# Analysis of B and Be Star Populations of the Double Cluster h and χ Persei

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## Abstract

We present blue optical spectra of 82 members of h and χ Per obtained with the WIYN telescope at Kitt Peak National Observatory. From these spectra, several stellar parameters were measured for the B type stars, including *V sin i*, $T_{eff}$, *log* $g_{polar}$, $M_\star$, and $R_\star$. Strömgren photometry was used to measure $T_{eff}$ and *log* $g_{polar}$ for the Be stars. We also analyze photometric data of cluster members and discuss the near-IR excesses of Be stars.

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## Tables of Measured Stellar Parameters

NGC 869 = h Persei

| WEBDA | V sin i (km s$^{-1}$) | Error V sin i (km s$^{-1}$) | $T_{eff}$ (K) | Error $T_{eff}$ (K) | log g (dex) | Error log g (dex) | log $g_{polar}$ (dex) | $M_\star$ ($M_\odot$) | $R_\star$ ($R_\odot$) |
|---|---|---|---|---|---|---|---|---|---|
| 16 | 75 | 15 | 19466 | 150 | 2.38 | 0.05 | 2.49 | 29 | 50.9 |
| 49 | - | - | 23547 | 1680 | 2.99 | 0.12 | 2.99 | 23.3 | 25.6 |
| 63 | 148 | 44 | 21600 | 200 | 3.75 | 0.02 | 3.86 | 8.8 | 5.8 |
| 87 | 83 | 24 | 10500 | 50 | 4 | 0.02 | 4.07 | 2.7 | 2.5 |
| 90 | 57 | 24 | 22000 | 300 | 3.58 | 0.02 | 3.61 | 10.9 | 8.6 |
| 133 | 331 | 32 | 16350 | 350 | 3.85 | 0.05 | 4.17 | 4.9 | 3 |
| 138 | 98 | 9 | 19060 | 250 | 3.83 | 0.02 | 3.9 | 7 | 4.9 |
| 197 | 261 | 57 | 11300 | 50 | 4.3 | 0.02 | 4.48 | 2.5 | 1.5 |
| 250 | 110 | 20 | 16350 | 50 | 3.9 | 0.02 | 3.98 | 5.4 | 3.9 |
| 260 | 179 | 12 | 25743 | 850 | 3.38 | 0.08 | 3.56 | 15.6 | 10.9 |
| 289 | 66 | 10 | 19550 | 150 | 3.75 | 0.02 | 3.79 | 7.8 | 5.9 |
| 323 | 44 | 14 | 20600 | 100 | 3.75 | 0.02 | 3.77 | 8.7 | 6.4 |
| 339 | 86 | 12 | 25690 | 800 | 3.43 | 0.08 | 3.48 | 16.8 | 12.3 |
| 350 | 134 | 13 | 18100 | 200 | 3.78 | 0.03 | 3.89 | 6.6 | 4.8 |
| 380 | 110 | 8 | 18600 | 100 | 3.85 | 0.02 | 3.93 | 6.7 | 4.6 |
| 517 | 149 | 17 | 19904 | 800 | 3.15 | 0.05 | 3.32 | 10.9 | 12 |
| 530 | 60 | 8 | 23606 | 600 | 3.85 | 0.05 | 3.87 | 10.6 | 6.3 |
| 551 | 220 | 14 | 19360 | 300 | 3.49 | 0.02 | 3.72 | 8 | 6.5 |
| 566 | 308 | 45 | 19842 | 400 | 2.99 | 0.02 | 3.46 | 9.8 | 9.6 |
| 590 | 120 | 9 | 22000 | 200 | 3.5 | 0.02 | 3.6 | 10.9 | 8.6 |
| 662 | 66 | 19 | 23908 | 1050 | 3.05 | 0.1 | 3.09 | 21.3 | 21.7 |
| 678 | 103 | 16 | 21650 | 350 | 3.37 | 0.03 | 3.46 | 11.6 | 10.4 |
| 692 | 168 | 25 | 25930 | 1000 | 3.43 | 0.08 | 3.58 | 15.4 | 10.5 |
| 731 | 162 | 8 | 20791 | 550 | 3.7 | 0.05 | 3.83 | 8.5 | 5.9 |
| 748 | 231 | 42 | 11650 | 150 | 3.85 | 0.05 | 4.05 | 3.2 | 2.8 |
| 768 | 49 | 11 | 17140 | 250 | 3.37 | 0.03 | 3.4 | 7.8 | 9.2 |
| 769 | 127 | 7 | 22100 | 250 | 3.64 | 0.03 | 3.74 | 10 | 7.1 |
| 789 | 183 | 29 | 17450 | 50 | 4 | 0.02 | 4.14 | 5.6 | 3.3 |
| 803 | 273 | 23 | 22800 | 100 | 3.4 | 0.02 | 3.69 | 11 | 7.8 |
| 843 | 112 | 14 | 21150 | 150 | 3.3 | 0.02 | 3.41 | 11.5 | 11 |
| 846 | 206 | 28 | 19950 | 50 | 3 | 0.02 | 3.27 | 11.3 | 13 |
| 847 | 78 | 29 | 28760 | 300 | 3.62 | 0.03 | 3.65 | 18.7 | 10.8 |
| 859 | 207 | 6 | 21830 | 500 | 3.65 | 0.05 | 3.82 | 9.1 | 6.1 |
| 864 | 152 | 28 | 23680 | 700 | 3.75 | 0.05 | 3.85 | 10.8 | 6.4 |
| 922 | 257 | 17 | 21593 | 600 | 2.98 | 0.02 | 3.35 | 12.5 | 12.4 |
| 1001 | 65 | 17 | 22450 | 150 | 3.5 | 0.02 | 3.54 | 11.8 | 9.7 |
| 1067 | 54 | 26 | 22020 | 300 | 3.73 | 0.02 | 3.75 | 9.9 | 6.9 |
| 1078 | 197 | 18 | 28816 | 200 | 3.67 | 0.02 | 3.79 | 16.7 | 8.6 |
| 1085 | 82 | 15 | 22383 | 350 | 3.48 | 0.02 | 3.54 | 11.7 | 9.6 |
| 1132 | 103 | 6 | 23443 | 700 | 3.04 | 0.05 | 3.15 | 18.7 | 19.1 |
| 1141 | 230 | 13 | 19728 | 350 | 3.06 | 0.02 | 3.37 | 10.4 | 11 |
| 1162 | 72 | 10 | 19150 | 100 | 2.3 | 0.02 | 2.4 | 32.9 | 59.6 |
| 1174 | 66 | 9 | 19100 | 100 | 3.85 | 0.02 | 3.89 | 7 | 5 |
| 1181 | 76 | 6 | 17066 | 200 | 3.87 | 0.03 | 3.92 | 6 | 4.4 |
| 1261 | - | - | 24724 | 1680 | 3.18 | 0.12 | 3.18 | 21.1 | 19.6 |
| 1268 | 141 | 21 | 25521 | 600 | 3.4 | 0.05 | 3.53 | 15.7 | 11.3 |
| 1278 | 191 | 6 | 24051 | 1680 | 3.04 | 0.12 | 3.3 | 17.1 | 15.3 |
| 1364 | 230 | 10 | 19960 | 300 | 3.24 | 0.02 | 3.52 | 9.5 | 8.9 |
| 1387 | 71 | 20 | 20480 | 300 | 3.82 | 0.02 | 3.86 | 8.2 | 5.6 |
| 1391 | 152 | 20 | 22150 | 150 | 3.5 | 0.02 | 3.64 | 10.8 | 8.3 |
| 1516 | 151 | 15 | 25017 | 900 | 4.13 | 0.07 | 4.19 | 10 | 4.2 |
| 1548 | 182 | 21 | 14250 | 50 | 4.3 | 0.02 | 4.38 | 3.7 | 2 |
| 1586 | - | - | 22501 | 1680 | 2.9 | 0.13 | 2.9 | 22.9 | 28.1 |

From the measured values of *V sin i*, $T_{eff}$, and *log* $g_{polar}$, measurements of $M_\star$ and $R_\star$ can be made using the Schaller et al. (1992) evolutionary tracks.

NGC 884 = χ Persei

| WEBDA | V sin i (km s$^{-1}$) | Error V sin i (km s$^{-1}$) | $T_{eff}$ (K) | Error $T_{eff}$ (K) | log g (dex) | Error log g (dex) | log $g_{polar}$ (dex) | $M_\star$ ($M_\odot$) | $R_\star$ ($R_\odot$) |
|---|---|---|---|---|---|---|---|---|---|
| 1770 | 231 | 18 | 17650 | 250 | 3.72 | 0.02 | 3.94 | 6.2 | 4.4 |
| 1772 | 391 | 37 | - | - | - | - | - | - | - |
| 1793 | 113 | 28 | 11400 | 50 | 4.5 | 0.02 | 4.56 | 2.4 | 1.4 |
| 1873 | 162 | 21 | 21350 | 150 | 3.75 | 0.02 | 3.87 | 8.7 | 5.6 |
| 1899 | 131 | 16 | - | - | - | - | - | - | - |
| 1926 | - | - | 30151 | 1133 | 3.45 | 0.07 | 3.45 | 28 | 16.5 |
| 2014 | 290 | 23 | 19350 | 50 | 3.7 | 0.02 | 3.97 | 6.9 | 4.5 |
| 2048 | 98 | 11 | 19250 | 250 | 3.88 | 0.03 | 3.94 | 6.9 | 4.6 |
| 2049 | 365 | 18 | 20160 | 350 | 2.91 | 0.02 | 3.58 | 9.3 | 8.2 |
| 2057 | 149 | 12 | 19360 | 250 | 3.73 | 0.02 | 3.85 | 7.4 | 5.3 |
| 2085 | 261 | 10 | 19600 | 300 | 3.58 | 0.02 | 3.85 | 7.6 | 5.5 |
| 2091 | 278 | 33 | 29752 | 300 | 4.69 | 0.05 | 4.72 | 10.7 | 2.4 |
| 2094 | 79 | 7 | 19660 | 250 | 3.83 | 0.02 | 3.88 | 7.5 | 5.2 |
| 2112 | 85 | 16 | 22016 | 300 | 3.73 | 0.02 | 3.78 | 9.7 | 6.6 |
| 2119 | 256 | 6 | 18100 | 100 | 3.75 | 0.02 | 3.99 | 6.3 | 4.2 |
| 2138 | - | - | 24135 | 1133 | 3.03 | 0.08 | 3.03 | 24.1 | 24.8 |
| 2185 | 183 | 19 | 17450 | 250 | 3.97 | 0.03 | 4.11 | 5.7 | 3.5 |
| 2190 | 270 | 35 | 22300 | 200 | 3.3 | 0.02 | 3.61 | 11.1 | 8.6 |
| 2191 | 261 | 8 | 18050 | 50 | 3.8 | 0.02 | 4.04 | 6.2 | 3.9 |
| 2218 | 207 | 32 | 11100 | 50 | 4.2 | 0.02 | 4.3 | 2.6 | 1.9 |
| 2227 | 57 | 5 | 21500 | 100 | 3.75 | 0.02 | 3.78 | 9.2 | 6.5 |
| 2232 | 109 | 7 | 20950 | 350 | 3.62 | 0.03 | 3.71 | 9.1 | 7 |
| 2255 | 319 | 16 | 19680 | 300 | 3.27 | 0.02 | 3.7 | 8.4 | 6.7 |
| 2311 | 49 | 22 | 23500 | 200 | 3.5 | 0.02 | 3.51 | 13.2 | 10.5 |
| 2336 | 166 | 10 | 19350 | 50 | 3.95 | 0.02 | 4.07 | 6.7 | 4 |
| 2347 | 85 | 9 | 21240 | 300 | 3.86 | 0.03 | 3.91 | 8.5 | 5.4 |
| 2361 | 75 | 11 | 25426 | 500 | 3.36 | 0.05 | 3.4 | 17.7 | 13.9 |
| 2392 | 89 | 8 | 20400 | 400 | 3.6 | 0.05 | 3.67 | 8.9 | 7.2 |
| 2468 | 135 | 54 | 10600 | 50 | 4.1 | 0.02 | 4.2 | 2.6 | 2.1 |
| 2520 | 56 | 4 | 23371 | 350 | 3.69 | 0.02 | 3.71 | 11.4 | 7.8 |
| 2540 | 251 | 19 | 20080 | 300 | 3.52 | 0.02 | 3.78 | 8.3 | 6.1 |
| 2554 | 65 | 8 | 10800 | 50 | 3.6 | 0.02 | 3.67 | 3.4 | 4.5 |
| 2555 | 129 | 22 | 18200 | 50 | 4.05 | 0.02 | 4.13 | 6 | 3.5 |
| 2563 | - | - | 27330 | 1133 | 3.48 | 0.07 | 3.48 | 19.3 | 13.2 |
| 2605 | 65 | 6 | 25357 | 350 | 3.63 | 0.03 | 3.66 | 13.9 | 9.2 |
| 2622 | 360 | 4 | 18100 | 50 | 3.5 | 0.02 | 3.95 | 6.4 | 4.4 |
| 2716 | 188 | 13 | 19750 | 50 | 3.75 | 0.02 | 3.91 | 7.5 | 5 |
| 2729 | 193 | 38 | 11300 | 100 | 4.15 | 0.05 | 4.25 | 2.8 | 2.1 |
| 2907 | 156 | 33 | 15400 | 100 | 4.1 | 0.02 | 4.2 | 4.4 | 2.8 |

## Spectral Line Fitting

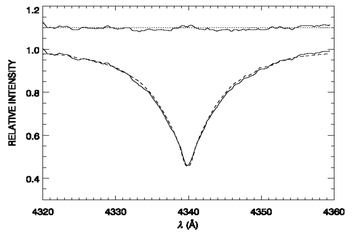



**Figure 1**

Observed and modeled spectra for the star NGC 869-1174 are shown, where Figure 1 displays the Hγ line and Figure 2 displays the He I λ4471 line.

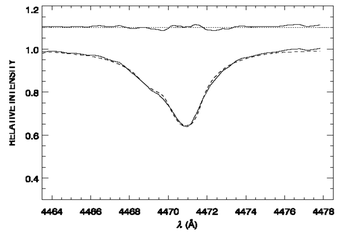



**Figure 2**

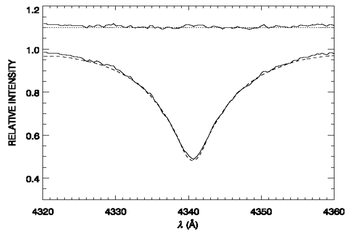



**Figure 3**

Observed and modeled spectra for the star NGC 884-1261 are shown, where Figure 3 displays the Hγ line and Figure 4 displays the He I λ4388 line.

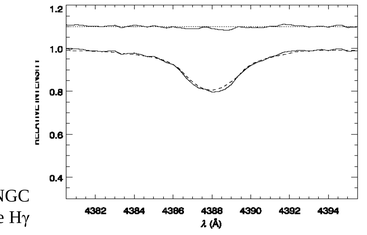



**Figure 4**

Shown above are samples of the model spectral fits used to measure values for $T_{eff}$, *log* $g_{polar}$, and *V sin i* for B-type stars. *V sin i* was determined by comparing the He I λλ4388, 4471, 4713, Mg II λ4481 with the Kurucz ATLAS9 models (Kurucz 1994), and taking a weighted average of these 4 values. For stars having $T_{eff}$ > 15000 K, the TLUSTY BSTAR2006 models (Lanz & Hubeny 2007) were used. For stars having $T_{eff}$ < 15000 K, the Kurucz ATLAS9 models were used. Our program minimizes the error between the observed spectral line and the theoretical line profile, returning the best fit stellar parameters. The Hγ line was used to determine $T_{eff}$ and *log* $g_{polar}$, as this line is particularly sensitive to these parameters. Strömgren photometry was used to derive $T_{eff}$ and *log* $g_{polar}$ for Be stars based on the method of McSwain et al. (2008).

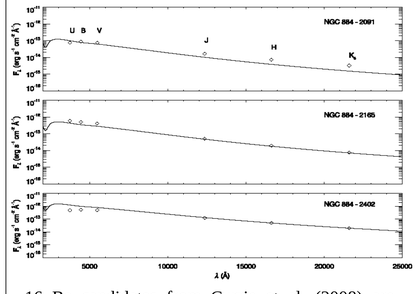



**Figure 5**: Spectral energy distribution plots for 3 stars in χ Persei are displayed. Assuming a constant E(B-V) = 0.56 for the cluster, reddened blackbody curves have been overlaid with these plots to investigate their near-IR excesses. All 3 stars are proposed Be candidates (Currie et al. 2008), yet only NGC 884-2091 has emission present in our spectrum and observed near-IR excess.

16 Be candidates from Currie et al. (2008) are present in our data or the results of Huang & Gies (2006). 5 stars show no evidence for circumstellar emission, and 1 additional star (NGC 869-566) has been observed to be a Be star in the past (Hiltner 1956) but has no emission present in our spectrum. 10/16 of Currie's Be candidates in our spectra do show emission.

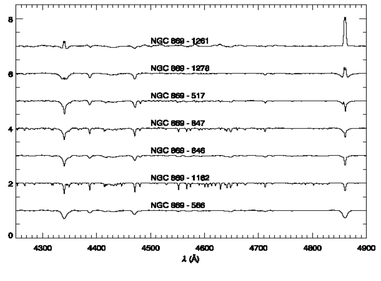



**Figure 6:** Spectra of 7 Be candidates (Currie et al. 2008) in h Persei are displayed, showing the Hγ and Hβ lines. Stars 517, 1261, and 1278 do show emission in these lines. Weak emission in Hβ is also present in 846 and 847. 566 may be a transient Be star, while 1162 is a normal B-type star.

## HR Diagrams

**Figure 7: h Persei**

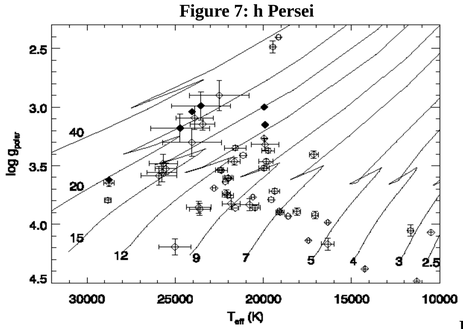
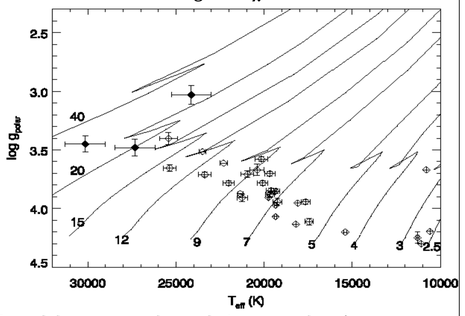



**Figure 8: χ Persei**




We compared our measured $T_{eff}$ and *log* $g_{polar}$ to the evolutionary tracks of Schaller et al. (1992) to measure $M_\star$ and $R_\star$. Normal B-type stars are shown as open diamonds and Be stars are shown as filled diamonds. The ZAMS mass of each evolutionary track is labeled along the bottom. The age of NGC 869 is 11.7 Myr, and the age of NGC 884 is 10.8 Myr.

## Conclusions and Further Work

- 16 Be candidates from Currie et al. (2008) are present in our data or the results of Huang & Gies (2006). 5 stars show no evidence for emission and are likely normal B-type stars.
- The star NGC 869-566 is likely a transient Be star.
- 10/16 of Currie's Be candidates in our data do show emission.
- The Be candidates without emission in our spectra may be transient Be stars and should be monitored in the future.
- The SEDs need to be fit using modern flux models, rather than blackbody curves, and allowing for variable reddening throughout the clusters.
- The new SED fits can be used to model the Be disk sizes and temperatures.

## References

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