the southern Cepheid $\ell$ Car to yield the mean angular diameter and angular pulsation amplitude have been made with the Sydney University Stellar Interferometer at a wavelength of 696 nm. The resulting mean limb-darkened angular diameter is $2.990 \pm 0.017$ mas (i.e. $\pm 0.6$ per cent) with a maximum-to-minimum amplitude of $0.560 \pm 0.018$ mas corresponding to $18.7 \pm 0.6$ per cent in the mean stellar diameter. Careful attention has been paid to uncertainties, including those in measurements, in the adopted calibrator angular diameters, in the projected values of visibility squared at zero baseline, and to systematic effects. No evidence was found for a circumstellar envelope at 696 nm. The interferometric results have been combined with radial displacements of the stellar atmosphere derived from selected radial velocity data taken from the literature to determine the distance and mean diameter of $\ell$ Car. The distance is determined to be $525 \pm 26$ pc and the mean radius $169 \pm 8 R_{\odot}$. Comparison with published values for the distance and mean radius shows excellent agreement, particularly when a common scaling factor from observed radial velocity to pulsation velocity of the stellar atmosphere (the $p$-factor) is used.

Key words: techniques: interferometric – stars: distances – stars: individual: $\ell$ Car, HR 3884.

1 INTRODUCTION

The accurate determination of the zero-point of the Cepheid period–luminosity relation is an important step in the refinement of the extragalactic distance scale. The combination of interferometric and spectroscopic data, as discussed by Davis (1999), is an approach to this task that is now feasible. The first demonstration of the combination of interferometric and spectroscopic data to determine both the mean diameter and distance of a Cepheid was made by Lane et al. (2000) based on interferometric observations with the Palomar Testbed Interferometer (PTI) of $\zeta$ Gem. Lane, Creech-Eakman & Nordgren (2002) subsequently applied the technique to $\eta$ Aql and, with additional data, to $\zeta$ Gem, again based on PTI observations. Kervella et al. (2004a) have reported the measurement of the angular pulsations of seven Galactic Cepheids made with the European Southern Observatory’s Very Large Telescope Interferometer (VLTI) and, in combination with spectroscopic data, have determined the distances to the Cepheids.

One of the prime programmes for which the Sydney University Stellar Interferometer (SUSI) (Davis et al. 1999) was developed was the measurement of the mean diameters and angular pulsation amplitudes of Cepheids but, in its initial configuration, it lacked the required sensitivity. The recent commissioning of a red beam-combination system in SUSI (Davis et al. 2007a) has resulted in a significant increase in sensitivity. In this paper, we report SUSI measurements of the mean angular diameter and angular pulsation amplitude of $\ell$ Car, one of the seven Cepheids measured with the VLTI by Kervella et al. (2004a). A preliminary analysis was presented at a European Southern Observatory symposium in 2005 (Davis et al. 2007b), and Jacob (2008) has discussed the SUSI Cepheid programme including an analysis of a subset of the $\ell$ Car observations reported here.

Spectroscopic radial velocity measurements from the literature have been combined to produce a radial velocity versus pulsation phase curve and, after scaling with a fixed $p$-factor as discussed in Section 6.3, this has been integrated to give the radial displacement of the Cepheid surface as a function of pulsation phase. The radial displacement and limb-darkened angular diameter data have been combined to determine the distance and mean radius of $\ell$ Car.

The resulting distance and mean radius are compared with values in the literature determined by the same technique and by the infrared surface brightness method and excellent agreement is found, particularly when all values are scaled to a common $p$-factor.

2 THE PULSATION PHASE

Although it might seem premature to discuss the pulsation phase prior to discussing the observations, it is necessary to ensure that
both interferometric and spectroscopic phases are synchronised since the epochs of the interferometric and spectroscopic observations do not overlap. A problem in the case of \( \ell \) Car is the fact that there is evidence that its period has undergone changes. Szabados (1989) reported that the period of \( \ell \) Car changed from 35.5318 d prior to JD 244 0000 to 35.5513 d. Shobbrook (1992) refined the Szabados period, with additional photometry in 1990, to 35.5443 d and Berdnikov & Turner (2004), based on photometry in 2002, give a value of 35.5572 d. Taylor et al. (1997) have listed values back to 1901 and found in their own spectroscopic study of \( \ell \) Car from early 1991 to late 1996 that an increase in the period was evident although the uncertainties were large.

The approach that we have adopted is as follows. Since the largest body of radial velocity data available to us is the combined Mount Stromlo Observatory (MSO) and Mount John University Observatory (MJUO) observations analysed by Taylor et al. (1997) and their phases are effectively based on the Shobbrook (1992) ephemeris, albeit with small adjustments to bring the early MJUO data into line with the MSO data, we have adopted the Shobbrook (1992) ephemeris for the analysis of both interferometric and additional spectroscopic data. The adopted period is 35.5443 ± 0.0006 d with 244 7880.81 ± 0.10 the zero point of maximum light in heliocentric Julian Date (JD). The phases of individual data points have been computed from the JD of observation for both interferometric and spectroscopic data.

Because of the variations in period, it is found that there are small phase shifts between data sets taken at different epochs. The change in phase across any given data set as a result of adopting the Shobbrook period rather than, for example, that of Berdnikov & Turner (2004) is negligible, and a small phase shift of the whole data set to bring it into alignment with the Taylor et al. (1997) data is justified. Details of the alignment of the different sets of data will be discussed when combining data and, in particular, spectroscopic data in Section 6.

3 THE INTERFEROMETRIC OBSERVATIONS

Measurements of the squared fringe visibility \( V^2 \) were made with SUSI (Davis et al. 1999) using the red beam-combination system, which employs the fringe-scanning technique (Davis et al. 2007a). This beam-combination system uses matched filters with a central wavelength of 700 nm and spectral bandwidth of 80 nm. The observations to determine the angular diameter of \( \ell \) Car were made with a baseline of 40 m with additional measurements at 5 m to enable the zero baseline value of \( V^2 \) to be checked.

3.1 Calibrators

Calibrators were selected as close in the sky as possible to \( \ell \) Car with the additional requirement of being minimally resolved. The limiting sensitivity of SUSI at 700 nm is \( \sim +5 \) which limited the choice of calibrators, and compromise was necessary. The calibrators used are listed in Table 1 with their spectral types, adopted uniform-disc angular diameters and angular distances from \( \ell \) Car. Common calibrators were used throughout to eliminate the potential influence of calibrator diameters on the pulsation curve. The effective wavelength of observations of all three calibrators has been estimated to be 695.0 ± 2.0 nm following a similar analysis to that described by Davis et al. (2007a).

The uniform-disc angular diameters have been determined from measurements made with the Narrabri Stellar Intensity Interferometer (NSII; Hanbury Brown, Davis & Allen 1974) and with the Mark III Optical Interferometer (Mark III; Mozurkewich et al. 2003). In the case of \( \beta \) Car, the value measured with the NSII has been adopted after correction from the limb-darkened angular diameter to the uniform-disc angular diameter using the appropriate correction factor for 695 nm interpolated from the tabulation of Davis, Tango & Booth (2000). In the absence of measured angular diameters for \( \iota \) and \( s \) Car, limb-darkened angular diameters have been determined by interpolation in a plot of NSII and Mark III limb-darkened angular diameters for unreddened visual magnitude \( V_0 = 0 \) versus \( (B − V)_0 \) for \( (B − V)_0 < 0.6 \). The interpolated limb-darkened angular diameters have been corrected to the \( V_0 \) magnitudes of the stars and corrected for limb-darkening to give the uniform-disc angular diameters listed in Table 1, again using appropriate correction factors interpolated from the tabulation of Davis et al. (2000). The uncertainties in the uniform-disc angular diameters have been estimated from the scatter in the plot of limb-darkened angular diameters versus \( (B − V)_0 \).

### Table 1. Calibrators used for the observations of \( \ell \) Car.

| HR | Star  | Spectral type | \( m_{\text{V05}} \) | \( \theta_{\text{UD}} \) (mas) | \( \Omega \) (°) |
|----|-------|---------------|----------------|----------------------------|----------------|
| 3685 | \( \beta \) Car | A2 IV | 1.6 | 1.54 ± 0.07 | 7.9 |
| 3699 | \( \iota \) Car | A8 Ib | 2.0 | 1.55 ± 0.12 | 4.7 |
| 4114 | \( s \) Car | F2 II | 3.5 | 0.90 ± 0.07 | 6.5 |

\( m_{\text{V05}} \) is the estimated magnitude at 695 nm, \( \theta_{\text{UD}} \) is the adopted uniform disc angular diameter at 695 nm and \( \Omega \) is the angular distance of the calibrator from \( \ell \) Car.

3.2 The observations

Observations of calibrators and \( \ell \) Car were alternated in each observing session so that every \( \ell \) Car observation was bracketed by observations of calibrators. Each observation consisted of a set of 1000 scans each 140 \( \mu \)m long and consisting of 1024 by 0.2 ms samples. Each scan set was followed by photometric and dark scans.

One complete observation of \( \ell \) Car, including the bracketing calibrators, took a total of \( \sim 18 \) min.

Observations were made with a baseline of 40 m on 31 nights for \( \ell \) Car between 2004 March 2 and 2007 May 24. Initially, all 31 nights were included in the analysis but four nights were subsequently rejected when their values were found to lie more than four standard deviations from the fit to limb-darkened angular diameter versus radial displacement of the stellar surface (Section 7), and the analysis was then repeated without them. The maximum deviation from the fit after rejection of the four points was \( < 3.1 \sigma \).

Examination of the data for three of the four rejected nights revealed that they were obtained during a short period from late 2004 March to early April when there was significant leakage of the metrology laser light into the signal beams. On the fourth rejected night, the data were poor, showing large scatter with only two out of the six points lying within one standard deviation of the mean for the night.

The projected baseline (i.e. the effective baseline of an observation) was less than 40 m due to the southerly declinations of \( \ell \) Car and its calibrators.

Observations were also made with a 5 m baseline, close to the phases of maximum and minimum angular diameter, on 2007 March 13 and May 5. These will be discussed in Section 5.1.

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4 ANALYSIS OF INTERFEROMETRY

The initial analysis of the fringe scans for ς Car and the calibrators was carried out in the SUSI software ‘pipeline’ (Davis et al. 2007a) which outputs the raw and seeing corrected squared visibility amplitudes ($V^2$), the JD, projected baseline, hour angle, fluxes, etc. for each set of scans. For the early observations up to 2004 April 7, full sets of photometry files were not recorded. In these cases, photometry files were duplicated to enable the scans to be processed in the pipeline and it is noted that the analysis has shown that this procedure has a negligible effect on the resulting values of $V^2$. For each night, the output file from the pipeline was imported into an Excel spreadsheet for examination of the data and for further analysis.

For each set of calibrator scans, a transfer function ($T$) was calculated. $T$ is given by

$$T = \frac{V^2_{\text{obs}}}{V^2_{\text{exp}}},$$

where $V^2_{\text{obs}}$ is the observed, seeing corrected value of $V^2$ and $V^2_{\text{exp}}$ is the expected value of $V^2$ calculated from the uniform-disc angular diameter, effective wavelength and projected baseline.

The values of $V^2_{\text{obs}}$ for ς Car were then multiplied by the weighted mean value of $T$ for the two calibrators bracketing the ς Car observation to give the ‘true’ calibrated value of $V^2$ for ς Car, i.e.

$$V^2_{\text{true}}(\text{ς Car}) = \frac{V^2_{\text{obs}}(\text{ς Car})}{T}.$$  

The mean value of $V^2_{\text{true}}$ (ς Car) for each night is listed in Table 2 with the date (Universal Time), the mean JD, the mean projected baseline, the calibrators used and the number of scan sets for ς Car. The uncertainty in $V^2_{\text{true}}$ (ς Car) takes into account the uncertainties in the uniform-disc angular diameters of the calibrators although these are generally negligible compared to the uncertainties in the values of $V^2_{\text{obs}}$ for both calibrators and ς Car.

5 THE ANGULAR DIAMETER

The uniform-disc angular diameter ($\theta_{UD}$) for each night was determined by fitting the equation

$$V^2 = \left| \frac{2J_1(\lambda)}{\lambda} \right|^2$$

(3)

to the individual values of $V^2_{\text{true}}$ (ς Car) assuming that $V^2_{\text{true}}$ (ς Car) at zero baseline was unity. In equation (3), $J_1(\lambda)$ is a Bessel function and $x = \pi b \theta_{UD}/\lambda$, where $b$ is the projected baseline and $\lambda$ is the wavelength of the observation.

The effective wavelength for ς Car will be a function of pulsation phase as the star changes colour during its cycle. Calculations of effective wavelength for supergiants following the procedure described by Davis et al. (2007a) give the mean effective wavelength for ς Car as 696.2 nm with a variation of ~ ±0.7 nm, or ±0.1 per cent, over a complete pulsation cycle. The systematic uncertainty in the calculated effective wavelength is conservatively estimated to be ±2.0 nm and we therefore adopt a fixed value of 696.2 ± 2.0 nm as the effective wavelength for ς Car. Since the expected variation is significantly less than the adopted uncertainty and is, generally, small compared with the observational uncertainties in the angular diameters, the adoption of a fixed value is justified.

### Table 2. Calibrated values of $V^2$.

| Date   | JD  | $b$ (m) | $V^2_{\text{true}}$ (ς Car) | Calibrators (Carinae) | $N$ |
|--------|-----|---------|-----------------------------|-----------------------|-----|
| 040302 | 3067.039 | 33.72 | 0.388 ± 0.020 | β and ℏ | 8 |
| 040307 | 3072.020 | 33.41 | 0.385 ± 0.010 | β and ℏ | 8 |
| 040317 | 3081.940 | 33.49 | 0.274 ± 0.013 | β and ℏ | 3 |
| 040318 | 3083.028 | 33.69 | 0.269 ± 0.004 | β and ℏ | 3 |
| 040401 | 3096.964 | 33.67 | 0.301 ± 0.014 | β and ℏ | 12 |
| 040414 | 3109.958 | 33.59 | 0.349 ± 0.006 | β, ℏ and σ | 7 |
| 040416 | 3112.026 | 32.53 | 0.341 ± 0.005 | β, ℏ and σ | 3 |
| 040417 | 3112.976 | 33.42 | 0.334 ± 0.016 | β, ℏ and σ | 6 |
| 040418 | 3113.934 | 33.76 | 0.294 ± 0.009 | β, ℏ and σ | 6 |
| 040420 | 3115.940 | 33.74 | 0.278 ± 0.005 | β, ℏ and σ | 7 |
| 040421 | 3116.976 | 33.26 | 0.286 ± 0.005 | β, ℏ and σ | 6 |
| 040422 | 3117.900 | 33.82 | 0.255 ± 0.009 | β, ℏ and σ | 6 |
| 040424 | 3119.933 | 33.65 | 0.284 ± 0.010 | β, ℏ and σ | 5 |
| 040430 | 3125.918 | 33.69 | 0.278 ± 0.018 | β, ℏ and σ | 3 |
| 040504 | 3129.899 | 33.65 | 0.261 ± 0.011 | β, ℏ and σ | 7 |
| 040508 | 3133.958 | 33.52 | 0.326 ± 0.013 | β, ℏ and σ | 4 |
| 040512 | 3137.933 | 33.32 | 0.397 ± 0.014 | β, ℏ and σ | 9 |
| 050118 | 3389.187 | 33.66 | 0.388 ± 0.015 | β, ℏ and σ | 9 |
| 050203 | 3405.120 | 33.67 | 0.241 ± 0.006 | β, ℏ and σ | 13 |
| 050204 | 3406.117 | 33.70 | 0.241 ± 0.004 | β, ℏ and σ | 12 |
| 050205 | 3407.955 | 33.75 | 0.239 ± 0.008 | β, ℏ and σ | 8 |
| 050206 | 3408.070 | 33.59 | 0.213 ± 0.007 | β, ℏ and σ | 3 |
| 050207 | 3409.144 | 33.61 | 0.233 ± 0.004 | β, ℏ and σ | 9 |
| 050210 | 3412.117 | 33.62 | 0.258 ± 0.007 | β, ℏ and σ | 7 |
| 050211 | 3413.150 | 33.52 | 0.256 ± 0.004 | β, ℏ and σ | 5 |
| 050212 | 3414.140 | 33.56 | 0.295 ± 0.005 | β, ℏ and σ | 6 |
| 070524 | 4244.919 | 32.48 | 0.391 ± 0.005 | β and σ | 7 |

The format for the date (Universal Time) is yymmdd, JD is the mean Julian Date of the observations minus 245 0000, $b$ is the mean projected baseline and $V^2_{\text{true}}(\text{ς Car})$ is the mean of $N$ values of $V^2_{\text{true}}$ (ς Car) (further details are given in the text).

5.1 The zero baseline value of $V^2_{\text{true}}(\text{ς Car})$

It is important to check the validity of the assumption that $V^2_{\text{true}}$ (ς Car) is unity at zero baseline. If it differs from unity as a result of the presence of a companion or scattered light from extended circumstellar matter, for example, it would translate to errors in the angular diameters. A large circumstellar envelope (CSE) has been discovered around ς Car at N band using long-baseline interferometry by Kervella et al. (2006), and its signature was detected by the same authors in their K-band observations. CSEs have also been detected in the K band around Polaris and δ Cep by Mérand et al. (2006) and around Y Oph by Mérand et al. (2007). Nardezzo et al. (2008) confirm a dominant absorption component in Hα for ς Car, whose velocity is constant and near zero in the stellar rest frame, and they attribute this to a CSE. These detections of CSEs, particularly around ς Car, emphasize the importance of checking the validity of our assumption. In order to carry out this check, observations were made at a baseline of 5 m on 2007 March 13 at phase 0.023 and on 2007 May 5 at phase 0.514. The observations were therefore close to minimum and maximum angular diameter, respectively. The observations were made after the initial analysis of the 40 m data had been completed, so values for the uniform-disc angular diameter at the two phases could be interpolated from a plot of uniform-disc angular diameter versus phase. Given the angular diameter, and assuming $V^2_{\text{true}}(\text{ς Car})$ to be unity at zero baseline, the expected value of $V^2_{\text{true}}(\text{ς Car})$ at the projected baseline for each night was calculated. If the assumption that $V^2_{\text{true}}(\text{ς Car})$ is unity
at zero baseline is valid, the observed and expected values will be in agreement. The results are listed in Table 3 and show that at minimum angular diameter the observed and expected values of $V_{\text{true}}^2 (\ell \text{ Car})$ differ by 0.004 ± 0.013 and at maximum angular diameter by 0.004 ± 0.012. The assumption that $V_{\text{true}}^2 (\ell \text{ Car})$ is unity at zero baseline is therefore justified and there is no evidence of a significant effect of a CSE at 696 nm.

### 5.2 The uniform-disc angular diameters

The uniform-disc angular diameters corresponding to the dates of observation, together with the corresponding pulsation phases determined using the ephemeris of Shobbrook (1992) as discussed in Section 2, are listed in Table 4.

Table 3. The results of the 5 m observations near minimum and maximum values of the angular diameter of $\ell$ Car.

| Date     | JD     | $\phi$ | $\theta_{\text{UD}}$ (mas) | $\bar{\ell}$ (m) | $V_{\text{exp}}^2$ | $V_{\text{obs}}^2$ | $N$ | $(V_{\text{exp}}^2 - V_{\text{obs}}^2)$ |
|----------|--------|--------|-----------------|------------------|-----------------|-----------------|-----|-----------------|
| 070313   | 4172.984 | 0.023  | 2.62 ± 0.01     | 4.21             | 0.9855 ± 0.0001 | 0.990 ± 0.013   | 5   | 0.004 ± 0.013   |
| 070505   | 4225.968 | 0.514  | 3.13 ± 0.01     | 4.08             | 0.9806 ± 0.0001 | 0.985 ± 0.012   | 8   | 0.004 ± 0.012   |

The format for the date is yymmd. JD is the mean Julian Date of the observations minus 245 0000, $\phi$ is the mean pulsation phase for the observations, $\theta_{\text{UD}}$ is the estimated uniform-disc angular diameter, $\bar{\ell}$ is the mean baseline of the observations, $V_{\text{exp}}^2$ is the expected value of $V^2$ for the uniform-disc angular diameter, baseline and effective wavelength (696.2 nm), $V_{\text{obs}}^2$ is the mean value of the $N$ observed values of $V^2$ and $(V_{\text{exp}}^2 - V_{\text{obs}}^2)$ is the difference between the expected and observed values of $V^2$ (further details are given in the text).

### 5.3 The uniform-disc angular diameter of the calibrator $\iota$ Car

A check was made on the consistency of the transfer function $T$ determined for the three primary calibrators, namely $\beta$, $\iota$ and $s$ Car. For each pair of consecutive observations of calibrators, the transfer functions were plotted against each other. For example, where observations of $\beta$ Car and $s$ Car bracketed an observation of $\iota$ Car, the transfer function of $\beta$ Car was plotted against the transfer function of $s$ Car. For all the 40 m observations, this resulted in 67 data points for $s$ Car v. $\beta$ Car, 85 points for $\iota$ Car v. $\beta$ Car and 51 points for $\iota$ Car v. $s$ Car. Linear regression fits of the form $y = bx$ were made to each of the three plots.

In the case of $s$ Car v. $\beta$ Car, $b = 1.001 ± 0.006$ indicating that these two calibrators are consistent with each other. However, in the case of $\iota$ Car v. $\beta$ Car, $b = 0.897 ± 0.007$ and for $\iota$ Car v. $s$ Car, $b = 0.897 ± 0.009$. Since both these latter two plots show essentially the same slope, which differs significantly from the value of unity expected if the calibrators were consistent, it suggests that the value adopted for the uniform-disc angular diameter of $\iota$ Car is too small. One possible explanation for this inconsistency is that $\iota$ Car is a binary system but there is no evidence in the literature to support this. A careful examination of the SUSI data for the signature variations expected from a binary system has proved negative. It appears that the value adopted for the uniform-disc angular diameter of $\iota$ Car is too small. Although it is hard to justify, arbitrarily increasing the angular diameter of $\iota$ Car to 1.77 ± 0.12 mas, 2σ greater than predicted, gives $b$ values closest to unity for $\iota$ Car v. $\beta$ Car and $\iota$ Car v. $s$ Car ($b = 1.001 ± 0.011$ for $\iota$ Car v. $s$ Car and $b = 1.003 ± 0.009$ for $\iota$ Car v. $\beta$ Car). The implications of making this change to the value of the uniform-disc angular diameter of $\iota$ Car will be discussed in Section 8 but the analysis will initially be completed with the data in Table 4 which is based on the uniform-disc angular diameter of $\iota$ Car being equal to 1.55 ± 0.12 mas.

### 5.4 Limb-darkening factors

In order to determine the true, limb-darkened angular diameters, the uniform-disc angular diameters have to be multiplied by limb-darkening factors ($\rho_2$) that are dependent on the centre-to-limb (CTL) intensity distributions for the star. The CTL intensity...
distributions are dependent on wavelength, and on the effective temperature ($T_{\text{eff}}$), surface gravity ($\log g$) and composition ([Fe/H]) of the stellar atmosphere.

The form of the CTL intensity distribution and its phase dependence has been questioned. Marengo et al. (2002, 2003) have computed CTL intensity distributions for the Cepheid $\xi$ Gem and shown that their distributions computed for hydrodynamic models in spherical geometry differ from those for hydrostatic, plane–parallel models, particularly at certain ranges in phase. Nardetto et al. (2006b) have used a hydrodynamic model of $\delta$ Cep to derive intensity distributions in the continuum and in four spectral lines. They found that limb-darkening in the continuum revealed a systematic shift in phase of the derived angular diameter of 0.02. However, the distance is not affected because it is linked to the amplitude of the angular diameter curve, which is only slightly changed by the shift effect. They further claim that considering the time dependence of limb-darkening does not seem to be a priority for the Interferometric Baade–Wesselink (IBW) method. The validity of this claim is considered in Section 8.1 and the use of a phase-dependent limb-darkening factor is justified for the wavelength of the observations presented here (696 nm).

In the absence of a CTL intensity distribution computed for a hydrodynamic model of $\ell$ Car, as done for $\xi$ Gem, use has been made of the tabulation of $\rho_\delta$ by Davis et al. (2000) computed for the extensive grid of CTL intensity variations given by Kurucz (1993a,b) for his model atmospheres.

A value of [Fe/H] = 0.3 has been adopted for $\ell$ Car following Cayrel de Strobel et al. (1997). Taylor (1999) has tabulated 47 values of $T_{\text{eff}}$ and $\log g$ as a function of phase, and these data have been adopted to establish a $\rho_{696}$ versus phase curve. For each phase tabulated by Taylor, a value for $\rho_{696}$ was interpolated from the Davis et al. (2000) tabulation. A sixth-order Fourier series was fitted to the resulting values of $\rho_{696}$ versus phase (the lowest order to give a smooth and accurate representation of the data; the data have a standard deviation from the fitted curve of 0.002 24). The coefficients of the fit were then used to compute values for $\rho_{696}$ for the phases of the SUSI uniform-disc angular diameter determinations. These values are listed in Table 4 and plotted in Fig. 2. Fig. 2 also includes the values determined for the Taylor phases and the curve fitted to them. Taylor included estimates of the uncertainties in the values of $T_{\text{eff}}$ and $\log g$ in her tabulation and from these uncertainties it is estimated that the values of $\rho_{696}$ in Table 4 are accurate to ±0.001, with the caveat that we are assuming that the Kurucz models upon which Davis et al. (2000) based their tabulation of limb-darkening factors are appropriate for $\ell$ Car. The mean value of $\rho_{696}$ for the fitted curve is 1.057.

5.5 The limb-darkened angular diameters

The uniform-disc angular diameters have been converted to limb-darkened angular diameters ($\theta_{1\text{LD}}$) in Table 4 using the listed limb-darkening correction factors. The uncertainties in the uniform-disc and limb-darkened angular diameters given in Table 4 do not include the uncertainty in the effective wavelength, which is a systematic uncertainty of ±0.3 per cent. Its effect on the mean angular diameter and on the distance to $\ell$ Car will be discussed in Section 8. The uncertainty in the limb-darkened angular diameter in Table 4 does, however, include the uncertainty in the limb-darkening correction factor.

6 THE SPECTROSCOPIC DATA

In order to determine the distance and mean diameter of $\ell$ Car, the radial displacements of the stellar surface as a function of phase are required for combination with the limb-darkened angular diameters. The starting point for establishing the radial displacements is the observed radial velocity curve as a function of phase.

6.1 The radial velocity data

The most extensive radial velocity data set is that by Taylor et al. (1997) based on 67 spectra from MSO in Australia and 70 spectra from MJUO in New Zealand. Early measurements of radial-velocity-induced spectral line displacements were generally made by line centroid or bisecion estimates made by eye [e.g. Dawe (1969) which was the last published velocity curve for $\ell$ Car prior to Taylor et al. (1997)].

Taylor et al. (1997) determined radial velocities by averaging the radial velocities for 19 metallic lines measured by the line-bisector method (Wallerstein et al. 1992) from an average of depths 0.7, 0.8 and 0.9 (continuum at 0.0 and core at 1.0). The MSO and MJUO
sets of data were initially phased using the ephemeris of Shobbrook (1992), but Taylor et al. (1997) found a small phase shift between the earliest MJUO observations and later observations and derived a small phase correction to bring all the MSO and MJUO observations into phase alignment. We have adopted their tabulated data that include the phase adjustments with three exceptions. The JDs 244 9408.65 and 245 0380.57 for MSO data and 244 9408.66 for MJUO data correspond to times during daylight hours, so data for these dates have been omitted leaving a total of 134 data points.

Bersier (2002) lists HJDs for 19 radial velocity measurements for \( \ell \) Car but does not give phases. For \( \ell \) Car, the maximum difference between HJD and JD is negligible at less than \( 3 \times 10^{-5} \) of the pulsation period and has been ignored. Phases have been computed with Shobbrook’s ephemeris and the resulting data are in good phase agreement with the data of Taylor et al. (1997), discussed above, but there is an offset in radial velocity. Kervella et al. (2004b) first noted this and chose ‘to shift the Taylor et al. (1997) data set by \(-1.5 \text{ km s}^{-1}\) to bring all the data on the well-established CORAVEL system of Bersier (2002)’. Since the data set of Taylor et al. (1997) is significantly more numerous than that of Bersier (2002) (134 data points versus 19), and the decision has been made to adopt the Taylor et al. (1997) as the basic data set, we have adjusted the Bersier radial velocities. This decision is supported by the work of Kiss (1998) who found that, while ‘CORAVEL measurements have excellent internal accuracy, their absolute values are very uncertain’. The Bersier data, determined by the cross-correlation technique rather than the line-bisector method employed by Taylor et al. (1997), were combined with the Taylor et al. data with a range of offsets for the Bersier radial velocities. For each offset, a sixth-order Fourier series was fitted over the range in phase from \(-0.037\) to \(0.75\) (the reasons for the choice of the order of the fit and of the range in phase will be discussed in Section 6.2), and the minimum value of \( \chi^2 \) corresponds to the addition of \(2.0 \text{ km s}^{-1}\) to the Bersier data. In view of the resulting good agreement between the Bersier and Taylor et al. data over the whole pulsation cycle including the amplitude of the radial velocity variation, the Bersier data have been accepted in spite of the different technique used for measuring the line shifts.

Petterson et al. (2005) have measured 34 radial velocities at the MJUO and while these are more recent than those of Taylor et al. (1997), the technique for measuring the radial velocities by the line-bisector method is identical. As well as giving the JDs of the observations, the authors have listed phases based on an ephemeris by Pel (1976) which are significantly offset from the data of Bersier and Taylor et al. We have computed the phases from the given JDs, using the ephemeris of Shobbrook (1992), and find a small phase offset from the Taylor et al. data suggesting a glitch or period change between the Taylor et al. and the later Petterson et al. observations. In order to establish the optimum phase adjustment, the Petterson et al. data were combined with the Taylor et al. data with a range of phase offsets. For each offset, a sixth-order Fourier series was fitted over the range in phase from \(-0.037\) to \(0.75\), as in the case of the Bersier radial velocities, and the minimum value of \( \chi^2 \) corresponds to the subtraction of \(0.02\) in phase from the Petterson et al. (2005) data. The adjusted Petterson et al. data are in excellent agreement with the combined Taylor et al. and Bersier radial velocity data with the exception of the five data points for JD 245 1163.0392, 245 0683.1543, 245 0683.8039, 245 0684.1304 and 245 0684.8105 which all lie several times the quoted uncertainties from the combined Taylor et al., Bersier and Petterson et al. plot of radial velocity against phase. The Petterson et al. data have been accepted with the exception of the five discrepant points.

Nardetto et al. (2006a) have published radial velocities for \( \ell \) Car determined by three different methods of measuring line displacements. These methods differ from those used for the data considered so far and result in a range of amplitudes of the radial velocity curve bracketing the amplitude of the curve determined from the Taylor et al., Bersier and Petterson et al. curve with none of the three agreeing with it. In view of the disagreement with the other three sources, the Nardetto et al. (2006a) data have not been included.

6.2 The radial velocity curve

Fig. 3 shows the assembled radial velocity data versus phase together with the fitted curve. Attempts were made to fit a Fourier series to the assembled data, but even with a 16th-order series the fit was poor in parts. Taylor (1999) overcame this difficulty by fitting a sixth-order Fourier fit to the ascending branch of the curve and a ninth-order fit to the descending branch. After some experimentation, it was found that the good fit shown in Fig. 3 could be obtained by dividing the curve into three ranges in phase and making a separate sixth-order Fourier series fit to each. The ranges of the fits, which overlap, are listed in Table 5. In each case, the reduced \( \chi^2 \) values indicated that the published uncertainties in the radial velocities are optimistic. Adopting uncertainties of \(\pm 0.45\), \(\pm 0.50\) and \(\pm 1.0 \text{ km s}^{-1}\) for the rising, middle and falling sections, respectively, gave reduced \( \chi^2 \) values close to unity. The coefficients of the fits were matched (further details are given in the text).

| Section          | Phase range | \( N \) | \( N_F \) | Phase(M) |
|------------------|-------------|--------|--------|--------|
| Rising           | \(-0.037\) to \(0.75\) | 137    | 6      | 0.710  |
| Rising to middle | 0.701 to 0.896 | 42     | 6      | 0.890  |
| Middle           | 0.862 to 1.031 | 38     | 6      | 0.015  |
| Middle to falling|             |        |        |        |
| Falling          |             |        |        |        |
| Falling to rising|             |        |        |        |

\( N \) is the number of data points in each range in phase, \( N_F \) is the order of the Fourier series fit and Phase(M) is the phase at which the separate fits were matched (further details are given in the text).
were employed to compute radial velocities at intervals of 0.005 in phase over the ranges of the fits, and plots were made of the fits in the overlapping regions. The phases for the transitions from one fit to the next were chosen by the inspection of these plots and were the phases at which the overlapping fits were closest to each other. For the transition between the rising and middle sections, the radial velocities at phase 0.710 were adjusted to an intermediate value to give a smooth transition between the fits on either side. Similarly, for the transition between the middle and falling sections, the radial velocity at phase 0.890 was adjusted and, for the transition between the falling and rising sections, the radial velocity at phase 0.015 was adjusted. The adjustments to the radial velocities were small, averaging ~0.3 per cent of the mean radial velocities at the transitions. The fits are summarized and the phases at which they were matched are listed in Table 5.

The radial velocity curve shown in Fig. 3, assembled from the Fourier series fits listed in Table 5, has been adopted for the subsequent analysis.

6.3 The \( p \)-factor

The radial velocity curve in Fig. 3 is for the measured radial velocities but does not represent the true radial velocity of the stellar surface since it is a value integrated over the stellar surface. It includes projection and limb-darkening effects that vary from the centre to the limb of the star. These effects depend on spectral line shape, which is not only a function of phase but is also affected by the velocity structure within the line-forming region and the contributions from the different layers of the atmosphere. Conventionally, in the absence of sufficiently detailed modelling of the stellar atmosphere, the measured radial velocities are multiplied by a constant, known as the \( p \)-factor, to correct them to the radial velocity of the stellar surface. There are a number of issues to be considered in the choice of \( p \) since any error or uncertainty in the value adopted translates directly to the distance determined for the Cepheid when the spectroscopic and interferometric data are combined.

The evaluation of \( p \)-factors is generally derived from model stellar atmosphere models, but Mérand et al. (2005) have presented a measured value of 1.27 ± 0.06 for the \( p \)-factor for \( \delta \) Cep based on interferometric measurements with the CHARA (Center for High Angular Resolution Astronomy) array and on the Hubble Space Telescope parallaxes (Benedict et al. 2002). The accuracy is limited by the parallax, and the authors conclude that theoretical studies using realistic hydrodynamical codes are needed.

The literature dealing with the theoretical evaluation of the \( p \)-factor from model atmosphere studies is extensive but with no clear results applicable to \( \ell \) Car. While Sabbey et al. (1995) claim that the phase dependence of \( p \) increases the Baade–Wesselink (BW) radius by ~4–6 per cent, depending on the constant value of \( p \) used for comparison, Nardetto et al. (2004) claim that their choice of a constant \( p \)-factor for the IBW method, compared to a time-dependent one, leads to a systematic error of the order of only 0.2 per cent in the final distance determination for \( \delta \) Cep.

The projection factor is also sensitive to the CTL intensity distribution or limb-darkening, but it is not clear whether a mean value for the limb-darkening is adequate or whether a phase dependence is significant for the \( p \)-factor. However, it is clear that the phase dependence of limb-darkening is significant for the conversion of uniform-disc angular diameters to limb-darkened angular diameters at 696 nm, as mentioned in Section 5.4 and justified in Section 8.1.

In most cases, more detailed modelling and, in particular, the hydrodynamic modelling in spherical geometry that predicts a phase dependence of \( p \) have been done for a particular Cepheid, most commonly \( \delta \) Cep and \( \zeta \) Gem, and the results are not in a form that can be scaled to other Cepheids. The concluding recommendation of these studies is generally that each Cepheid should be individually modelled. This is not within the scope of our programme, and we have therefore decided to use a fixed value but to make available all the relevant data to enable the results to be updated by others when improved values for \( p \), or an appropriate model for \( \ell \) Car, have been developed.

A brief summary and discussion of the fixed values of \( p \) adopted for \( \ell \) Car in the literature is appropriate at this point. As noted by Taylor et al. (1997), the value of \( p \) depends not only on the technique used to measure the radial velocities, but also on the strength of the lines chosen and their wavelengths. Taylor et al. (1997) adopted a value of 1.38 ± 0.03 (Albrow & Cottrell 1994) but revised their results (Taylor & Booth 1998) using \( p = 1.39–0.03 \log P = 1.34 \) (Hindsley & Bell 1986; Gieren, Barnes & Moffett 1993). Kervella et al. (2004b), in a comparison of the interferometric and surface-brightness techniques, used the same formula with \( p = 1.343 \) for \( \ell \) Car. In this comparison, they only considered radial velocity points in the phase interval 0.0 to 0.8 following Storm et al. (2004). However, Kervella et al. (2004a) adopted a value of 1.36 for \( p \) for all the seven Cepheids in their programme which included \( \ell \) Car and justified it on the grounds that Burki, Mayor & Benz (1982) had shown that this value was appropriate for the radial velocity measurements by Bersier (2002) that they had used. Nardetto et al. (2007) have used a hydrodynamic model of \( \ell \) Car to validate a spectroscopic method of determining the \( p \)-factor in which it was divided into three subconcepts. While their work is not directly applicable to our data, because it was restricted to a single specific spectral line and the method employed for measuring the line differed from that for the data we are using, they derived a value of 1.27 ± 0.02 for \( p \). Groenewegen (2007) has evaluated a relationship between the \( p \)-factor and pulsation period based on five Cepheids with interferometrically measured angular diameter variations and known distances taken from the literature. Based on a total of seven stars with periods in the range 5–35 d, it is claimed that there is no evidence for a period dependence of the \( p \)-factor although values found range from 1.193 to 1.706, albeit with large uncertainties in the majority of cases. For \( \ell \) Car, the \( p \)-factor is found to be 1.193 ± 0.058 ± 0.120 based on the distance of 498 ± 50 pc determined by Benedict et al. (2007) with the Hubble Space Telescope Fine Guidance Sensors. The first uncertainty is from the fitting process and the second is due to the uncertainty in the distance. The majority of distance determinations to \( \ell \) Car to date, which are listed in Table 6 and include the distance determined here, suggest a larger value for the distance to \( \ell \) Car, implying a larger value for the \( p \)-factor of the order of 1.29 if determined by the approach employed by Groenewegen. Based on the five Cepheids analysed, which had interferometrically determined angular diameters and distances, Groenewegen (2007) concluded that a constant value of \( p = 1.25 ± 0.05 \) was appropriate. But, as has been discussed, at least in the case of \( \ell \) Car a larger value is indicated.

To summarize, there is no agreement on the optimum fixed value of the \( p \)-factor to use although it is clear that it depends on the individual Cepheid and on the details of the observing and analysis techniques used for both spectroscopy and interferometry. Faced with these difficulties, we have adopted a constant value of 1.30 ± 0.05. The influence of this decision on the mean diameter and distance of \( \ell \) Car will be discussed in Section 8.
Table 6. The distance to \( \ell \) Car.

| Distance (pc) | Radius (\( R_\odot \)) | \( p \) | ID | Distance for \( p = 1.30 \) (pc) | Radius for \( p = 1.30 \) (\( R_\odot \)) | Reference |
|--------------|----------------|------|----|----------------------------|----------------------------|--------|
| 550 \( \pm 17 \) | 173 \( \pm 5 \) | 1.34 | BE | 534 \( \pm 22 \) | 168 \( \pm 7 \) | 1 |
| 566 \( ^{+24}_{-29} \) | 182\( ^{+5}_{-5} \) | 1.34 | IBW | 548\( ^{+30}_{-27} \) | 176\( ^{+9}_{-9} \) | 2 |
| 560 \( \pm 23 \) | 179 \( \pm 7 \) | 1.34 | IRSB | 542 \( \pm 30 \) | 173 \( \pm 10 \) | 2 |
| 559 \( \pm 19 \) | 179.9 \( \pm 6.4 \) | 1.34 | IRSB-Bay | 541 \( \pm 27 \) | 174 \( \pm 9 \) | 3 |
| 485 \( \pm 64 \) | -- | -- | RH | -- | -- | 4 |
| 498 \( \pm 50 \) | -- | -- | HST | -- | -- | 5 |
| 525 \( \pm 26 \) | 168.8 \( \pm 8.2 \) | 1.30 | IBW | 525 \( \pm 26 \) | 169 \( \pm 8 \) | This work |

\( p \) is the \( p \)-factor, the column headed ID contains acronyms for the methods employed with the key at the foot of the table (further details are given in the text).

Acronyms: BE – Barnes–Evans; IBW – Interferometric Baade–Wesselink; IRSB – Infrared Surface Brightness; IRSB-Bay - Infrared Surface Brightness (Bayesian); RH – Revised Hipparcos Parallaxes; HST – Hubble Space Telescope Fine Guidance Sensors. References: 1 – Taylor & Booth (1998); 2 – Kervella et al. (2004b); 3 – Barnes et al. (2005); 4 – van Leeuwen (2007) and 5 – Benedict et al. (2007).

6.4 The radial displacement curve

Integration of the radial velocity curve shown in Fig. 3 gave the radial velocity of the centre of mass \( V_r \), equal to \(+4.13 \pm 0.01 \) km s\(^{-1} \) where the uncertainty has been estimated using the bootstrapping method. This differs from the value of \(+4.21 \pm 0.01 \) km s\(^{-1} \) given by Taylor et al. (1997) but is based on the assembly of a larger body of radial velocity data.

The radial displacement of the stellar surface in solar radii \( \Delta R(\phi) \), as a function of phase \( \phi \), was found by integrating the radial velocity \( V_r(\phi) \), after correction for \( V_c \), using

\[
\Delta R(\phi) = \frac{P}{R_\odot} \int (V_r(\phi) - V_c) d\phi,
\]

where \( P \) is the pulsation period in seconds and \( R_\odot \) is the solar radius in km.

The integrations were made at intervals in phase of 0.005 and the resulting values of radial displacement, after the determination and subtraction of the mean value, were fitted with a Fourier series. Series of increasing order were fitted and it was found that the reduced \( \chi^2 \) value for the fits had a minimum value for a 16th-order fit. This has been adopted for the subsequent analysis. The uncertainty in the radial displacements has been evaluated following Taylor et al. (1997) using the expression by Balona (1977):

\[
\sigma(RD) = \frac{P \sigma(RV)}{2 R_\odot \sqrt{N}},
\]

where \( \sigma(RD) \) is the uncertainty in radial displacement in solar radii, \( P \) is the pulsation period in seconds, \( \sigma(RV) \) is the standard deviation of the radial velocities about the fitted curve, \( (\sigma(RV) = 0.6 \) km s\(^{-1} \). \( R_\odot \) is the solar radius in km and \( N \) is the number of observations. Substitution in equation (5) gives \( \sigma(RD) = 0.13 R_\odot \) (less than 0.4 per cent of the total radial displacement due to the Cepheid pulsation).

7 THE COMBINATION OF INTERFEROMETRIC AND SPECTROSCOPIC DATA

The relationship between the limb-darkened angular diameter \( \theta_{\text{LD,obs}} \) and the radial displacement of the Cepheid surface is given by

\[
\theta_{\text{LD,obs}}(\phi_i) = \bar{\theta}_{\text{LD}} + 9.298 \left[ \frac{\Delta R(\phi_i)}{d} \right] \text{mas},
\]

where \( \bar{\theta}_{\text{LD}} \) is the mean limb-darkened angular diameter (the limb-darkened angular diameter at zero displacement), \( \Delta R(\phi) \) is the radial displacement in solar radii for the \( i \)th observation at phase \( \phi_i \), \( d \) is the distance in pc and the constant converts the term in metres from Fiala (1999).

A weighted linear least-squares fit has been made to \( \theta_{\text{LD,obs}}(\phi) \) versus \( \Delta R(\phi) \) to determine \( \bar{\theta}_{\text{LD}} \) and \( d \) for \( \ell \) Car. A small phase shift was found between the angular diameter and radial velocity data, which is not surprising since the epoch of the first SUSI observation was more than 40 pulsation periods after the last radial velocity observation. The phase offset was established by repeating the fit with a range of phase offsets to find the minimum value of reduced \( \chi^2 \) for the fit. The phase offset was found to be a correction of \(-0.0635 \pm 0.015 \) to the phases of the radial displacements relative to the phases of the angular diameters. The fit using this offset gives the mean limb-darkened angular diameter of \( \ell \) Car equal to 2.981 \( \pm 0.005 \) mas and the distance to \( \ell \) Car equal to 523 \( \pm 15 \) pc. The observational data are shown in Fig. 4 with the fitted line.
mean limb-darkened angular diameter of \( \ell \) Car, with the systematic uncertainty in parentheses, is \( \theta_{LD} = 2.990 \pm 0.014(\pm 0.009) \) mas. This value is in excellent agreement with the only other direct interferometric determination by Kervella et al. (2004a) of 2.988 \( \pm 0.012 \) mas.

The corresponding two values for the distance presented in Section 7, namely 523 \( \pm 15 \) and 526 \( \pm 15 \) pc, are in good agreement and we adopt 525 \( \pm 16 \) pc for the distance. There are two systematic uncertainties in the distance due to the effective wavelength (\( \pm 0.3 \) per cent) and the \( p \)-factor (\( \pm 3.8 \) per cent). The value for the distance to \( \ell \) Car, with the systematic uncertainty in parentheses, is 525 \( \pm 16 \) (\( \pm 20 \)) pc. Combining the uncertainties quadratically gives the distance as 525 \( \pm 26 \) pc.

8.1 A constant versus a phase-dependent limb-darkening factor

The limb-darkening factor for converting uniform-disc angular diameters to limb-darkened angular diameters is expected to vary with pulsation phase and we have taken this into account as discussed in Section 5.4. However, the question has been asked as to whether this was necessary and would a constant value, equal to the mean value taken from the curve in Fig. 2, have given different results. To examine this, the entire analysis has been repeated using the mean value of the limb-darkening factor of 1.057, given in Section 5.4, in place of the phase-dependent values given in Table 4.

The mean limb-darkened angular diameter was found to be unchanged as expected. The mean limb-darkened angular diameter of \( \ell \) Car was 2.979 \( \pm 0.017 \) mas for the uniform-disc angular diameter of the calibrator \( \iota \) Car equal to 1.55 mas and 2.997 \( \pm 0.017 \) mas for \( \iota \) Car equal to 1.77 mas, where the statistical and systematic uncertainties have been combined quadratically. In each case, the values are slightly smaller than the values for the phase-dependent limb-darkening factor (0.002 mas), but this is a result of the rounding of the mean value of the limb-darkening factor.

The distance to \( \ell \) Car is changed because the mean limb-darkening factor results in a smaller angular pulsation amplitude (0.525 \( \pm 0.018 \) mas compared with 0.560 \( \pm 0.018 \) mas). The corresponding values for the distance are 559 \( \pm 17 \) and 561 \( \pm 17 \) pc compared with 523 \( \pm 15 \) and 526 \( \pm 15 \) pc for the phase-dependent limb-darkening factor. The mean of the two values in each case is 560 \( \pm 18 \) and 525 \( \pm 16 \) pc. The difference is significant and justifies the use of the phase-dependent limb-darkening factor. Kervella et al. (2004b) neglected the phase dependence of the limb-darkening factor in their study of \( \ell \) Car. Their decision was based on the estimate by Marengo et al. (2003) that the variation would be less than 0.3 per cent peak to peak in the \( H \) band for \( \iota \) Gem and the fact that it would be even less in the \( K \) band. At 696 nm, the limb-darkening factor varies by more than 1.3 per cent, as shown in Fig. 2, and cannot be ignored.

8.2 A comparison of distance and radius determinations

Table 6 lists recent values for the distance to \( \ell \) Car from the literature together with the value determined in this work for a phase-dependent limb-darkening factor. For the latter, the statistical and systematic uncertainties have been combined quadratically. The value by Taylor & Booth (1998) using the Barnes–Evans (BE) method, which succeeds the value by Taylor et al. (1997), has an unrealistic published uncertainty of \( \pm 4 \) pc because systematic effects have not been taken into account. Gieren, Fouqué & Gómez (1997) have shown that a systematic uncertainty of the order of
The uncertainty in the p-factor is a major contributor to the uncertainties in the distance and mean radius. The SUSI data may be useful in the future if ℓ Car specific hydrodynamic spherical models are generated that consider the possibility of a phase-dependence of limb-darkening and the p-factor as discussed, for example, by Sasselov & Karovska (1994) and Marengo et al. (2002). To facilitate such possible applications, the calibrated V values may be obtained from the lead author (JD).

ACKNOWLEDGMENTS

The SUSI programme is funded jointly by the Australian Research Council and the University of Sydney. MJI acknowledges the support of an Australian Postgraduate Award, APJ and JRN the support of University of Sydney Postgraduate Awards and APJ the support of a Denison Postgraduate Award during the course of this work. We are grateful to the referee who made a number of suggestions that have helped clarify and justify the approach we have adopted in our analysis. This research has made use of the SIMBAD data base, operated at CDS, Strasbourg, France.

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