Multiwavelength Observations of a Coronal Hole

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Abstract. We present microwave, optical and EUV observations of a coronal hole observed on 1996 August 26. The coronal hole is seen in emission at 17 GHz. This is an unexplained phenomenon and we try to constrain the emission mechanism by comparing observations in and outside the coronal hole. We found that the coronal hole contains enhanced unipolar magnetic regions with which the radio emission is associated. Based on the observations, we conclude that the radio enhancement must originate from the upper chromosphere where the temperature is around $10^5$ K. We suggest possible reasons for the radio enhancement.

1. Introduction

Coronal holes are large-scale structures in the solar corona containing predominantly open magnetic field lines (see Zirker 1977, for a review). High speed solar wind is channeled along these field lines, thus linking the coronal holes to the recurrent geomagnetic storms. The coronal holes became a subject of great interest when a large number of high quality X-ray images were obtained by the Skylab mission. Coronal holes appear around the poles as well as at low latitudes. The polar holes are prominent during solar minimum and almost disappear during solar maximum. The low-latitude coronal holes present an entirely different perspective because we can look directly along the field lines during their central meridian passage. Coronal holes rotate rigidly (Wagner 1975; Timothy et al. 1975). This means a relative motion with respect to the photosphere and the interesting possibility of magnetic reconnection at the coronal hole boundaries (Wang et al. 1996).
Radio observations of coronal holes generally show the same trend as at other wavelengths: reduced radio emission as compared to the quiet sun (Borovik et al. 1990). However, at wavelengths < 2 cm (15 GHz), the coronal holes are seen in emission (Wefer & Bleiweiss 1976). This radio enhancement seems to disappear at wavelengths shorter than a few mm (Kosugi et al. 1986). After the advent of the Nobeyama Radioheliograph (Nakajima et al. 1994), the polar coronal holes are routinely observed to be brighter than the quiet Sun at 17 GHz. It is best to study the radio enhancement in low-latitude coronal holes because there is no confusion from the limb brightening. We have observed such a radio enhancement in the “elephant trunk” coronal hole (Whole Sun Month campaign, 1996 August 10 – September 8, see Gibson & Biesecker 1997). We present preliminary results and discuss the possible reasons for the short-wavelength radio enhancement in coronal holes. This study has important implications for models of the upper chromosphere and the lower transition region because the radio enhancement in question seems to arise from this region.

2. Observational Results

In Fig. 1 (left), we have shown the elephant trunk coronal hole as imaged by the SOHO/EIT at 195 Å. The coronal hole extends from the north pole beyond the equator, turns towards the active region near the east limb and stops there. The elongated depression region to the east of the elephant trunk coronal hole is a filament channel. In Fig. 1 (right), we have shown the 17 GHz Nobeyama radioheliogram. Both the south and north polar coronal holes are bright in microwaves. In addition, the low latitude section of the coronal hole is also bright (arrows), although to a smaller extent. We see that the only brightness depression is from the dark filament to the west of the coronal hole.
Figure 2. The 'elephant trunk' coronal hole in EUV (EIT 195) and in microwaves (17 GHz - contours). The solid (dashed) contours are enhancements (depressions) relative to the quiet Sun level. The contour levels are at -500, -250, 500, 750, 1000, 1500, 2000 and 2500 K. Filaments (F) coronal hole (CH) and the radio bright points (BP) are indicated by arrows. Note that two sections of the coronal hole are bright in microwaves.

2.1. Coronal hole bright points

The radio image in Fig. 2 shows several bright points (BPs) within the coronal hole region, with a brightness temperature 3 to 4 times larger than the coronal hole enhancement. The BPs are similar to the polar-plume bases in polar holes. In Fig. 3 (left) we have shown an east-west cut across the coronal hole at the location where it makes the eastward turn. We see a background radio enhancement with a superposed BP. The size of the BP is about 20 arc sec while the radio enhancement has a size of about 300 arc sec. These BPs were variable over a time scale of about 30 min (see Fig. 3 (right)). The bright point variability is an important piece of new information on the radio properties of coronal holes.

2.2. Radio enhancement and photospheric magnetic field

In the longitudinal magnetogram obtained by the Kitt Peak Vacuum Tower Telescope there were five patches of mixed (M) and unipolar (U) magnetic structure spanning the coronal hole in the north-south direction (see Fig. 4). In these patches, the positive magnetic polarity dominates and the magnetic field seems to be somewhat elevated compared to the neighboring quiet regions. In Fig. 5,
Figure 3. (left) Brightness variation along an east-west cut of the coronal hole showing the BP (solid line) and the coronal hole (dashed line). (right) Time variation of the brightness temperature in a small area around the BPs in the southern patch of radio enhancement.

we have shown a sub-image of the magnetogram, along with the radio enhancement (contours) superposed. The radio emission is associated with U-patches with enhanced positive polarity. The radio emission at the M-patches (the resultant polarity is still positive) is at the quiet Sun level. It must be pointed out that the magnetogram was taken about 14 hours later and can be used only for comparing the long time scale features.

2.3. Summary of observations

The Observational results can be summarized as follows:

1. Both equatorial and polar coronal holes are brighter than the quiet Sun at 17 GHz. Taken together with the published results, we infer that the radio enhancement occurs in a narrow frequency range from 15 GHz to beyond 38 GHz. At about 98 GHz, the coronal hole has the same brightness temperature as the quiet sun.

2. The radio brightness enhancement consists of a diffuse component and bright points in the equatorial region. This pattern is similar to the diffuse enhancement and polar plumes in the polar coronal holes.

3. The radio enhancement is typically $10^3$ K for the diffuse components and about 3000 K for the bright points.

4. The polar brightness enhancement is generally greater than that in the low-latitude region, probably due to the contribution from limb brightening.

5. The radio enhancement is associated with enhanced unipolar magnetic region as seen in longitudinal photospheric magnetogram.
3. Why Radio Enhancement?

At present, there is no satisfactory explanation for the radio enhancement. It has been suggested that the temperature and density structure in the coronal hole may be different from that outside (Kosugi et al. 1986) such as shallower gradients of temperature and density (e.g., Withbroe 1977). Here, we examine the evidences and suggest possible approaches towards an explanation of the radio enhancement. In order to decide the layer from which the radio emission may originate, we consider the equation of radiative transfer for the observed brightness temperature:

\[ T_b = T_{ch}e^{-\tau_c} + T_c(1 - e^{-\tau_c}) \]  

where \( T_b \) is the brightness temperature, \( T_c \) and \( T_{ch} \) are the coronal and chromospheric temperatures, and

\[ \tau_c = 0.2n_e^2H_c f^{-2}T_c^{-3/2} \]  

is the coronal optical depth, typically far less than unity at frequencies where the radio enhancement is found. For \( \tau_c \ll 1 \), we can rewrite the brightness temperature as,

\[ T_b = T_{ch}(1 + \tau_cT_c/T_{ch}) \]  

The coronal contribution to the brightness temperature is significant when

\[ \tau_c > T_{ch}/T_c. \]  

For \( T_{ch} = 10^4 \) K and \( T_b = 1.5 \) MK, we need \( \tau_c = 0.007 \) to get a coronal contribution same as that of the chromospheric contribution. However, this never happens. For example, the average density in the coronal hole was obtained
Figure 5. Association of the radio enhancement (contours on the right panel) in the coronal hole with respect to the longitudinal magnetic field (left panel). M is the mixed polarity region with no radio enhancement. As in Fig. 4, the bright (dark) elements correspond to positive (negative) magnetic polarity.

from SOHO/CDS observations as $2.5 \times 10^8$ cm$^{-3}$ (DeForest et al. 1997). This gives a coronal optical depth of $\sim 1.2 \times 10^{-4}$ and the coronal contribution to the $T_b$ would be only about 200 K. Note that the density used here is similar to the densities obtained by Doschek et al. (1997) for polar coronal holes on different days. In the quiet corona, the density is higher by a factor of 2.4 and the temperature is about 2 MK. This gives a coronal contribution of about 600 K. The coronal contribution from holes may be slightly higher if the scale height is larger, but may not be too high compared to the contribution from the quiet corona. Therefore, one can rule out the possibility of coronal origin for the radio enhancement in the coronal holes.

In the above equations, we have not included the contribution from the chromosphere-corona transition region (TR). The TR contribution to the brightness temperature in microwaves must be negligibly small as was shown by Grebinskii (1987). He combined the existing models of the solar atmosphere excluding the transition region in the temperature range $2 \times 10^4 - 2 \times 10^5$ K and found
that the derived radio spectrum agreed with the observed quiet Sun spectrum. In other words, the TR must have a very small filling factor. This has to be true even for the transition region in the coronal holes. The TR contribution must be extremely small from another point of view: since the TR is optically thin, any significant contribution will result in an observed polarization. The Nobeyama radioheliograph can measure very low polarizations, but the coronal hole was not polarized. Thus we conclude that the observed radio enhancement is likely confined to the upper chromosphere where the temperature is around 10,000 K.

3.1. Reconnection and heating

Parker (1991) explored the possibilities of wave heating of the coronal hole plasma and concluded that activity in the small-scale magnetic fields (network microflares due to reconnection of bipoles) at the bottom of the coronal holes provides sufficient energy in the form of Alfvén waves that dissipate over distances of 5–20 $R_\odot$. While an estimated 20% of the released energy goes into Alfvén waves, the remaining 80% dissipates quickly at the coronal base. This may be one possible source of heating that results in the radio enhancement. This mechanism has to operate more efficiently in the coronal hole compared to the quiet Sun to produce the observed effect. The frequent BPs in the coronal hole supports such a possibility. It must be pointed out that Wang et al. (1996) have also proposed a reconnection process taking place at the coronal hole boundary consistent with the locations of at least some of the radio BPs.

3.2. Change in turbulent conductivity

Another important physical consequence of the small-scale energy releases at the base of the coronal holes is the presence of enhanced turbulence. The turbulent conduction far exceeds the classical conduction at lower temperatures and thus one would expect enhanced energy dumping in the upper chromosphere (Fielder & Cally 1990, see also Mariska 1992). The variability observed in the coronal hole BPs is supportive of the idea of energy release and the presence of turbulence and hence this must be explored further. One needs, of course, a detailed comparison with the quiet chromosphere in order to understand the radio enhancement in the coronal holes.

3.3. Cross field conduction

The fact that the transition region makes negligible contribution to the microwave brightness temperature implies a very small filling factor. i.e., the presence of unresolved fine structures (Feldman 1983, Grebinskii 1987, Zirin 1996, Avrett 1997). Based on the initial suggestion by Rabin (1986), Athay (1990) modeled the lower TR as a roughened surface (model of the unresolved fine structure) with hot valleys and cool peaks and was able to account for the low temperature branch of the emission measure curve. The primary effect is the cross field conduction which causes the parallel conduction flux flow across the magnetic field to the cool peaks. The cross field conduction is proportional to $T^{-5}B^{-2}$ (where $T$ is the temperature and $B$ is the magnetic field) and hence becomes dominant at the upper chromospheric temperature. One possibility worth investigating is the role of the magnetic field strength in the cross field
conduction. The enhanced magnetic field patches associated with the radio enhancement suggests that the possibility of energy pile-up in the bottom of the coronal hole compared to a quiet Sun, resulting in the observed radio enhancement.

4. Conclusions

We have presented observations of diffuse and bright point-like radio enhancement in the elephant trunk coronal hole observed during the Whole Sun Month. The bright point emission is variable over a time scale of 30 minutes and may be a signature of the dynamical processes taking place in the coronal hole. We argued that the radio enhancement corresponds to the upper chromosphere and speculated possible mechanisms of the enhanced radio emission.

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Group Discussion

Jones: It appeared to me that the enhanced radio emission was associated with positive unipolar areas in the coronal hole and not with intrusions of negative polarity suggesting that the radio emission is more associated with open field configurations.

Gopalswamy: I agree that the radio enhancement is associated with the positive unipolar regions. However, the coronal hole itself seems to be a single one attached to the north polar coronal hole (which itself is of positive polarity). It remains to be seen whether the regions with mixed polarity have overall weak positive polarity. Otherwise, it is difficult to see a neutral line within a single coronal hole.

Balasubramaniam: Do the radio brightenings within the coronal hole represent some kind of a low lying closed loop reconnective structure within an open ended magnetic structure that expands into space?

Gopalswamy: The bright points seem to be confined to the chromospheric heights. We do not see any correspondence in Yohkoh/SXT or SOHO/EIT bright points. However, we do see them associated with bright features in He II 304 Å (SOHO/EIT), which further confirms that they are not associated with the open ended magnetic structure.

van Ballegooijen: The radio emission in the coronal hole shows point sources superposed on a more diffuse background. Where are these point sources located relative to the magnetic field?

Gopalswamy: The bright points do not show any preferred association with the magnetic field. They are seen on the network as well as on cell interiors. However, the magnetogram we used was taken ~14 hours after the radio image. We plan to compare with simultaneously obtained magnetogram.