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OUT-OF-ECLIPTIC STUDIES OF CORONAL HOLES AND THEIR RELATION TO THE SOLAR WIND

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Recently solar physicists have gained the ability to view the solar corona from a new perspective, by means of space observations at x-ray and extreme ultraviolet (EUV) wavelengths, which permits us to observe the forms of the hot, but very tenuous, corona against the relatively cool solar disk (Figure 1). Ground-based observations of the corona, except for relatively low-resolution radio data, require natural (via eclipse) or artificial occultation of the bright disk, limiting coronal observations to "side views" through the atmosphere extending beyond the occulting disk. The direct face-on view provided by EUV and x-ray space observations, combined with detailed information on density and temperature of the emitting regions conveyed by the spectral character of the ultraviolet and x-ray data, has given us the first detailed information on the complex structures of the corona and their interrelations.

The possibility of looking down on the sun from a spacecraft high above the ecliptic plane opens up yet another perspective on the sun, one that is certain to help us understand the nature of coronal holes at high latitudes, and their relationship to the expansion of the three-dimensional solar wind.

The large dark area on the x-ray image of Figure 1 is a coronal hole — a phenomenon whose properties are just now becoming understood, largely through EUV and x-ray observations. Although the existence of large regions of low coronal density had earlier been inferred from coronagraph "side views", we are now obtaining detailed knowledge of their size, shape, density, temperature, magnetic field, and evolution from spacecraft observations at EUV and x-ray wavelengths.

Briefly, coronal holes are large regions of the corona whose density is some 3-10 times less than that of the "average" quiet corona. The temperature, at least at the level where measurable x-ray and EUV radiation is emitted, is also less, having a value of about 1 x 10^6°K instead of about 1.8 x 10^6°K, as in the average corona. Analysis of low-resolution OSO data (Munro and Withbroe, 1972) suggested that the temperature gradient between the 10^4°K chromosphere and 10^6°K corona is about an order of magnitude less in coronal holes than in the average sun. As a result, the energy loss to the corona by thermal conduction back to the chromosphere, which is a very important energy sink for the average corona, may be much less significant for coronal holes. Due to the low density in holes the radiative losses are also less (which is of course why they appear dark in the x-ray image of Figure 1). Since energy losses by radiation and conduction are both drastically decreased in holes, we may conclude that either the heating of the corona is less in holes or some additional mechanism of energy loss is present in holes that is not found in other regions of the quiet sun.

Coronal holes are assuming great importance today because of their apparent association with high-speed streams of the solar wind. The association, first suggested by Krieger et al (1973) on the basis of rocket x-ray data, has been put on a much firmer footing from detailed correlative studies of OSO-7 and Skylab data during the period 1973 to 1974. Nolte et al (1976) found that every large near-equatorial hole observed during the Skylab mission was associated with a high-speed stream at 1 a.u. Furthermore, there was a clear positive correlation between the velocity of the observed solar wind stream and the area of the associated coronal hole as measured from Skylab x-ray photographs. Finally, a very high correlation was found between the polarity of the interplanetary magnetic field associated with the high-speed streams and the magnetic field underlying the associated coronal holes.

During the Skylab mission coordinated ground-based and space data revealed that the location of coronal holes can also be detected through ground-based observations of subtle properties of certain Franhofer absorption lines, notably He I, λ 10830 (Harvey et al, 1975). This discovery has permitted the mapping of coronal hole boundaries during the two years after the termination of the Skylab mission. These two years were a time of large and persistently recurring high-speed solar wind streams, and significantly, a pattern of long-lived coronal holes was detected from the He I 10830 observations. Harvey et al (1976) have shown that, as before, there is a good correlation between central meridian passage of holes that cross the equator and high-speed streams during that time. In addition, when the data also include high latitude holes that also extend down to ± 40° latitude, the correlation becomes even better. Thus there appears little question that the high-speed streams are related to coronal holes, and in addition there is evidence that some of the streams observed in the ecliptic plane are associated with holes at latitudes at least as high as 40°.

To establish that the holes are the origin of the high-speed solar wind streams, however, it is necessary to identify a physical mechanism in addition to finding a high correlation between the two phenomena. In a search for a physical mechanism, we first note that coronal holes occur over areas of unipolar photospheric magnetic fields. Although magnetic fields are measurable only in the photosphere, they may be mapped upwards into the corona, using potential theory along with the assumption that above about 1.6 to 2.5 solar radii they are stretched out radially by the expanding solar wind (Newkirk, 1972). Such calculations show the magnetic fields underlying holes to reach the source surface and thus to open out into the interplanetary medium, while fields underlying other regions in the corona generally close back on themselves (Altshuler et al, 1976). Thus holes seem an easy pathway for the escape of coronal plasma into the solar wind.

We have already noted that the density and temperature structure of holes in the low corona suggest that either the coronal heating rate is less in holes or excess energy may be available to accelerate the solar wind outward in holes. It is interesting that coronal holes are almost impossible to detect in the chromosphere or below, suggesting that at those levels the atmospheric structure does not depend on whether or not a hole exists in overlying corona. This suggests (although it does not prove) that the amount of mechanical heating that passes upward through the photosphere is independent of the existence of coronal holes. Under that assumption Pneuman (1973) and Noci (1973) showed that the solar wind, expanding outward in regions of open field lines, would carry off energy through acceleration of the solar wind and through outward thermal conduction, sufficient to compensate for the decreased energy losses from holes by radiation and inward thermal conduction. The exact mechanism by which originally closed field lines break open to allow the expansion of the solar wind and the creation of a hole is not yet clear, but arguments based on energy flow support the reality of the process.

If radial outflow really occurs over coronal holes, it should give rise to observable doppler shifts of XUV emission lines. Preliminary reports (Cushman and Rense, 1976) indicate the detection of outward velocities of the order of 16 km/sec, which may in fact be the beginnings of the solar wind expansion. However, the data are scanty and further verification is needed.

What does all of this have to do with the out-of-ecliptic mission? The significance lies in the fact that coronal holes have been found to occur very frequently at the solar poles. The polar holes appear to be very similar to equatorial holes in their physical properties, with a major difference that they are much larger. A plausible hypothesis is that they too give rise to high-speed solar wind streams. These streams may emanate from the poles but spread out to lower latitudes, even reaching the ecliptic plane if the polar hole extends to low enough latitudes.

Unfortunately observations of polar holes from the orbit of earth still suffer partly from the projection problem described at the beginning of this paper. Because polar holes always occur near the limb (as opposed to near-equatorial holes, which are carried past disk center by rotation), we always observe them from the side. This of course leads to loss of spatial resolution due to foreshortening. In addition, observations from the side are particularly troublesome for observations of coronal holes, which are by their nature only very weakly emitting, and therefore are very easily obscured by foreground and background emission from the neighboring "normal" corona.

It is also extremely difficult to get accurate measurements of magnetic fields associated with polar holes. Firstly, projection effects lead to loss of resolution. Secondly, the sensitivity of a magnetograph is proportional to the line-of-sight component of the field direction; for vertical fields near the limb this becomes very small.

Finally, of course, velocities of radial outflow above a coronal hole at the polar limb would not give rise to a line-of-sight doppler shift when observed from the orbit of earth.

What might one hope to observe from a spacecraft situated over the pole? Figure 2 shows a reconstruction of the appearance of the south polar hole as it would have been observed from such a vantage point during nine months of the Skylab mission. The images of Figure 2 were rectified using Skylab data from the Naval Research Laboratory XUV monitor instrument (Sheeley, 1975, personal communication). The large size of the hole compared to typical equatorial holes (cf. Figure 1), and its extended lifetime, are immediately apparent.

A spacecraft able to observe the sun from higher latitudes (say greater than 60°) for several months at a time, and properly instrumented, should be able to accomplish many significant observations of coronal holes. Large and sophisticated instruments such as have been flown on Skylab are by no means necessary, and are probably out of the question for the foreseeable future. The following are examples of important observational objectives, that could be met by realistic instrumentation aboard an out-of-ecliptic mission.

1) Continuous mapping of the location of polar holes, and study of their evolution. A simple imager at any of a number of XUV or x-ray wavelengths, chosen such that the emission within the band pass largely originates at temperature in excess of about 1.5×10^{6}°K, would be adequate. Spatial resolution of about 30 arcsec would be sufficient. For a small instrument, count rates would be quite low, but time resolution need be only of the order of many hours, so long integration times are

possible. Images could be built up by scanning a point detector (perhaps using the rotation of the spacecraft for scanning). Data on the location of the hole and its boundaries would be correlated with measurements from the same spacecraft of local plasma parameters (density, velocity, magnetic field, composition, temperature), and as the spacecraft traverses directly above different parts of the hole or its boundaries, some idea of the three-dimensional flow field could be obtained. In addition, from the absolute intensities recorded, some useful limits on the density and temperature of the emitting plasma inside the hole could be obtained.

2) With imagery at two or more XUV or x-ray wavelengths, one can obtain much better information on the physical conditions in the coronal hole itself. Approximate values of density and temperature can be determined independently, and combined with modeling techniques, the data can give information on the variation of the parameters with height. Since both the density and temperature distribution in the low corona strongly determine the plasma flow properties at one a.u., correlation with these properties measured at the spacecraft itself will be very important.

3) XUV spectroscopy at high spectral resolution ($\lambda/\Delta\lambda \gtrsim 3 \times 10^4$) would be very useful to measure the outflow velocity of material in the polar hole, in the manner already reported by Cushman and Rense (1976) for equatorial holes. Unfortunately the weakness of XUV emission lines in coronal holes, combined with the requirement for high spectral resolution, implies either a rather large instrument or extremely long integration times. This experiment, while very important, may therefore not be a suitable candidate for a very early exploratory out-of-the-ecliptic mission.

4) Measurement of the polar magnetic field from an out-of-ecliptic spacecraft appears to be a natural and important objective. As mentioned above, there are considerable advantages in observing polar magnetic fields from more nearly above the poles. Spatial resolution of 30 arcsec would be adequate to determine the gross structure of the fields and to follow their evolution. A small magnetograph operating with a solid etalon fabry-perot filter in visual wavelengths might well be feasible for inclusion on an exploratory out-of-ecliptic mission.

All of the above objectives would be considerably furthered by simultaneous measures from the ecliptic plane, in order to obtain stereoscopic information. In the case of magnetic fields, for instance, observations from the earth would record those fields not recorded from the out-of-ecliptic spacecraft, and vice versa. Comparison of relative signal strengths from such paired observations could help determine the vector field in the photosphere, thus putting potential mapping of high-latitude magnetic fields on a more secure footing. Similarly observations from an earth-orbiting satellite of the XUV or x-ray structures in coordination with simultaneous out-of-ecliptic observations of the same structures would yield the 3-dimensional structure unambiguously.

We should note that the success of a program to study polar holes from out-of-ecliptic may depend strongly on the phase of the cycle during which the program is carried out. It appears that polar holes may shrink and even disappear near sunspot maximum, doubtless reflecting the shrinkage and disappearance of the unipolar magnetic field cap associated with reversal of the general dipole field of the sun, which occurs about that time. At about sunspot minimum, unipolar magnetic fields at the poles and polar coronal holes appear to reach their greatest extent. From the point of view of studying polar holes and their relation to the solar wind, then, it may be useful to time the passage of an out-of-ecliptic satellite over the solar poles, or at least over high latitudes, to occur with a few years either side of sunspot minimum.

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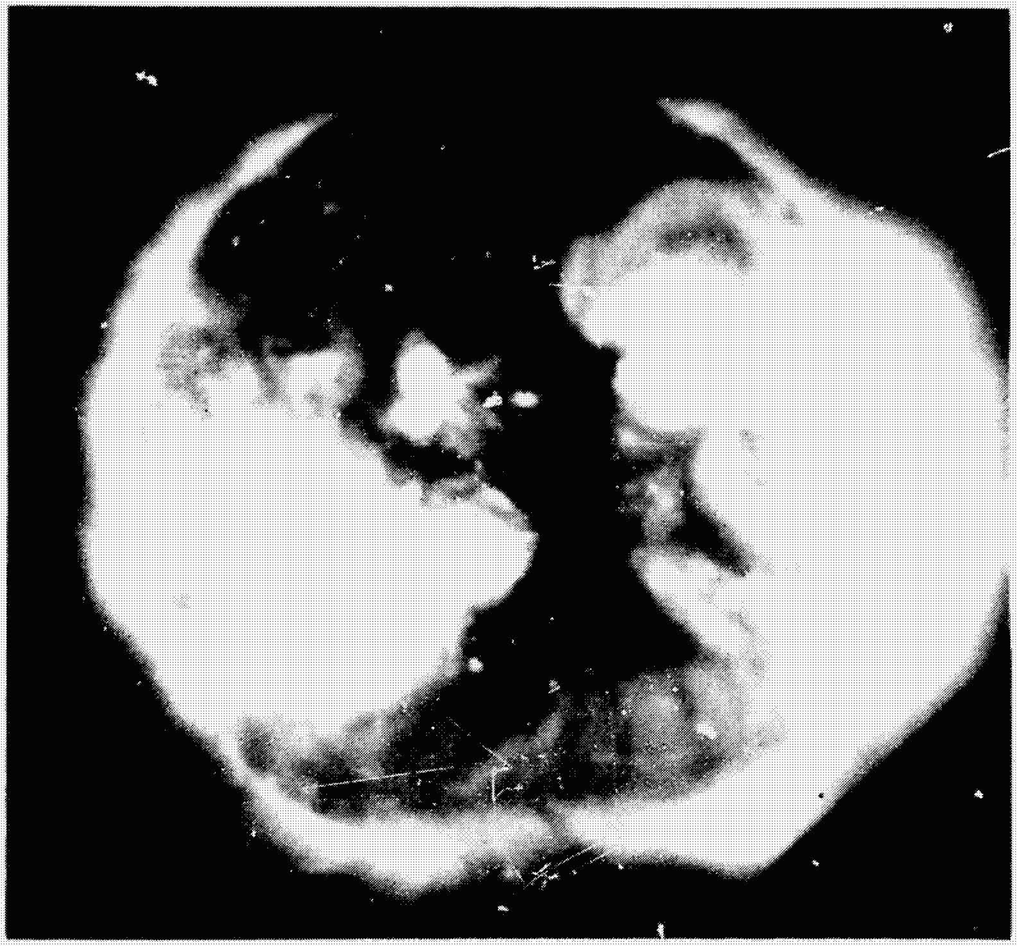
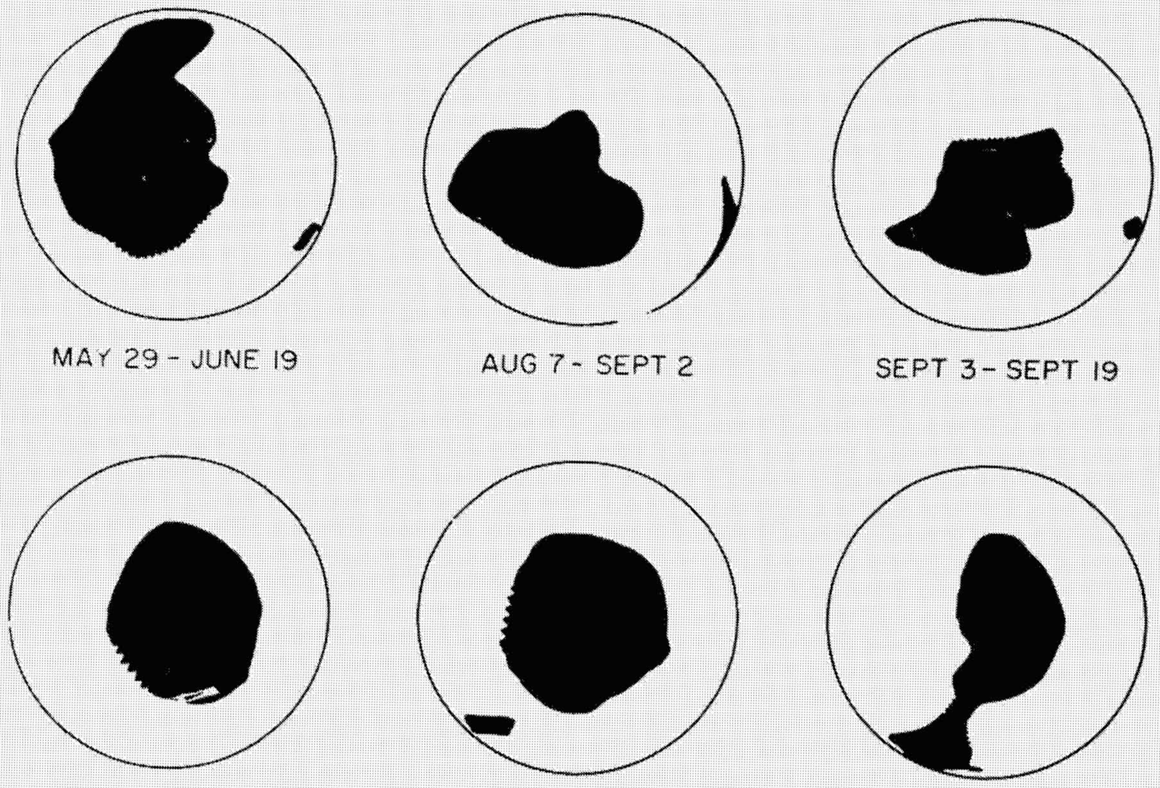
Figures

Figure 1. Skylab soft x-ray image of the sun, June 1, 1973. Filter bandpass 2-32A and 44-54A. See Vaiana (1976) for details. Photo courtesy American Science and Engineering, Inc., and Harvard College Observatory.

Figure 2. Diagram of the evolution of a coronal hole as it would have been seen from above the south pole. Data are rectified from ATM Skylab observations, May 1973 to February 1974, made with the Naval Research Laboratory XUV monitor instrument. Data courtesy N.R. Sheeley, Naval Research Laboratory.



SOUTH POLAR HOLE, 1973-1974,
RECTIFIED FROM
NRL XUV MONITOR DATA



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