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The Solar Continuum in the Far-Infrared and Millimetre Regions

R. W. Noyes

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The solar continuum in the far-infrared and millimetre regions

By R. W. Noyes
Smithsonian Astrophysical Observatory, Harvard College Observatory, Cambridge, Massachusetts, 02138

Two properties of the far-infrared solar continuum make its study important for determining the temperature structure of the solar chromosphere:

(*a*) The opacity increases toward longer wavelengths as the square of the wavelength, so chromospheric structures that are transparent in the visible tend to become optically thick and hence more easily observable in the far infrared.

(*b*) Since the opacity is due to free-free transitions of hydrogen or of the negative hydrogen ion, we may rigorously assume local thermodynamic equilibrium in the absorption and emission; i.e. we are certain that temperatures deduced from observations are true electron temperatures. This avoids serious problems of interpretation that are present in chromospheric observations at shorter wavelengths.

On the basis of solar models deduced from observations in the visible spectrum, several predictions have been published concerning the limb darkening or brightening of the Sun in the far infrared (see, for example, de Jager 1964; Noyes, Gingerich & Goldberg 1966; Léna 1966). All have concurred in predicting that the Sun should show considerable limb brightening at wavelengths longer than about 15 or 20 μm and that the brightness temperature observed at various wavelengths should pass through a minimum at about 35 μm. Recent observational results, however, have shown that this prediction is grossly in error: Léna (1968) finds definite limb darkening persisting to within at least 10 sec arc of the limb at 24 μm; Noyes, Beckers & Low (1968), observing during a solar eclipse, found the limb darkening at 22·5 μm to persist to within at least 2 sec arc of the limb, or $\cos\theta = 0{\cdot}05$. This implies that the minimum of brightness temperature must occur at a wavelength greater than 100 μm. Such a result is in agreement with Beer (1966), who observed the brightness temperature to a wavelength of 43 μm and reported no sign of an increase at longer wavelengths.

At a recent international meeting held to discuss the implications of new observations on the solar model, these results were compared with other continuum data in the visible and ultraviolet and were found to be in substantial agreement. A summary of the discussions, along with the model that resulted (known as the Bilderberg Continuum Atmosphere, or BCA), is presented elsewhere (Gingerich & de Jager 1968). Here I summarize those aspects that are especially relevant to infrared, submillimetre, and millimetre observations.

The lack of limb brightening in the 20 μm region to within 2 sec arc of the limb requires that the temperature minimum lie above about $\tau_{5000} = 2\times 10^{-3}$. In addition, the flatness of the 20 μm limb-darkening curves, in conjunction with ultraviolet data, suggests that the region throughout which the temperature is near its minimum is very broad, probably extending over a height range of several hundred kilometres.

Above this quasi-isothermal region the temperature must rise rapidly, as can be seen by the data on the brightness temperature in the millimetre region. Figure 1 and table 1 show published data for this region. In spite of the scatter in the data, the trend to higher temperatures at longer wavelengths is obvious. The solid line in figure 1 shows the

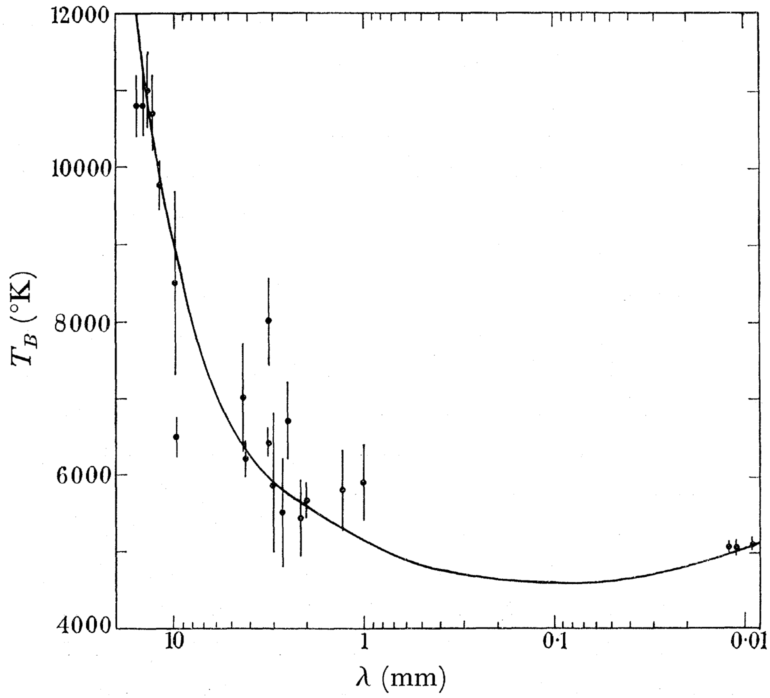

FIGURE 1. Data from table 1 on solar brightness temperature T_B in the submillimetre and millimetre regions, plotted against wavelength λ. The solid line is the predicted brightness temperature from the BCA model.

TABLE 1. BRIGHTNESS TEMPERATURE MEASUREMENTS IN THE SUBMILLIMETRE AND MILLIMETRE RANGES

λ (mm)	T_B	ΔT_B	reference
0·0086	5160	40	Saiedy 1960
0·0111	5040	30	Saiedy 1960
0·0120	5050	80	Saiedy 1960
1·0	5900	500	Low & Davidson 1965
1·3	5800	500	Bastin *et al.* 1964
2·0	5670	230	Wort 1962
2·15	5430	500	Tolbert & Straiton 1961
2·5	6700	500	Bastin *et al.* 1964
2·73	5500	700	Tolbert & Straiton 1961
3·0	5870	950	Tolbert & Straiton 1961
3·2	6400	200	Simon 1965
3·2	8000	560	Tolbert 1966
4·3	6200	310	Tolbert 1966
4·3	7000	700	Coates 1958
8·6	6500	260	Tolbert 1966
8·6	8500	1200	Coates 1958
11·8	9750	300	Staelin *et al.* 1968
12·8	10700	500	Staelin *et al.* 1968
13·5	11000	500	Staelin *et al.* 1968
14·3	10800	400	Staelin *et al.* 1968
15·8	10800	400	Staelin *et al.* 1968

brightness temperature (uncorrected for limb brightening) predicted by the BCA.† The correction for limb brightening beyond 1 mm is very uncertain, due to the presence of optically thick inhomogeneities in the high chromosphere. Chromospheric spicules, in particular, are thought to have typical densities $n_e \sim 10^{11}\ \mathrm{cm^{-3}}$, thicknesses $L \sim 1000$ km, and temperatures $T_e \sim 2\times10^4$ °K. Thus, their optical thickness

$$\tau_\lambda = \kappa_\lambda L = \zeta\lambda^2 N_e^2 T_e^{-\frac{3}{2}} L,$$

where
$$\zeta = 1{\cdot}47\times10^{-22}\ \ln\,(367 T_e N_e^{-\frac{1}{3}})$$

(de Jager 1964), becomes greater than unity for $\lambda \gtrsim 1{\cdot}5$ mm. While drift curves at 1 mm indicate considerable limb-brightening (Noyes *et al.* 1968), observations at 8·6 mm (Coates, Gibson & Hagen 1958) show only slight brightening confined to a narrow ring at the extreme limb.

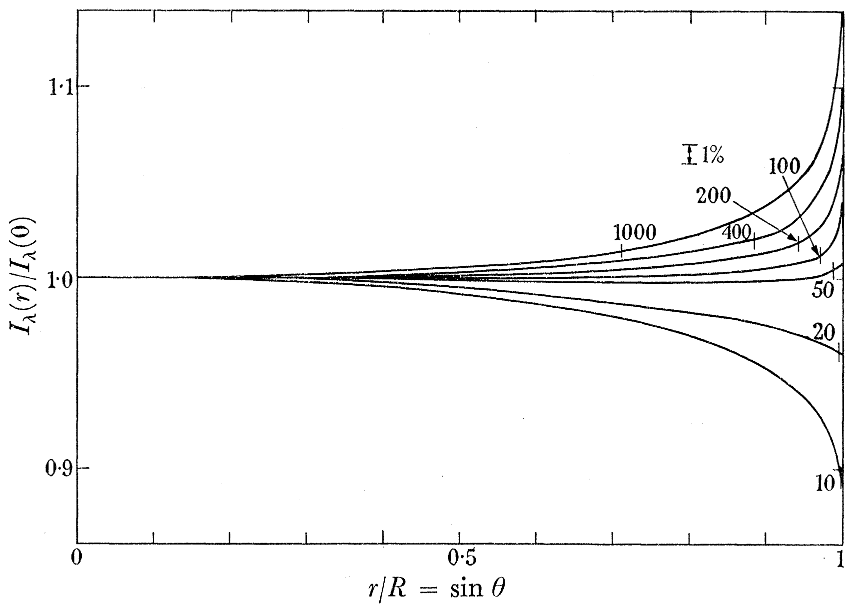

Figure 2. Centre-to-limb variation of the solar continuum predicted by the BCA model for various wavelengths in the far infrared. The curves are labelled with the wavelength in microns. The vertical lines represent the resolution limit $1{\cdot}22\ \lambda/D$, where D is 36 in.

Because of the problem of an inhomogeneous upper chromosphere, it is doubtful whether a model such as the BCA has any validity for wavelengths much in excess of 1 mm. In addition, variations in the upper chromosphere due to the solar cycle probably affect measurements at these wavelengths. At shorter wavelengths, however, we see to a depth where departures from homogeneity are probably not so serious and where the mean atmosphere is less likely to depend on the solar cycle. Thus it is probable that sub-millimetre observations can be related to a single run of temperature with height. In addition, such observations can make an important contribution because the model is rather poorly determined above $\tau_{5000} = 10^{-3}$, i.e. for wavelengths greater than about

† Extrapolated upward according to $T(\tau_1) = 4820 + 215/\sqrt{\tau_1}$ above $\tau_1 = 10^{-3}$, where τ_1 is the optical depth at 1 mm. Since the millimetre data alone determined the model in this height range, the agreement between the model and the data is good.

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100 μm. For example, the discrepancy between the model and the observations for wavelengths near 1 mm is very interesting and could well be real.

Figure 2 shows the limb brightening at submillimetre wavelengths predicted by the BCA. With a 36 in. telescope (the largest currently under consideration for infrared studies from above the tropopause), the Rayleigh limit $1{\cdot}22\lambda/D$ allows a resolution of about $4{\cdot}6\lambda_{mm}$ min arc, where λ_{mm} is the wavelength in millimetres. The short vertical lines in figure 2 mark off this distance inside the limb. We see that, although the presence of limb brightening should be detectable with 1 % relative photometry at wavelengths longer than about 100 μm, the detailed shape of the limb darkening curve will be lost. With a smaller telescope the problem is, of course, even more serious. The only hope of solving this problem above the atmosphere seems to be via airborne eclipse measurements, which should yield a resolution of a few seconds of arc.

Absolute radiometry in the submillimetre region remains a valuable tool for better determination of the thermal structure near the temperature minimum, but inasmuch as we are dealing with temperature differences of 100 °K or less throughout much of the region, we require an accuracy of 1 % or better. In the millimetre region, where there already appears to be a steep temperature gradient, the accuracy requirements are less stringent.

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