DISTRIBUTION OF ABSOLUTE ENERGY OF BRIGHT Be STARS IN PLEIADES

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Abstract. We present newly measured energy distributions from $\lambda\lambda$3200–7500 Å of five late-type Be stars in Pleiades cluster for search of peculiarities of Be stars continuum energy distributions. Empirical effective temperatures of Be stars have been derived by comparing observed and computed fluxes in the visible region. The variation of the flux in the Balmer continuum region of Pleione (28 Tau) has been discussed.

1. Introduction

Visible fluxes are very important for deriving effective temperatures of early-type stars since most of their energy is emitted in this wavelength region. The study of Be stars is hampered by the diversity of objects under study and by the wide range of phenomena exhibited by individual stars. Irregular variations of brightness, emission line strength, infrared excess, etc., are connected for a large number of Be stars. Because of the anomalous colours shown by many Be stars owing to excess and less emission shortward of Balmer discontinuity and in the Paschen continuum and infrared it is difficult to derive effective temperatures of some Be stars.

Many peculiarities have been recognized in the continua of Be stars. A study of Be stars by Schild *et al.* (1974) and Schild (1976) has shown that the Balmer jump is likely to be smaller in a Be star than in a normal B star. From a study of Be stars in clusters, Schild (1978) has found that among the early-type Be stars, many have filled-in the Balmer jump and in some stars the Balmer jump is in emission. Among the middle- and late-type Be stars several are found with larger than normal Balmer jump. Briot (1978) has found that for Be stars of later spectral type no excess or deficiency in the ultraviolet flux exists. However, Chkhikvadze (1980) has pointed out that a few Be stars with shells have anomalously large Balmer jump. Llorente de Andrés *et al.* (1981) have discussed that the ultraviolet excess observed for B0e stars is due to an overestimate of the interstellar reddening correction due to the neglect of the intrinsic reddening introduced by rapid rotation.

Still the understanding of Be stars have been limited, largely because the phenomena exhibited by the Be stars are found to widely varying extents among stars. The study of continuum energy distributions can potentially improve our understanding greatly.

To provide a basis for further exploration of energy distributions and to specify further the properties of the Be stars, particularly with regard to their continuous energy distributions, we have measured new continuum energy distributions of five Be stars in Pleiades cluster. We present first continuum energy distributions of three Be stars: namely, 17 Tau, η Tau, and 13 Tau.

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TABLE I

Parameters of Be stars

Star	HD	Sp. T.[a]	m_{5500}	T_{eff}	$\log g$	$E(B - V)$	$V \sin i$[b] (km s^{-1})
23 Tau	23480	B6IVe	$4^{m}_{.}420$	13000 K	4.0	$0^{m}_{.}08 \pm 0^{m}_{.}02$	285
17 Tau	23302	B6IIIe	3.866	14000 K	3.5	0.04 ± 0.02	215
η Tau	23630	B7IIIe	3.059	12000 K	3.5	0.04 ± 0.02	210
13 Tau	23016	B8Ve	5.697	12000 K	4.0	0.06 ± 0.02	355
28 Tau	23862	B8Vne	5.198	12000 K	4.0	0.07 ± 0.02	345

Source of date:
[a] Hirshfeld and Sinnott (1982).
[b] Uesugi and Fukuda (1982).

2. Observations and Reduction

A list of the most important parameters for the observed Be stars is in Table I. The new energy distributions were measured from $\lambda\lambda$ 3200–7500 Å (50 Å passband) during December 1980 with the 52 cm reflector. The spectral energy distributions of the stars were obtained with scans made with a Hilger and Watts monochromator. The entire spectrum 3200 through 7500 Å was covered. An exit slot of 0.7 mm, admitting 50 Å of the spectrum to fall on the photomultiplier was used for taking spectral scans. At least three scans of each star were taken during a night and the continuum was drawn through each scan. Each scan was reduced to instrumental magnitudes separately and all scans of individual stars during each night were averaged. The observations of each star were repeated on another night also. Along with the program stars the standard star α Leo and a comparison star 18 Tau were also observed. With the help of the standard star, the monochromatic fluxes of Be stars and a comparison star were extracted from the observed continuum energy distribution at upto 44 wavelengths separated by 100 Å. The absolute monochromatic magnitudes of Be stars correspond to Tug *et al.* (1977) calibration of α Lyrae. The standard deviation of the measurements on an individual night does not exceeds $\pm$ 0.03 mag. in the entire wavelength range. The magnitudes were corrected for interstellar reddening and were normalised to wavelength λ 5500 Å. The de-reddened magnitudes are listed in Table II. A plot of these is shown in Figure 1.

3. Correction for Interstellar Reddening

The determination of interstellar reddening for Be stars is complicated due to their high rotational velocities. Rapid rotation introduces an intrinsic reddening, which is significant for the rapidly rotating Be stars. Neglect of this effect yields an overestimate of interstellar reddening which, in turn, yields an overcorrection of ultraviolet fluxes resulting in a spurious ultraviolet excess. Briot (1978) has found that an ultraviolet flux excess for B0e stars is related to an overestimate of interstellar reddening corrections.

TABLE II

De-reddened mean-monochromatic magnitudes of Be stars normalised to wavelength λ5500 Å

Wavelength (Å)	$1/\lambda$ (μ^{-1})	Star				
		23 Tau	17 Tau	η Tau	13 Tau	28 Tau
3200	3.13	$0^m.432$	$0^m.248$	$0^m.575$	$0^m.600$	$1^m.549$
3300	3.03	0.430	0.232	0.653	0.618	1.488
3400	2.94	0.425	0.235	0.570	0.555	1.399
3500	2.86	0.420	0.261	0.565	0.606	1.282
3600	2.78	0.435	0.249	0.563	0.602	0.947
3700	2.70	0.425	0.251	0.434	0.474	0.684
3800	2.63	0.200	0.160	0.317	0.251	0.411
3900	2.56	0.007	−0.050	0.013	0.064	0.099
4000	2.50	−0.210	−0.302	−0.263	−0.190	−0.247
4100	2.44	−0.330	−0.372	−0.337	−0.341	−0.344
4200	2.38	−0.327	−0.334	−0.317	−0.313	−0.320
4300	2.33	−0.302	−0.317	−0.296	−0.309	−0.303
4400	2.27	−0.283	−0.286	−0.268	−0.278	−0.287
4500	2.22	−0.250	−0.263	−0.248	−0.244	−0.256
4600	2.17	−0.225	−0.236	−0.223	−0.225	−0.232
4700	2.13	−0.201	−0.207	−0.200	−0.188	−0.207
4800	2.08	−0.175	−0.181	−0.180	−0.180	−0.188
4900	2.04	−0.151	−0.160	−0.154	−0.161	−0.154
5000	2.00	−0.133	−0.133	−0.125	−0.116	−0.135
5100	1.96	−0.103	−0.106	−0.098	−0.100	−0.100
5200	1.92	−0.083	−0.075	−0.074	−0.076	−0.083
5300	1.89	−0.074	−0.051	−0.051	−0.048	−0.051
5400	1.85	−0.028	−0.034	−0.024	−0.019	−0.030
5500	1.82	0.000	0.000	0.000	0.000	0.000
5600	1.79	0.024	0.022	0.014	0.014	0.015
5700	1.75	0.041	0.041	0.041	0.054	0.045
5800	1.72	0.065	0.067	0.059	0.066	0.067
5900	1.69	0.087	0.098	0.085	0.100	0.092
6000	1.67	0.113	0.124	0.107	0.149	0.108
6100	1.64	0.130	0.147	0.132	0.143	0.132
6200	1.61	0.153	0.162	0.140	0.167	0.155
6300	1.59	0.183	0.180	0.174	0.180	0.176
6400	1.56	0.200	0.212	0.198	0.208	0.199
6500	1.53	0.226	0.241	0.209	0.227	0.229
6600	1.51	0.253	0.247	0.238	0.240	0.245
6700	1.49	0.263	0.271	0.249	0.256	0.273
6800	1.47	0.287	0.282	0.261	0.275	0.285
6900	1.45	0.307	0.300	0.284	0.286	0.300
7000	1.43	0.325	0.331	0.301	0.295	0.332
7100	1.41	0.352	0.336	0.345	0.309	0.350
7200	1.39	0.366	0.371	0.344	0.322	0.361
7300	1.37	0.388	0.357	0.348	0.336	0.367
7400	1.35	0.400	0.365	0.383	0.350	0.390
7500	1.33	0.418	0.399	0.395	0.370	0.424

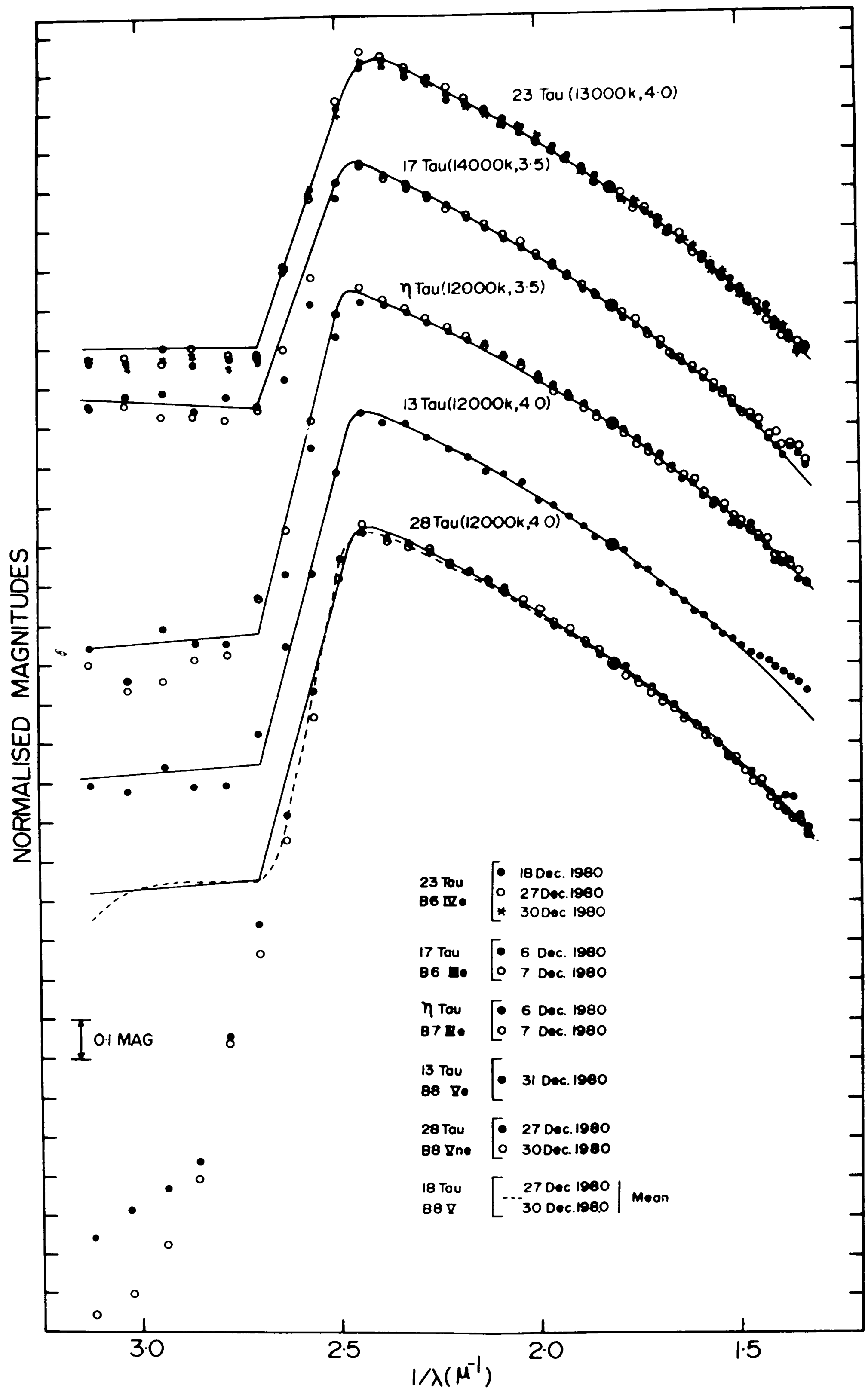

Fig. 1. Normalised de-reddened energy distribution curves of Be stars (cross, open and filled circles) superimposed by best fitting models (solid continuous curves). The normalisation have been done at λ5500 Å (double circles). The matching has been done by eye.

Recently, Llorente de Andrés *et al.* (1981) has also shown that rapid stellar rotation introduces an additional reddening (intrinsic rotational reddening) which produces an overestimate of the corrections for interstellar extinction. This overestimate of reddening correction results in the ultraviolet flux excess observed for many Be stars.

The direct measurements of $E(B - V)$ neglect the effect of intrinsic reddening in Be stars. The normal Q method of Johnson and Morgan (1953), valid for the Main-Sequence O- and B-stars, is likely to produce large errors because of the ultraviolet and near-infrared excess emissions in a few of Be stars.

In order to account for intrinsic rotational reddening in Be stars, we have used the distance moduli method for the determination of colour excess, $E(B - V)$, of Be stars. To determine interstellar reddening, we plotted colour excess, $E(B - V)$ (of about 60 normal B stars lying in the direction of program stars) against their apparent distance moduli ($m_v - M_v$). The $E(B - V)$ values for normal B stars were computed through the Q method. The normal B stars were selected from the *Photoelectric Catalogue* (Blanco *et al.*, 1968). To estimate apparent distance moduli of normal B stars, the M_v magnitudes were taken from the spectral type and luminosity class versus M_v calibration for early-type stars (Allen, (1971). From the distance moduli versus $E(B - V)$ plot for normal B stars, the $E(B - V)$ values of program Be stars corresponding to their distance moduli were estimated. The $E(B - V)$ values thus estimated are listed in Table I along with the expected errors. The reddening corrections were calculated by adopting the mean value of total to selective extinction, $R = 3.25$ (Moffat and Schmidt-Kaler, 1976) and using interstellar reddening curve for Pleiades region given by Lucke (1980).

4. Continuum and Effective Temperatures

We have used the synthetic spectra constructed by Kurucz (1979) with normal chemical composition for deriving effective temperatures of Be stars. The models were computed assuming plane parallel geometry, hydrostatic equilibrium, local thermodynamic equilibrium, no molecules with equation of state and radiative plus convective energy transport. Line blanketing was included by use of a statistical distribution function representation of the opacity of almost one million atomic lines.

The grid of models (Kurucz, 1979) for solar abundance and microturbulence velocity 2 km s^{-1} were superimposed on the observed spectra for deriving the effective temperatures; assuming $\log g = 4.0$ for luminosity class V and IV and $\log g = 3.5$ for luminosity class III. The models (solid continuous curves) fitted with observations (cross, open and filled circles) are shown in Figure 1. The numbers in the brackets denote the value of $T_{\rm eff}$ and $\log g$, respectively, of the best fitted models. The derived temperatures are listed in Table I. The effect of gravity on the energy distributions of these stars is relatively small. For example, a change in gravity from $\log g = 4$ to $\log g = 2$ would be equivalent to a change in temperature less than 500 K at 10000 K (Kontizas and Theodossiu, 1980). Therefore, in using fluxes to determine the temperatures of Be stars, the gravity will not need to be known with great accuracy (Nandy and Schmidt, 1975).

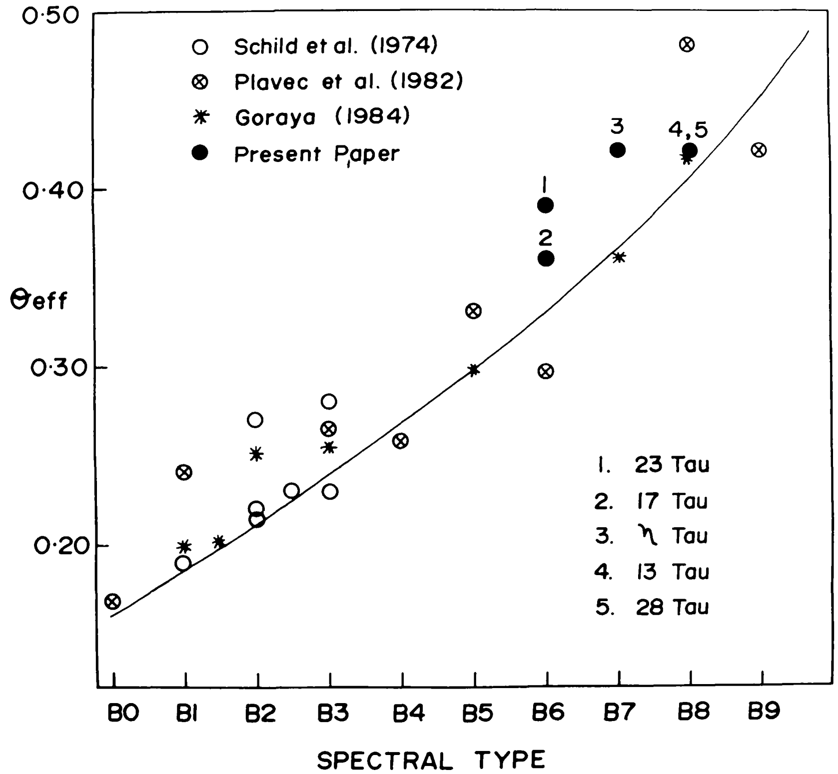

Fig. 2. The θ_{eff}-spectral type relation for Be stars. The solid continuous curve is the mean relation for normal B stars.

The photometric error of the observed fluxes introduces an uncertainty in temperature, which is $\pm 5\%$ around 20000 K and $\pm 2\%$ around 10000 K. The fit of the computed to the observed flux introduces an additional error that varies from $\pm$ 500 K for cool stars to $\pm$ 800 K for the hot ones. The temperatures derived here are plotted on the θ_{eff}-spectral type relation for normal B stars as shown in Figure 2. In Figure 2 we have also plotted other Be stars taken from Schild *et al.* (1974), Plavec *et al.* (1982), and Goraya (1984), whose effective temperatures have also been derived by model fitting. The solid curve in Figure 2 for normal B stars was obtained from the T_{eff} and spectral type data for early-type stars given by Kontizas and Theodossiu (1980).

A careful examination of Figure 2 reveals that, in general, the Be stars tend to show lower effective temperature than those of normal B stars.

5. Variation of Balmer Continuum in Pleione (28 Tau)

Pleione is a well-known shell star in the Pleiades cluster. It is the most interesting object. In Figure 1 the observed continuum of Pleione has been compared with that of the comparison star, 18 Tau, having the same spectral type and luminosity class as that of Pleione. It is clear from Figure 1 that the normal B star, 18 Tau, matches well with synthetic model in the Balmer as well as Paschen continuum. The Be star Pleione matches well with 18 Tau in Paschen continuum but deviates strongly in Balmer

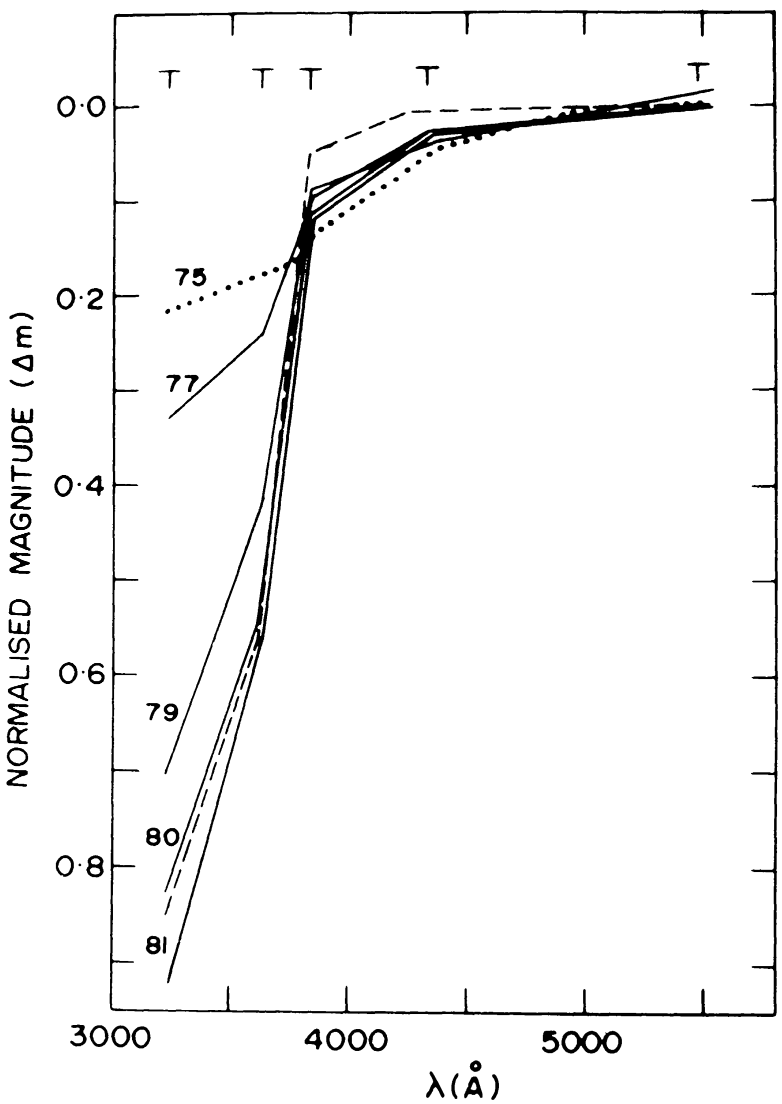

Fig. 3. Variation of the Balmer continuum in Pleione (28 Tau). The dotted curve is taken from Schild (1978). The continuous curves are taken from Van Leeuwen *et al.* (1980). The dashed curve is the present observation. All curves are normalised to λ5500 Å.

continuum. Pleione has anomalously large Balmer jump as compared to the normal B star. The shell outburst of Pleione which occured in 1973 has been reported by Sharov and Lyuty (1976). Schild (1976) has observed the normal Balmer continuum of Pleione. Schild (1978) again reported that the Pleione has large Balmer jump during 1975. Later on Hopp *et al.* (1982) found that during 1980–1982, Pleione has an unusual large Balmer jump. Recently, Van Leeuwen *et al.* (1982) performed measurements of Pleione with Walraven VBLUW system during 1977–1981 and found that Pleione has a very large Balmer jump. More recently, our spectrophotometric observations also show the Balmer jump strongly in absorption.

The variation of the Balmer continuum in Pleione during the period 1975–1981 has been shown in Figure 3. The numbers attached to each curve denote the year of observation. All the curves plotted in Figure 3 are differential magnitudes of Pleione normalised to λ5500 Å.

It is clear from Figure 3 that Balmer jump in Pleione has increased during the period 1980–1981, but the increase goes less rapidly than in the year 1977–1979. This shows that the ultraviolet blocking by the hydrogen shell clearly increased during the period 1980–1981. The blocking is prominent in the Balmer continuum and does not influence the Paschen continuum. Thus, we hope that the shell phase of Pleione is still persisting.

6. Conclusions

The observed Be stars in general have a tendency to show slightly lower effective temperature than normal B stars. For the Be stars 23 Tau, 17 Tau, η Tau, and 13 Tau, no excess or deficiency in the average ultraviolet flux is detected but a very faint excess is seen at the larger wavelengths for the stars 17 Tau and 13 Tau. The star Pleione has anomalously large Balmer jump, which shows that the Pleione shell episode which started in 1973, still goes on.

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