SPECTROPHOTOMETRIC STUDIES OF Ap STARS

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Abstract. Based on the observed energy distribution curves of about a hundred Ap stars, the various relationships among their physical parameters: namely, the temperature, colour index, bolometric correction and bolometric magnitude have been studied. The hotter Ap stars have been found to be apparently bluer than their normal counterparts, which is possibly due to the broad continuum features at λ4200 and λ5200 that are generally present in Ap stars only. The bolometric corrections are independent of parallax measurements; the Ap stars as well as the normal stars follow the same sequence of bolometric corrections when related to temperature. The Ap stars appear to be slightly evolved and their position in the HR diagram indicates the hydrogen shell burning phase. The mass range of Ap stars is similar to that of normal A stars.

1. Introduction

The effective temperatures, radii, bolometric magnitudes and bolometric corrections, estimated for a number of Ap stars from their continuum energy distributions are given in our earlier paper (Babu and Shylaja, 1981) herein after called as Paper I. The prime factor in these estimations is that they are based on homogeneous data. In the present paper, we have attempted a detailed discussion of these parameters.

2. Relationship between Colour and Temperature

With the values given in Paper I, we have plotted $(B-V)$ collected from the literature against θ_e obtained by us, in Figure 1. The temperature scale for the Main Sequence stars given by Code *et al.* (1976) is also included in the figure for comparison. In this, it may be seen that the stars with $0^m.0 < (B-V) < 0^m.2$ in general follow the Main Sequence temperature scale, while those with $(B-V) < 0^m.0$ show a tendency to fall below the Main Sequence scale. That is, the bluer Ap stars tend to be cooler than their normal counterparts for a given $(B-V)$. In other words it is obvious in this figure that for a given temperature most Ap stars tend to appear bluer than the normal stars. This is because the broad absorption feature at λ5200 or thereabouts present in the Ap stars affects the observations through the standard V filter, in the sense that the star would appear fainter in this filter than what it would have been in the absence of this absorption, while those through the B filter do not get affected. Thus the strength of this absorption feature can cause the so-called 'bluening' of these stars. But similarly, the presence of yet another absorption feature around λ4200 in some

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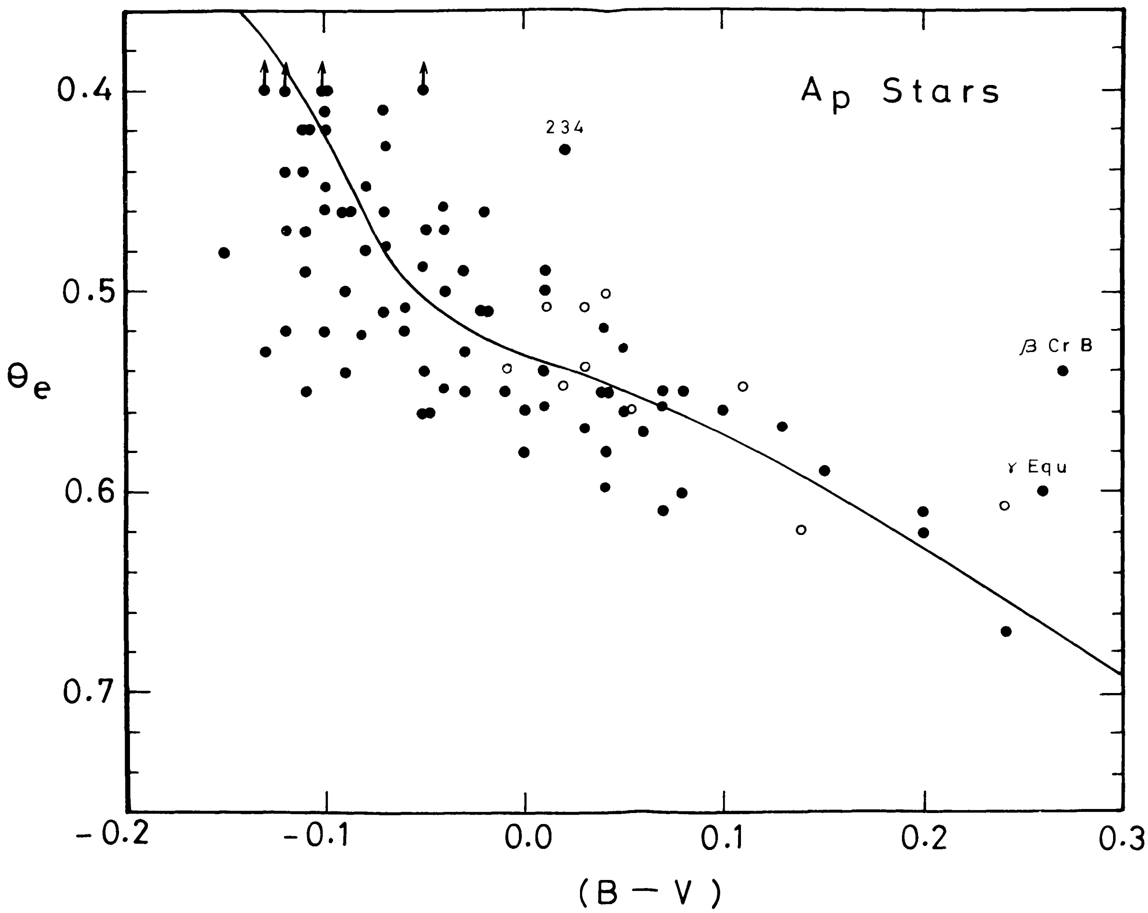

Fig. 1. Relationship between $(B-V)$ colour and $\theta_e(=5040/T_e)$ of Ap stars. The temperature scale for the Main Sequence stars (Code *et al.*, 1976) is shown by the solid line. Open circles represent the normal stars.

Ap stars would affect the B filter observations which would make the star fainter in blue, creating an apparent 'reddening' of the star. So, it may be concluded that the observed $(B-V)$ colours of Ap stars are dependent at least partly, on the presence and the relative strengths of the above mentioned absorption features, which also explains the scatter in Figure 1 to some extent. This would of course, get more complicated if there is any line blanketing in the star, which is the case in some of our program stars.

The location of the star HR 234 (=HD 4778) in this figure is away from the general trend giving an impression that its observed colour is too red for its temperature. But an inspection of its position in the sky reveals that it is almost at the edge of the Milky Way near the Perseus arm. In addition, its parallax also is quite small (0.007 arc sec). Thus there is a greater likelihood of this star being affected by interstellar extinction. Nevertheless, it has a fairly strong $\lambda 5200$ feature along with an indication of the $\lambda 4200$ feature, which also would influence its $(B-V)$ measurements. However, on the basis of its temperature, its $(B-V)$

colour must be $\leqslant -0^m.1$. The two other stars, β CrB and γ Equ which are at the right extreme of the figure, also show an enormous reddening effect, though they both have sizeable absorptions at $\lambda 5200$. This reddening has already been attributed to the heavy line blanketing present in these stars (Wolff, 1967), which is clearly seen in the short wavelength region of their energy curves (Paper I).

3. Relationship between Temperature and Bolometric Correction

Popper (1959) had pointed out that the bolometric correction is a function of colour for stars cooler than F0 type while for the hotter stars, it is a function of temperature. Later on Morton and Adam (1968) and Code *et al.* (1976) confirmed it by showing similar results. It is found to be same in the case of Ap stars also as is seen in Figure 2 where we have plotted θ_e against the bolometric correction, both values being from Paper I. The curve generated by the expression

$$\text{B.C.} = -12.98\theta_e^2 + 16.77\theta_e - 5.58, \tag{1}$$

which is given in an earlier work (Babu and Rautela, 1978) is seen to fit even the enhanced sample. The scatter around this curve is minimal and is only of the order of $\pm 0^m.03$ with a very few exceptions where it touched about $0^m.05$. This is because the bolometric correction is independent of the stellar distances and

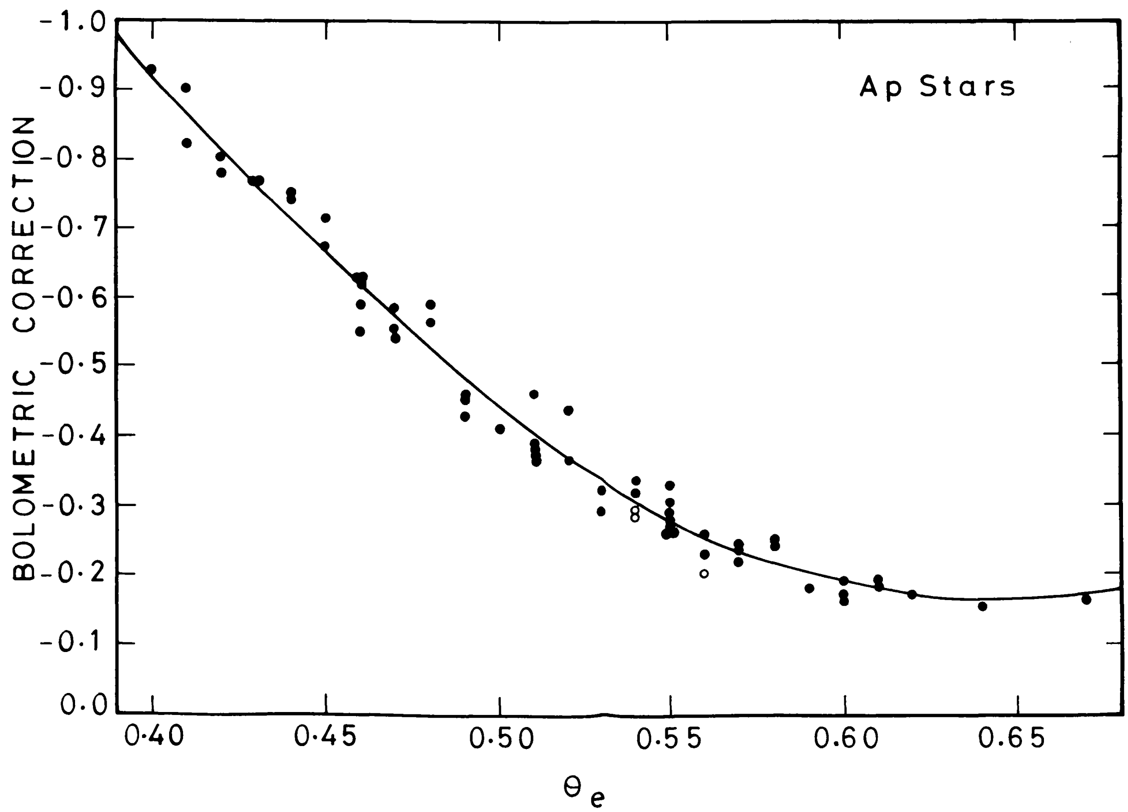

Fig. 2. Relationship between bolometric correction and θ_e of Ap stars. The solid line represents the relation obtained earlier by Babu and Rautela (1978). Open circles correspond to the normal stars.

thereby avoid all the major uncertainties which are inevitable in the parallax measurements. However, now that the direct relationship of the bolometric correction to the effective temperature is vividly shown by our figure with almost negligible deviations, the reality of our temperature estimations is significantly pointed out.

Further, the bolometric correction determined in this way is independent of blanketing effects and therefore should be valid for the unblanketed normal stars also. This is clearly shown by the merging of such normal stars observed by us into the same sequence as that of the rest.

4. Relationship between Temperature and Bolometric Magnitude

A plot between log T_e and M_{bol} is given in Figure 3 in order to study the evolutionary aspects of Ap stars. These two parameters, where $T_e = 5040/\theta_e$, also have been taken from Paper I. The Main Sequence band taken from Novotny (1973) is represented by broken lines. It is obvious from this figure that the Ap stars in general are either above or at the upper edge of the Main Sequence appearing as though they are in the process of just leaving it. In this connection, we have adopted the evolutionary tracks theoretically obtained by Iben (1967a, b) for comparison. Following these tracks, one can see that during the

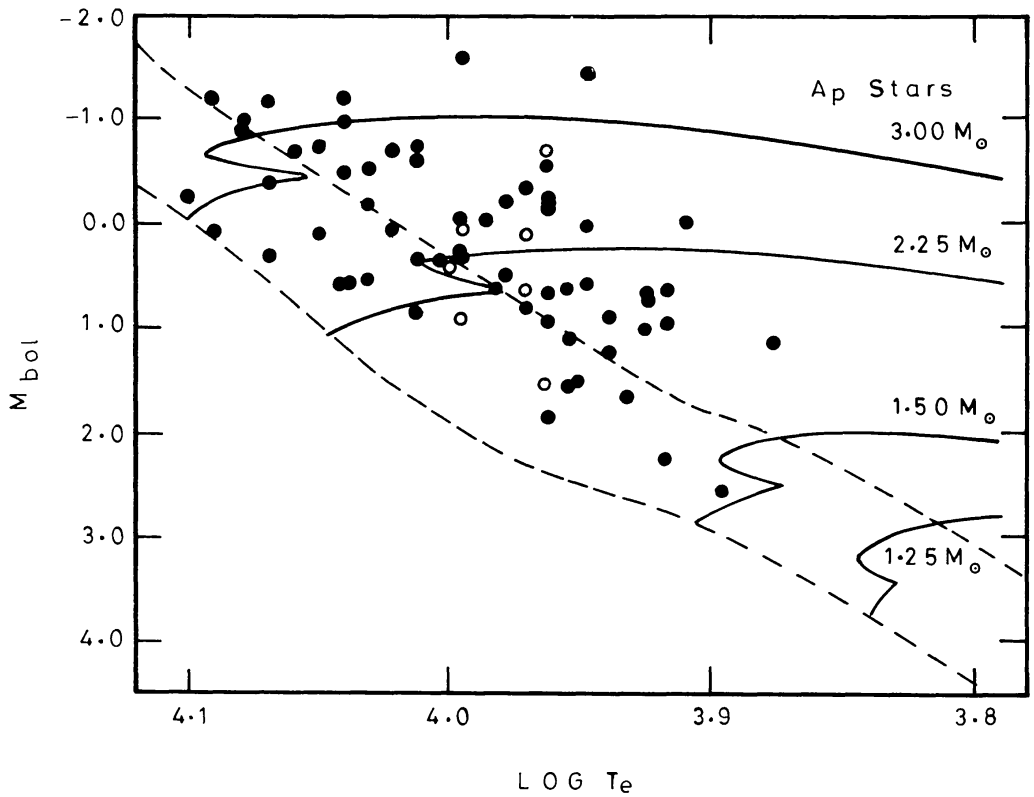

Fig. 3. Relationship between bolometric magnitude and temperature of Ap stars. The evolutionary tracks are from Iben (1967a, b) and the Main Sequence band is from Novotny (1973). Open circles denote the normal stars.

evolution from the Main Sequence, but still being very close to it, a thick hydrogen burning shell is formed in the star after the core hydrogen is depleted during its stay on the Main Sequence. At this stage the core contracts very rapidly and becomes nearly isothermal. The main phase of hydrogen burning in the shell lasts about 10^7 yr and by the time this phase ends, the star would reach the brightest point in the evolutionary track near the Main Sequence. But by then the core contracts still further raising the central temperature. This causes the envelope to expand rapidly while the hydrogen burning continues in an intermediate shell. The luminosity falls during this phase because the hydrogen shell source becomes less and less able to provide energy as a result of overall structural changes in the star and the expanding-cooling envelope absorbs a great deal of energy.

Now coming back to the figure, the Ap stars are generally located between the Main Sequence and the brightest points of the evolutionary tracks. This clearly indicates that they are in the hydrogen shell burning phase, a few of them even reaching almost the end of this phase. Eggen (1957) also had suggested earlier that this position of Ap stars may represent the transitional phase towards the yellow giants. But, how it is related, if at all, to the peculiarities observed in these stars is yet to be understood, especially if the peculiarities are regarded as surface phenomena. It is interesting to note that even if the values of $T_{\rm eff}$ and $M_{\rm bol}$ are corrected for being over estimated, the resulting shift of the points in the diagram is expected to be nearly parallel to the Main Sequence band. Thus the conclusion remains unaltered even then.

Though it is difficult to find out the exact masses of the individual stars from this figure, it is obvious that in general they range from about 1.5 $M_\odot$ to about 3.0 $M_\odot$. This incidentally, is the same range for the late B and A type normal stars (Allen, 1973).

5. Conclusions

Even though the physical parameters of Ap stars are known to be not significantly different from the normal A type stars, it has been noticed that the hotter Ap stars have a tendency to be bluer than their normal counterparts. This is partly due to the presence of the broad continuum absorption features at λ4200 and λ5200 in the Ap stars which may affect the $(B-V)$ measurements.

The variation of the bolometric correction of the Ap stars with temperature is same as that for the normal stars. In the light of the bolometric correction being independent of the parallax measurements, the minimal scatter in the bolometric correction and temperature relationship signifies the reality of our temperature estimations.

The Ap stars are slightly evolved and are in the process of leaving the Main Sequence. This indicates that they are in the hydrogen shell burning phase during their transition towards the yellow giants. However, the relationship between this phase of evolution and the peculiarities of Ap stars is yet to be understood. Their masses range from about 1.5 $M_\odot$ to about 3.0 $M_\odot$.

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