RADIO OBSERVATIONS OF CORONAL HOLES

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ABSTRACT

Coronal holes have been observed on several occasions with the 80 and 160 MHz radioheliograph at Culgoora. At 160 MHz the holes invariably appear as areas of low brightness, either on the disk or at the limb. At 80 MHz holes on the limb always appear less bright than their surroundings but on the disk they frequently appear brighter.

The simplest interpretation is that the coronal temperature in holes near the 80 MHz critical density (8×10^7 cm^{-3}) is higher than in normal quiet regions, but that the density at this level is lower.

1. INTRODUCTION

In the absence of solar activity, radio pictures of the Sun at metre wavelengths show several kinds of structure: bright regions (which are usually coronal streamers and are not related to the active regions and coronal condensations so prominent at centimetre and decimetre wavelengths and in soft X-rays); intermediate "quiet regions" (which correspond to the moderately bright loop-like structure seen in soft X-rays); and dark regions (which usually correspond to coronal holes). In this report we shall concentrate on the coronal holes and, in particular, their change in appearance with wavelength, using observations made with the 80 and 160 MHz radioheliograph at Culgoora.

2. OBSERVATIONS

A comparison of "quiet Sun" maps at 80 and 160 MHz (e.g. Figs. 1 and 2) shows that, as would be expected, the corona is less extensive at 160 MHz than at 80 MHz. The average brightness temperature in the central region tends to be fairly uniform at a value $\lesssim 10^6$ K; at the limb the brightness falls away quite steeply to about half the central value and then more slowly to a low intensity that blends into the sky

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background. Bulges and indentations in the contours near the limb are common.

Coronal Holes on the Solar Disk

Observations of the well-known coronal hole of the Skylab period, CH1, have been reported by Dulk et al. (1977). The hole was clearly visible on 160 MHz and higher-frequency maps as a depression with boundaries similar to, but not identical with, those seen on X-ray and EUV maps. However, at 80 MHz there was no indication of depressed brightness in the hole; in fact there was a brightness enhancement slightly to the west of the hole.

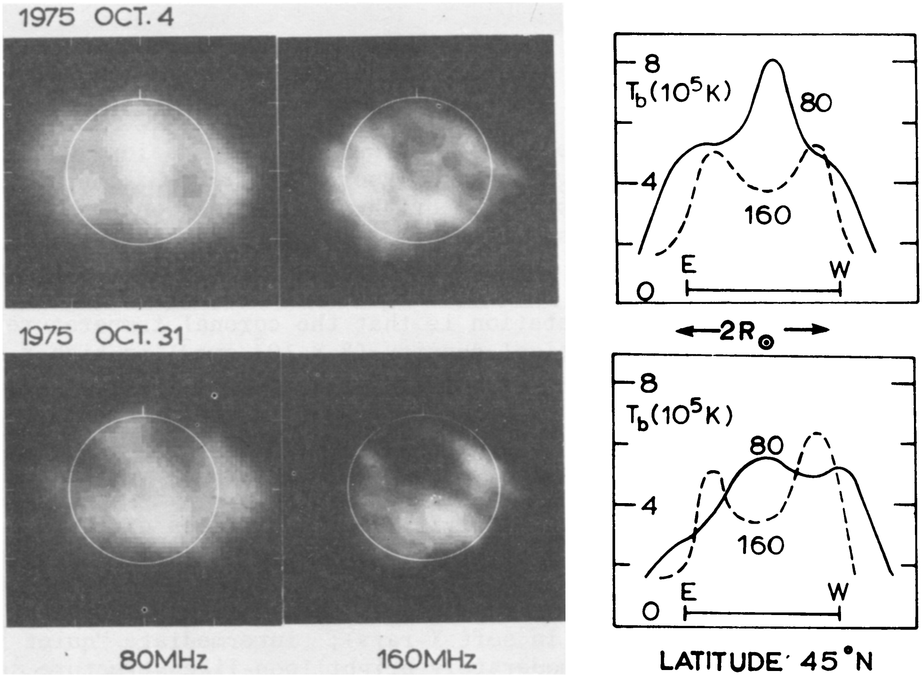

Fig. 1 - The large northern coronal hole of 1975 shown when it was near disk centre on two rotations, 1975 October 4 (top) and 1975 October 31 (bottom). The hole appears about 20% darker than its surroundings at 160 MHz and about 30% brighter at 80 MHz. The graphs at the right show the brightness temperature vs. position in the east/west direction at a latitude of 45°N. The scale of T_b assumes flux densities of 1.5 SFU (80 MHz) and 4.5 SFU (160 MHz).

Figure 1 shows radio pictures of another, very large, coronal hole which was observed on two successive solar rotations in 1975. The hole is clearly visible on the solar disk as a dark region at 160 MHz while a bright region is visible at the corresponding place at 80 MHz. The line drawings in Figure 1 show the observed brightnesses at the two frequencies on east-west scans across the Sun at latitude 45°N., the location of the deepest part of the hole. From these scans it is clear that the 80 MHz enhancements correspond very closely to the 160 MHz depressions. We note that the same hole appeared as a depression in brightness at 3.8 GHz (Shibazaki et al., 1977).

Coronal holes on the disk may not always appear as enhancements at 80 MHz, as indicated by Figure 1(b) of Dulk and Sheridan (1974). A low-brightness region was observed on FeXV maps obtained by the NASA-Goddard experiment on OSO-7 (Solar-Geophysical Data, 1972). The same region was seen as a slight depression both at 80 and 160 MHz.

Coronal Holes on the Limb

When coronal holes are on the limb their brightness temperature is less than that of their surroundings at both 80 and 160 MHz (and probably at all other wavelengths as well). Figure 2 compares radio

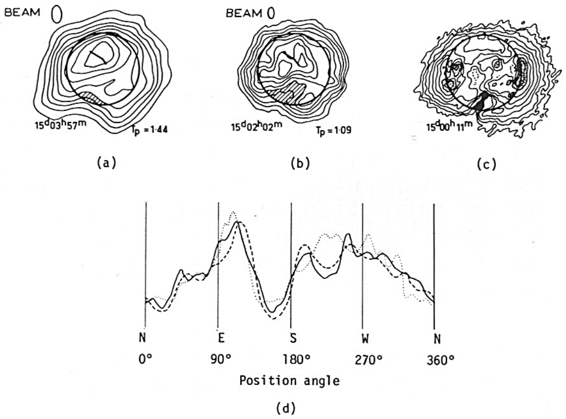

Fig. 2 - (a),(b),(c): Contour maps of coronal brightness on 1972 July 15: (a) observed at 80 MHz; (b) observed at 160 MHz; (c) the 284 Å line of FeXV. The circles represent the visible disk. The radio contours represent 0.1,0.2,...0.9 of T_p (units of 10^6 K), the peak brightness temperature of the map; the hatching emphasizes regions on the disk which are of unusually low brightness. On the EUV map the brightest regions, above contour 640, are stippled; on the disk, the darkest regions, below contour 10, are filled in. The dark line segment on the radio maps shows the position of a quiescent filament. (d): Scan of coronal brightness as a function of position angle at fixed heights above the limb. Full lines: 160 MHz at 1.2 $R_\odot$; dashed lines: 80 MHz at 1.45 $R_\odot$; dotted lines: K-corona at 1.57 $R_\odot$. The radio observations were made at the times of maps (a) and (b) and the K-corona observations (from the High Altitude Observatory in Hawaii) were made at about 18^h00^m UT on the previous day. The intensity scale is arbitrary for all data (after Dulk and Sheridan (1974) and Sheridan (1978)).

observations at 80 and 160 MHz with FeXV brightness observations on the same day, 1972 July 15. The outer contours in each case show general agreement in shape and extent. The darker regions in the south-central region on each map show the presence of a coronal hole near the limb. In Figure 2(d) we show scans made around the limb at fixed heights: $R = 1.2$, 1.45 and 1.57 $R_\odot$ at 160 MHz, 80 MHz and white light respectively; the white light data were obtained with the K-coronameter operated by HAO at Mauna Loa, Hawaii (Hansen et al., 1969). The coronal hole at PA = 160° can be seen on each scan. The brightness depression at 80 MHz is similar to that observed at 160 MHz and in white light.

Other examples of coronal holes near the limb have been given by: (i) Dulk et al. (1977), where CH1 was observed to be prominent near the northern solar limb at both 1.4 and 10.7 GHz; (ii) Sheridan (1978), where CH1 became visible at 80 MHz as it rotated to the limb; and (iii) Shibasaki et al. (1977) where a north polar hole was visible near the limb at 3.8 GHz.

3. INTERPRETATION

The radio brightness of the quiet Sun arises entirely from thermal bremsstrahlung due to electron-ion collisions in the ionized plasma. The electron density decreases with increasing height, and radiation at a given frequency can escape only from layers above the "plasma level", the height at which the electron plasma frequency is equal to the wave frequency and the index of refraction approaches zero. The radiation observed at metre wavelengths is emitted mainly from the layers not far above the corresponding plasma level and so the diameter of the Sun at 160 MHz is smaller than at 80 MHz.

It is interesting to consider how and why the observed brightness temperature varies across the Sun. But first we briefly review the emission theory.

The brightness temperature due to thermal bremsstrahlung is

$$T_b = \int_0^\infty T(\tau_\nu)\,\exp(-\tau_\nu)\,d\tau_\nu \ , \qquad (1)$$

where the optical depth at distance s from the observer is

$$\tau_\nu = \int_0^s \kappa_\nu\,ds \ , \qquad (2)$$

and the integral is along the (possibly refracted and scattered) ray path from the observer to the point s, perhaps including a reflection at the plasma level. The absorption coefficient κ_ν in (2) is given, for a fully ionized plasma with 10% helium, by

$$\kappa_\nu = 0.0108\, n_e^2\, T^{-3/2}\, \nu^{-2}\, \mu_\nu^{-1} \left[17.63+\ell n(T^{3/2}/\nu)\right] \mathrm{cm}^{-1} \ , \qquad (3)$$

where n_e is the electron density (cm^{-3}), T the electron temperature (K), ν the frequency (Hz) and μ_ν the index of refraction.

For an optically thin medium at constant temperature, T_c, (1) to (3) reduce to

$$T_b = T_c \tau_c , \tag{4}$$

where

$$\tau_c = C \nu^{-2} T_c^{-3/2} \int_0^\infty n_e^2 \, ds , \tag{5}$$

and the proportionality factor C depends only weakly on ν and T. For an optically thick medium we have

$$T_b = T_c . \tag{6}$$

We now consider possible reasons for the observed brightnesses of coronal holes and normal quiet regions, first at 80 MHz, then at 160 MHz.

At 80 MHz, the plasma level occurs at a density of 8 × 10^7 cm^{-3}; this density probably occurs in the corona rather than the transition region, even within coronal holes. Our calculations and those of others, starting with Smerd (1950), indicate that the corona above the plasma level, near disk centre, is optically thick, typically $\tau_c \approx 5$. Thus from (6) the measured brightness temperature equals the coronal electron temperature. The enhancements in brightness temperature over coronal holes on the disk therefore indicate that the electron temperature is higher there than in the surrounding quiet areas.

An alternative, although seemingly unlikely, interpretation could be that the corona at 80 MHz is not optically thick, which would make the brightness dependent on the density gradient near the plasma level. If this were the case, the higher brightness in a hole would imply a lower density gradient there than in normal quiet regions.

We noted earlier that the 80 MHz enhancement near CH1 was displaced to the west of the hole. This observation, if indeed the enhancement was related to the hole, would indicate an asymmetry in the emergence of magnetic flux from the hole.

Sufficiently far above the limb the corona at 80 MHz is optically thin. The brightness is then proportional to $\int n_e^2 \, ds$ by (4) and (5). Because n_e is lower at a given height in holes than in normal quiet regions, the 80 MHz brightness is also lower. The indentations in the 80 MHz contours and the dips in the limb scans of Figure 2 reflect this effect.

At 160 MHz the situation is more complicated. The plasma level corresponds to the height where n_e = 3.2 × 10^8 K, and this can occur either in the corona (for quiet regions) or in the upper transition region (for holes). Near disk centre, in quiet regions, the optical depth of the corona at 160 MHz is large, so, as with 80 MHz, $T_b \approx T_c$. In holes the corona has an optical depth of order unity, and thus the coronal material makes a substantial contribution to the observed brightness; however, the material of the transition region also contributes to the observed brightness, but because of its lower temperature its contribution is diminished. Thus coronal holes on the disk appear dark on 160 MHz pictures.

Above the limb, where the ray path is entirely in the corona and the corona is optically thin, the situation at 160 MHz is similar to that at 80 MHz: the brightness is proportional to $\int n_e^2\, ds$ and is lower at a given height if the line of sight passes through a hole than if it passes through a normal quiet region.

4. CONCLUSIONS

We have illustrated the features of coronal holes and quiet regions as they appear at 80 and 160 MHz. Our major result is the strong evidence that coronal holes on the disk at 80 MHz are sometimes brighter than surrounding quiet regions. This possibility had been raised by Dulk et al. (1977), but the 80 MHz enhancement in their data was displaced from the centre of the hole. At the limb, holes always appear as low-brightness indentations on quiet Sun maps.

We have qualitatively examined the reasons for the high brightness at 80 MHz and found that the coronal electron temperature is probably higher in the hole than in quiet regions, at least near the height where $n_e \approx 10^8\ \mathrm{cm}^{-3}$. We have not analysed the data quantitatively, partly because of observational uncertainties, and partly because of the more serious problem of the discrepancy between radio and other wavelengths as to the density-temperature structure of the transition region and low corona (Dulk et al., 1977; Chiuderi-Drago et al., 1977; Dulk, 1977; Chambe, 1978; Trottet and Lantos, 1978; Chiuderi-Drago, 1979). Progress must be made on the latter problem before we can be confident of any densities or temperatures that we might derive from radio observations alone.

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DISCUSSION

Newkirk: What is the quantitative temperature enhancement required at the 80 MHz level?

Sheridan: The observed 80 MHz enhancement (see Fig. 1) is about 20-30% brighter than the surrounding regions.

Moore: What is the height of formation of the 80 MHz emission in coronal holes? The recent Lyα/whitelight rocket observations from Harvard indicate that the temperature in coronal holes does increase with height by about a factor of two over a few solar radii, which would be consistent with your results.

Sheridan: The 80 MHz critical density (8×10^7 cm^{-3}) level would occur in the corona, even inside the hole, and so the result you quote would be in agreement with our observations.