ON THE INFRARED CONTINUUM OF THE SUN AND STARS

The increase of opacity in the solar atmosphere toward the infrared beyond 1.6 μ is well known, and the expected effects on the center-to-limb variation of the continuum intensity have already been pointed out (de Jager 1963; Pecker 1963). The height of origin of the continuous spectrum increases with increasing wavelength, passing through the level of the temperature minimum at some wavelength λ₀; therefore we expect that the Sun will show limb darkening shortward of λ₀ and limb brightening beyond λ₀.

We wish to present the results of calculations of the intensity and center-to-limb variation of the continuous solar spectrum for several models of the chromosphere. These calculations were carried out on an IBM 7094 computer, using a program described elsewhere (Gingerich 1963).

Figure 1 illustrates the center-to-limb variation for the Utrecht Reference Photosphere (Heintze, Hubenet, and de Jager 1964) from 1 to 100 μ. In this model, the temperature has a minimum at τ₅₀₀₀ = 0.02. We see that the Sun shows limb brightening at all values of cos θ, for wavelengths greater than λ₀ ∼ 35 μ.

The effect of the temperature inversion will be observable in limb-darkening curves at wavelengths considerably shorter than λ₀, provided we can observe close enough to the solar limb. Especially interesting are the regions around 10 and 20 μ, where the Earth's atmosphere is transparent enough for solar limb-darkening measurements. Figure 2 illustrates the limb brightening expected at 10 μ for three solar models: the Utrecht Reference Photosphere, that of Heintze (1965), and Pagel's (1961) Model I.
In Heintze's model the temperature minimum occurs at $\tau_{6000} \sim 0.07$; in Pagel's it occurs at $\tau_{6000} \sim 0.005$. Also plotted in the figure are observations at 10.2 $\mu$ by Pierce, McMath, Goldberg, and Mohler (1950), which show an intensity decreasing toward the limb throughout the range of observation. The observations extend in $\cos \theta$ only to $\cos \theta_{\text{min}} = 0.2$, and yet they serve to contradict the Heintze model, or indeed any model which places the temperature minimum deeper than $\tau_{6000} \sim 0.03$ (for which $\tau_{10 \mu} \sim 0.2 = \cos \theta_{\text{min}}$). At 20 $\mu$ the opacity is about four times as great as at 10 $\mu$,

![Graph showing center-to-limb variation of intensity at 10 $\mu$ for three solar models. Circles: observations at 10.2 $\mu$ (Pierce et al. 1950).](image)

and thus the temperature minimum will be visible at a value of $\cos \theta$ about four times as large as at 10 $\mu$. Figure 3 shows the calculated limb brightening at 20 $\mu$ for the three models.

We see that at 20 $\mu$ it should be easy to distinguish between these models, and indeed obtain detailed information about the actual $T(\tau)$ at and above the temperature minimum. If we can observe at 20 $\mu$ to $\cos \theta = 0.1$, we can determine the continuum source function to $\tau_{20 \mu} \sim 0.1$, which corresponds to $\tau_{6000} = 0.003$. Since the H$^{-}$ free-free continuum is formed in local thermodynamic equilibrium, the source function will yield $T(\tau)$. An observational search for solar limb brightening at 20 $\mu$ out to $\cos \theta = 0.1$ is under way.\(^1\)

\(^1\) Note added in proof: In observations obtained on March 22, 1966, at 24.3 $\mu$ we have been unable to detect either brightening or darkening of the extreme limb near $\cos \theta = 0.2$ (corresponding to $\cos \theta = 0.14$ at 20 $\mu$). This suggests that the region of the temperature minimum is broader and extends higher in the atmosphere than any of the above models indicates.
Fig. 3.—Center-to-limb variation of intensity at 20 μ for three solar models.

Fig. 4.—The solar emergent flux $F_\lambda$ divided by the flux $\pi B_\lambda$ of a black body at $T_{\text{eff}} = 5780°$ K for three solar models.
The high level of formation of the solar continuum at 10 and 20 μm suggests a number of other important observations which should be made:

1. Measure both continuum intensity and limb darkening over sunspots and plages to determine whether the temperature inversion occurs at a higher or lower level than in quiet regions and how the temperature profile around the minimum is affected by the presence of activity.

2. Measure the size and the intensity fluctuations of solar granulation at 10 and 20 μm. Considerable difference from the behavior in the visual continuum may be anticipated; for example, the supergranulation may be visible in the continuum at this higher level. Of course, high-resolution work at 10 or 20 μm requires a large telescope; to resolve 1″, a 100-inch telescope is necessary at 10 μm, and a 200-inch telescope is necessary at 20 μm.

3. Examine the time history of the granulation at 10 and 20 μm. The continuum at these wavelengths is formed in a region where the radiative relaxation rate is comparable to the frequency of the well-known oscillatory motions in the solar atmosphere. Thus, one might expect to see oscillatory intensity variations, coherent with the velocity oscillations and with phase and amplitude relations appropriate to a compression with a certain amount of radiative leakage (see Noyes and Leighton 1963).

Could we detect the presence of a temperature inversion in other stars by observing the flux near 10 and 20 μm? We may easily answer this question for a star like the Sun. Figure 4 illustrates the emergent flux from the Sun between 1 and 100 μm divided by the flux from a black body at the solar effective temperature. Three models are shown: the Utrecht Reference Photosphere, the Heintze model, and that of Pierce and Waddell (1961). The last has no temperature inversion. For a star with ő(T) like the Utrecht Reference Photosphere, it would be impossible to detect the temperature inversion by observing through the windows of the Earth’s atmosphere at 10 or 20 μm. The inversion would, however, be detectable for Heintze’s ő(T).

Other stars may well have temperature inversions that are detectable from the Earth. Extra opacity sources, e.g., molecules, in the infrared could shift the minimum in ő/ő(Teii) to shorter wavelengths. Further, the temperature inversion could occur at greater optical depths in other stars: (a) If the inversion is due to mechanical heating, it should lie deeper because the top of the convection zone lies deeper, (b) If the inversion occurs when the H- continuum becomes photo-ionization-dominated and therefore assumes the color temperature of the star, its location should be determined by the neutral hydrogen density (Cayrel 1963). For a giant, a given density occurs at a greater optical depth than it does in the Sun, so the inversion would lie deeper. In either case, the effect would be to move the minimum in ő/ő(Teii) to shorter wavelengths.

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REFERENCES