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On the Observation of Stellar Temperature Minima

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Summary. Minima of brightness temperature due to the presence of stellar temperature minima are predicted in the UV, infrared and radio frequency range. The theoretical temperature minima for stars in the range $T_{\text{eff}} = 4000$–6500 K and $\log g = 2$ to 4 used in this work are calculated on basis of the short period acoustic heating theory.

Key words: stellar chromospheres

1. Introduction

The region of a stellar temperature minimum between photosphere and chromosphere is of great interest for the theory of stellar atmospheres. Measurement of value and position of the temperature minimum very likely can be used as an observational tool for the determination of the mechanical energy flux that is generated by the star. If the short period acoustic heating theory of the chromosphere (cf. Ulmschneider and Kalkofen, 1977; Renzini et al., 1977; Ulmschneider et al., 1977) is valid, theoretical temperature minima are predicted, which in stars having effective convection zones, low gravity and high effective temperature lie much closer to the star than in the solar case. A test of these predictions would be of great interest. The value and position of a stellar temperature minimum may be inferred from observations of the monochromatic radiative flux or intensity as a function of wavelength. Rocket spectra of the sun (Tousey et al., 1964) show that the region near 0.168 μm (Si ^1D edge) marks the transition from an absorption plus emission spectrum on the longer wavelength side to an almost pure emission spectrum below 0.168 μm (Gingerich and Rich, 1968). A plot of the brightness temperature in the wavelength region 0.14–0.19 μm reveals a minimum temperature near 0.168 μm (Parkinson and Reeves, 1969; Widing et al., 1970; Brueckner and Nicolas, 1972; Nishi, 1973; Jordan and Ridgeley, 1974; Samain et al., 1975). A critical evaluation of these observations has been given by Vernazza et al. (1976). In the infrared near 300 μm the solar temperature minimum likewise can be seen as a minimum in the brightness temperature (Mankin, 1968; Eddy et al., 1969, 1973; Mankin and Strong, 1969; Clark et al., 1971; Gezari et al., 1973; Müller et al., 1975; Lindsey and Hudson, 1976). For a critical evaluation of some of these data see Vernazza et al. (1976). Similarly cores of strong resonance lines like the Ca II H+K and Mg II $h+k$ lines have been used for the observation of temperature minima in the sun, Arctur, Procyon, α Cen A and B (Ayres et al., 1974; Ayres and Linsky, 1975, 1976; Ayres et al., 1976). At all these wavelengths the monochromatic optical depth is roughly unity at the position of the temperature minimum.

It is the purpose of this work to show how these wavelengths of minimal brightness temperature change if the temperature minimum is situated at other positions in the star.

2. Results

On basis of the predictions of Ulmschneider et al. (1977) we have computed wavelengths at which the monochromatic optical depth is unity at the point of shock formation. These shock formation points (Ulmschneider and Kalkofen, 1977; Ulmschneider et al., 1977) are thought to be closely related to the heights of the temperature minimum. For the calculation of the optical depth we have used the opacity routines of Kurucz (1970) which include H I, H^-, H_2^+, He I–II, He^-, C I–IV, N I–V, O I–VI, Ne I–VI, Mg I–II, Si I–II, Al I continua, Rayleigh scattering on H, H_2 and He as well as Thomson scattering. No lines other than H lines were included. To judge the influence of the chromospheric temperature gradient on our results we have employed two hypothetical models, an isothermal model and a model with a temperature rising outwardly with 500 K per scale height. The gas pressure and the value of the temperature at the temperature minimum were taken from Ulmschneider et al. (1977).

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Table 1. Wavelengths λ of brightness temperature minima in µm as function of T_{eff} and $\log g$ for different values of α assuming an isothermal chromosphere. Values in bracket are for a chromosphere with a temperature rising outwardly with 500 K per scale height

T_{eff} (K)	$\log g$ (cm/s^2)	λ (µm) $\alpha=1.0$		$\alpha=1.5$	
4000	4	0.110	(0.110)	0.152	(0.152)
	3	0.168	(0.168)	0.168	(0.168)
	2	0.208	(0.208)	0.208	(0.251)
4500	4	0.152	(0.110)	0.152	(0.152)
	3	0.168	(0.168)	0.168	(0.168)
5000	4	0.152	(0.110)	0.152	(0.152)
	3	0.168	(0.168)	0.168	(0.168)
	2	0.208	(0.370)	0.208	(0.370)
5500	4	0.152	(0.124)	0.152	(0.152)
	3	0.168	(0.168)	0.208	(0.208)
5800	4.44	0.152	(0.152)	0.152	(0.152)
6000	4	0.152	(0.152)	0.168	(0.168)
	3	0.168	(0.370)	—	—
6500	4	0.152	(0.152)	0.168	(0.168)

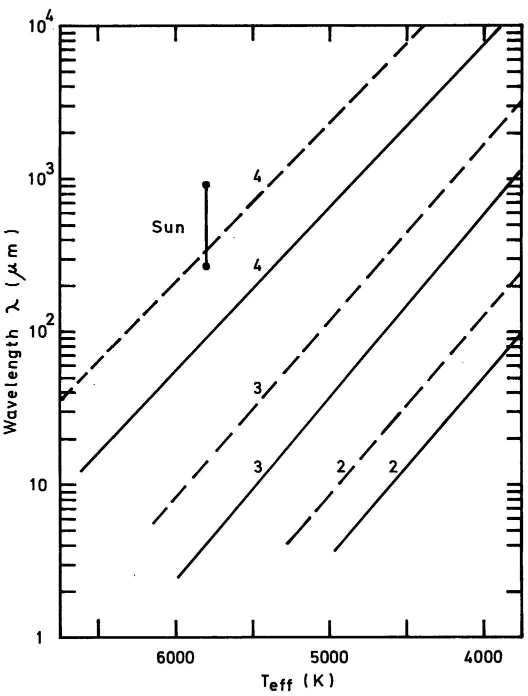

Fig. 1. Wavelengths of brightness temperature minima as function of T_{eff} with $\log g$ as parameter assuming isothermal chromospheres. Values for $\alpha=1.5$ are shown drawn, for $\alpha=1.0$ are dashed. α is the ratio of mixinglength to pressure scale height

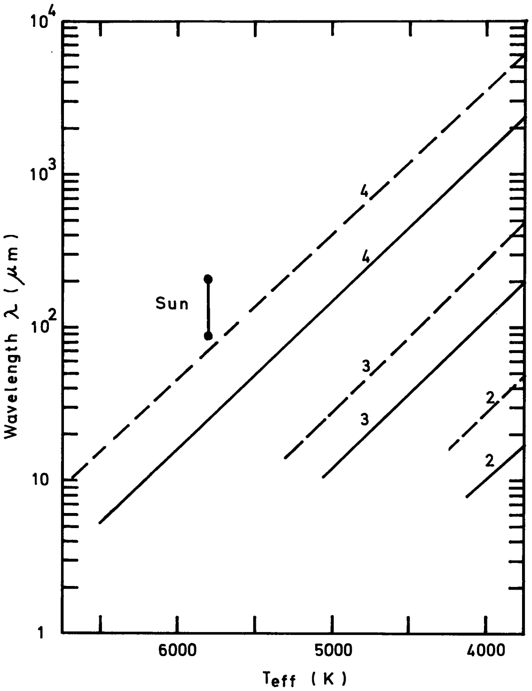

Fig. 2. Same as Figure 1 but for chromospheres with an assumed outward temperatures rise of 500 K per scale height

Table 1 shows the result for the ultraviolet spectral range. We give the wavelength at which the minimum of the brightness temperature should be observed as function of the effective temperature T_{eff} and of the logarithm of the surface gravity g if the predicted temperature minima of Ulmschneider et al. (1977) were correct. Optical depth unity is found here mainly in absorption edges of C I ($2p^3P$ 0.110 µm, $2p^1D$ 0.123 µm), Si I ($3p^{2}\,{}^1D$ 0.168 µm, $3p^{2}\,{}^3P$ 0.152 µm), Al I ($3p^2P$ 0.208 µm), Mg I ($3p^3P$ 0.251 µm) and the Ba limit. In reality as judged from the observed behaviour of the brightness temperature (Fig. 4 of Vernazza et al., 1977) the absorption edges are much less pronounced due to the great number of metal lines in this spectral range which we did not include in our opacity routines. Inclusion of these lines would thus lead to a more continuous change of wavelength with T_{eff} and $\log g$. The wavelength of the minimum of the brightness temperature is seen to increase with depth of the temperature minimum. In the range of stars considered a total wavelength shift of about a factor of 2.5 is found. That this shift is so small is due to the with wavelength steeply decreasing absorption in the ultraviolet. For the same reason an outwardly rising temperature, as seen in Table 1, does not change the results drastically compared to the isothermal case.

Figures 1 and 2 show the results for the infrared region. Here again the predicted wavelength of the minimum of the brightness temperature is given as function of T_{eff} with $\log g$ as parameter. This wavelength is seen to vary by four orders of magnitude for the range of stars considered and is shorter, the deeper the temperature minimum occurs in the star. Due to higher electron pressure and higher opacity in the atmospheres with rising temperature, the wavelengths of minimum brightness temperature are seen to be lower than in the isothermal case. For stars of high T_{eff} and low gravity, the shock formation points are found in radiative damping zones (Ulmschneider et al., 1977). Because the acoustic wave after shock formation will be strongly damped radiatively, the temperature minima of these stars will lie at much greater heights compared with the shock formation points. For these stars an outward temperature rise starting at the shock formation point is thus unrealistic and wavelength predictions for these cases are missing in Figure 2.

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Note added in proof: A recent comparison of the predicted stellar temperature minima of Ulmschneider et al. (1977) with observations in the Ca II K line (Cram and Ulmschneider, 1977, submitted to Astron. Astrophys.) shows that some low lying theoretical temperature minima probably have to be revised upwards. Likewise some temperature minima at great heights probably occur at lower altitude. This in effect shrinks the wavelength range of predicted minima of brightness temperature of Figures 1, 2 and Table 1 towards the intermediate values.