ANALYSIS OF CEPHEID SPECTRA

Thesis submitted for the degree of
Doctor of Philosophy
by

Melinda Marie Taylor

Chatterton Astronomy Department
School of Physics
University of Sydney
Australia

November 1998
Dedicated to my Grandmother
Publications

The material in this thesis is based closely on the following publications:


Contents

1 Introduction ................................................................. 2
   1.1 Synopsis of Thesis .................................................. 6

2 Observational Analysis .................................................. 7
   2.1 Observational Programme .......................................... 7
   2.1.1 Telescope configurations ...................................... 8
   2.2 Reduction of Échelle Spectra ..................................... 9
       2.2.1 IRAF reduction procedure .................................. 9
       2.2.2 FIGARO reduction procedure ............................... 12
       2.2.3 Radial velocity standards ................................. 13

3 Radial Velocity Analysis ............................................... 15
   3.1 The Line Bisector Method ....................................... 15
   3.2 Preliminary Radial Velocity Results ............................ 17
   3.3 ℓ Carinae ............................................................ 18
       3.3.1 Period changes in ℓ Carinae .............................. 19
       3.3.2 Comparison with early spectroscopic data .......... 22
       3.3.3 An upper limit on cycle-to-cycle variations ........ 24
       3.3.4 Shock waves in the atmosphere of ℓ Carinae ....... 27
   3.4 β Doradus ............................................................ 29
       3.4.1 Bump Cepheids .............................................. 30
       3.4.2 Comparison with early spectroscopic data .......... 32
       3.4.3 An upper limit on cycle-to-cycle variations ....... 34

4 Effective Temperature, Surface Gravity and Microturbulence .... 37
   4.1 High Resolution Spectra and Static Model Atmospheres .... 38
4.1.1 Line widths ............................................. 41
4.2 Results of Analysis ........................................ 42
  4.2.1 Comparison with temperatures scales ............... 46
  4.2.2 Comparison with other reddenings ..................... 48
4.3 Effective Temperatures from MJUO Spectra ............. 49

5 Distances and Radii ........................................... 53
  5.1 The Barnes-Evans Technique .............................. 53
    5.1.1 Systematics in the BE method ....................... 56
    5.1.2 The distance to and radius of ℓ Car ................ 57
    5.1.3 The distance to and radius of β Dor ................ 61
    5.1.4 Comparison with previous determinations .......... 62
    5.1.5 Inverse least-squares fit? ......................... 66
  5.2 The Fourier Baade-Wesselink Technique ................ 66
    5.2.1 BW distances and radii ............................. 68
  5.3 Phase Mismatches ......................................... 71
  5.4 Reddening Effects ....................................... 72
  5.5 Period-Luminosity Relations ............................. 72

6 Atmospheric Line Phenomena ................................ 73
  6.1 Outline of Analysis ..................................... 74
  6.2 Analysis of Metallic Lines ............................... 76
    6.2.1 Line-level effects ................................ 76
    6.2.2 Line profile asymmetries ........................... 78
  6.3 Analysis of the Hα and Hβ Lines ....................... 84
    6.3.1 Hα and Hβ radial velocity curves ................. 85
    6.3.2 Line-profile asymmetries ......................... 90
    6.3.3 Comparative summary .............................. 94
    6.3.4 Emission in Hα & Hβ ............................. 98

7 Ongoing Research and Further Work ........................ 105
  7.1 A Dynamic Model Atmosphere ............................. 106
    7.1.1 HERMES ........................................ 106
    7.1.2 Initial conditions ................................ 107
    7.1.3 The model atmosphere ............................ 108
Contents

7.2 Further Work .................................................. 110
7.3 A Note on SUSI and the Study of Cepheids .................. 111
7.4 Summary ....................................................... 112

Acknowledgements .................................................. 115

References ......................................................... 117

Appendices ........................................................ 123

A Radial Velocity Data for Metallic and Hydrogen lines ......... 123

B Effective Temperature, Surface Gravity, Microturbulence and Surface-brightness Data ........................................ 131

C Photometric and Radial Displacement Data ..................... 137

D Absorption Line Lists ............................................ 139
List of Figures

2.1 A reduced spectrum of Ė Car ............................................. 12
3.1 Schematic representation of a spectral line showing the bisector ... 16
3.2 Mean metallic line radial velocity curve for Ė Car, phased using Shob-
brook’s 1992 ephemeris ..................................................... 21
3.3 Mean metallic line radial velocity curve for Ė Car with new ephemeris 22
3.4 Radial velocity curve of Ė Car produced using 11 Fe I lines .......... 23
3.5 Residual velocities in Ė Car plotted against phase .................... 25
3.6 Histogram showing how Ė Car’s velocities from MJUO and MSO are
distributed around the fitted velocity curve .......................... 26
3.7 A reduced spectrum of β Dor ............................................. 29
3.8 Radial velocity curve for β Dor derived from the Fe I line at 6546.2395 Å 31
3.9 Radial velocity curve of β Dor produced using 11 Fe I lines ......... 33
3.10 Residual velocities of β Dor plotted against phase .................. 34
3.11 Histogram showing how β Dor’s velocities from MJUO and MSO are
distributed around the fitted curve ................................. 36

4.1 Observational spectra and theoretical fit ................................ 40
4.2 Line width versus phase ..................................................... 42
4.3 Derived Teff, log g, ξ, SB for Ė Car ..................................... 43
4.4 Derived Teff, log g, ξ, SB for β Dor ..................................... 44
4.5 Effective temperature curves for Ė Car ................................ 47
4.6 Effective temperature curves for β Dor ................................. 48
4.7 Derived temperature curve for Ė Car from MSO and MJUO data .. 51

5.1 Angular diameters and linear displacements of Ė Car plotted against
phase ................................................................. 58
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2</td>
<td>Phase corrected angular diameters and linear displacements for ( \ell ) Car plotted against phase</td>
<td>59</td>
</tr>
<tr>
<td>5.3</td>
<td>Linear displacement vs. angular diameter for ( \ell ) Car’s ( V, (V - K) ) data</td>
<td>60</td>
</tr>
<tr>
<td>5.4</td>
<td>Linear displacement vs. angular diameter for ( \ell ) Car’s ( K, (J - K) ) data</td>
<td>60</td>
</tr>
<tr>
<td>5.5</td>
<td>Linear displacement vs. angular diameter for ( \beta ) Dor’s ( V, (V - K) ) data</td>
<td>63</td>
</tr>
<tr>
<td>5.6</td>
<td>Linear displacement vs. angular diameter for ( \beta ) Dor’s ( K, (J - K) ) data</td>
<td>63</td>
</tr>
<tr>
<td>5.7</td>
<td>Comparison of surface-brightness relations</td>
<td>70</td>
</tr>
<tr>
<td>6.1</td>
<td>‘Standard’ radial velocity curve for ( \beta ) Dor</td>
<td>77</td>
</tr>
<tr>
<td>6.2</td>
<td>‘Standard’ radial velocity curve for ( \ell ) Car</td>
<td>77</td>
</tr>
<tr>
<td>6.3</td>
<td>Residual velocities for various classes of lines in ( \beta ) Dor</td>
<td>79</td>
</tr>
<tr>
<td>6.4</td>
<td>Residual velocities for various classes of lines in ( \ell ) Car</td>
<td>80</td>
</tr>
<tr>
<td>6.5</td>
<td>Asymmetry curves for metallic line forming regions in ( \beta ) Dor</td>
<td>81</td>
</tr>
<tr>
<td>6.6</td>
<td>Asymmetry curves for metallic line forming regions in ( \ell ) Car</td>
<td>82</td>
</tr>
<tr>
<td>6.7</td>
<td>Radial velocity curve derived from the ( H\alpha ) line in ( \beta ) Dor</td>
<td>86</td>
</tr>
<tr>
<td>6.8</td>
<td>Radial velocity curve derived from the ( H\beta ) line in ( \beta ) Dor</td>
<td>86</td>
</tr>
<tr>
<td>6.9</td>
<td>Radial velocity curve derived from the ( H\alpha ) line in ( \ell ) Car</td>
<td>87</td>
</tr>
<tr>
<td>6.10</td>
<td>Radial velocity curve derived from the ( H\beta ) line in ( \ell ) Car</td>
<td>87</td>
</tr>
<tr>
<td>6.11</td>
<td>Asymmetry curve for the ( H\alpha ) line in ( \beta ) Dor</td>
<td>91</td>
</tr>
<tr>
<td>6.12</td>
<td>Asymmetry curve for the ( H\beta ) line in ( \beta ) Dor</td>
<td>91</td>
</tr>
<tr>
<td>6.13</td>
<td>Asymmetry curve for the ( H\alpha ) line in ( \ell ) Car</td>
<td>93</td>
</tr>
<tr>
<td>6.14</td>
<td>Asymmetry curve for the ( H\beta ) line in ( \ell ) Car</td>
<td>93</td>
</tr>
<tr>
<td>6.15</td>
<td>Stacked spectra of the ( H\alpha ) line in ( \beta ) Dor</td>
<td>96</td>
</tr>
<tr>
<td>6.16</td>
<td>Stacked spectra of the ( H\beta ) line in ( \beta ) Dor</td>
<td>97</td>
</tr>
<tr>
<td>6.17</td>
<td>Stacked profiles of the ( H\alpha ) line in ( \ell ) Car</td>
<td>100</td>
</tr>
<tr>
<td>6.18</td>
<td>Stacked profiles of the ( H\beta ) line in ( \ell ) Car</td>
<td>101</td>
</tr>
<tr>
<td>7.1</td>
<td>Height of the dynamic model as a function of time</td>
<td>108</td>
</tr>
<tr>
<td>7.2</td>
<td>Velocity at different heights in the model atmosphere as a function of time</td>
<td>109</td>
</tr>
<tr>
<td>7.3</td>
<td>Temperature at different heights in the model atmosphere as a function of time</td>
<td>110</td>
</tr>
</tbody>
</table>
List of Tables

2.1 Table of Cepheid Observations .......................... 8

3.1 Absorption lines used to obtain bisector velocities for \( \ell \) Car ........ 19
3.2 \( \ell \) Car’s period defined at various epochs from 1901 to 1997 .......... 20
3.3 Tabulation of Hertzsprung bump progression in Cepheids ............ 32

4.1 Spectral lines used in derivation of \( T_{\text{eff}} \), log \( g \) and \( \xi \) ........... 38
4.2 Comparison of derived effective temperatures for \( \ell \) Car and \( \beta \) Dor . 46
4.3 Reddenings derived from spectral type .......................... 49
4.4 Spectral lines used in derivation of \( T_{\text{eff}} \) using MJUO spectra .... 50

5.1 Derived BE distances and mean radii of \( \ell \) Car ..................... 59
5.2 Derived BE distances and mean radii for \( \beta \) Dor .................... 62
5.3 Distances and radii for \( \ell \) Car and \( \beta \) Dor ..................... 65
5.4 BW data and quality .............................................. 68
5.5 Derived BW radii, magnitudes and distances for \( \ell \) Car and \( \beta \) Dor .. 69

6.1 Comparison of properties of the H\( \alpha \) and H\( \beta \) radial velocity curves of
Cepheids of different periods, ........................................ 89
6.2 Summary of asymmetry curve parameters for the H\( \alpha \), H\( \beta \) and metallic
lines in \( \ell \) Car and \( \beta \) Dor ........................................ 94
6.3 Summary of emission features in \( \ell \) Car and \( \beta \) Dor .................... 102

7.1 Input parameters for HERMES code .......................... 107

A.1 Mean radial velocities for \( \ell \) Car derived from MSO spectra .......... 124
A.2 Mean radial velocities for \( \ell \) Car derived from MJUO spectra .......... 125
A.3 Radial velocities for \( \beta \) Dor derived from the Fe I at 6546.2395 \( \AA \) ... 126
List of Tables

A.4 Radial velocities and asymmetries from the Hα and Hβ lines in β Dor 127
A.5 Radial velocities and asymmetries from the Hα and Hβ lines in ℓ Car 129

B.1 Effective temperature, surface gravity, microturbulence and surface-brightness parameters derived for ℓ Car .......................... 132
B.2 Effective temperature, surface gravity, microturbulence and surface-brightness parameters derived for β Dor ................................. 134
B.3 Additional effective temperature and surface-brightness parameters derived for ℓ Car from MJUO spectra ................................. 136

C.1 Data used in derivation of the distance and radius of ℓ Car .......... 137
C.2 Data used in derivation of the distance and radius of β Dor .......... 138

D.1 High excitation potential (EP) FeI lines .............................. 139
D.2 Absorption line wavelengths ............................................. 140
Abstract

Using high resolution optical spectra from Mount John University Observatory, Mount Stromlo Observatory and the Anglo-Australian Observatory, new, high accuracy radial velocity curves have been obtained for the two bright southern Cepheids ℓ Carinae (HR 3884) and β Doradus (HR 1922). An indepth investigation into period variations, cycle-to-cycle and long-term variations in the velocity curves and the reliability of the combination of velocity data from different observatories is carried out. Evidence for shock waves in the atmosphere of ℓ Car and resonance in β Dor is discussed.

A grid of static model atmospheres incorporating plane-parallel geometry is compared with the observational spectra of both Cepheids, using line depth ratios, to determine the variation in effective temperature, surface gravity and microturbulence with phase. This information is used to determine the phase dependence of the surface-brightness for both Cepheids. The surface brightness variation with phase was found to follow an almost linear relationship.

The distance to and radius of the Cepheids are determined using both a near-infrared version of the Barnes-Evans method and the Fourier Baade-Wesselink (BW) method. The derived radii and distances agree within the limits of the errors for both methods. The Fourier BW method was found to be very sensitive to phase shifts between the photometric and spectroscopic data and the derived distance highly dependent on the assumed reddening.

An investigation into line profile variations in ℓ Car and β Dor has revealed the magnitude of these phenomena increase as the pulsational period of the Cepheid increases. It is estimated that line level variations introduce an additional uncertainty into derived radii of approximately 4 per cent for β Dor and 10 per cent in ℓ Car. The uncertainty introduced into derived distances and radii by line profile asymmetries was estimated to be of the order of 6 per cent in β Dor and 10 per cent in ℓ Car.

A comparative analysis is made of the hydrogen line radial velocity curves of ℓ Car and β Dor. A trend in the properties of these radial velocity curves with period has been revealed. In longer period Cepheids, the Hα line seems to be forming in a
region that does not partake in the pulsation as a whole, probably in a chromospheric shell.

A quantitative analysis of the asymmetries in these lines reveal large redward asymmetries near maximum infall velocity. The magnitude of these asymmetries and the period for which they are present are larger in ℓ Car than in β Dor. The blueward asymmetries in the Hα line in ℓ Car are comparable in magnitude to the redward asymmetries while the other lines exhibit only small blueward asymmetries.

A qualitative analysis of these line profiles with phase reveal no conclusive evidence for line doubling in these Cepheids. Evidence of emission is found in the Hα and Hβ lines of β Dor and ℓ Car. The strength and duration of the emission is found to be greater in the longer period Cepheid. Although it is likely that this emission is shock-related, theoretical work is needed to determine the exact origin of the emission.

A non-LTE radiative hydrodynamic model for ℓ Car has been created. This atmosphere will be used in further work to calculate synthetic spectral line profiles which will aid the interpretation of our observational results.