OBSERVATIONAL EVIDENCE FOR SOLAR WIND

ACCELERATION AT THE BASE OF CORONAL HOLES

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ABSTRACT

A new EUV spectrometer with a CODACON microchannel plate detector has been developed to measure Doppler shifts of coronal and transition region lines. The results of three sounding rocket flights of this instrument indicate that EUV resonance emission lines are systemaically shifted toward shorter wavelength within coronal holes. This "blue-shift" signature, first identified within compact low latitude holes, has now also been observed in a well developed polar coronal hole. The maximum measured shift within these coronal holes corresponds to a velocity relative to the remaining solar disc of 12 km s^{-1} in λ625 Mg X ($T \sim 10^{6.15}$K) and 7 km s^{-1} in λ629 OV ($T \sim 10^{5.4}$K). The existing data indicate that these blue-shifts are a common (and possibly universal) signature of coronal holes. These data provide important information on the acceleration of coronal plasma in open magnetic field regions, although the interpretation of observed Doppler shifts to derive a systematic mass flux is to some extent model dependent. A straightforward hypothesis is that the blueshift signature is a direct manifestation of the high speed solar wind deep within the transition region and inner corona.

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Introduction

During the past decade it has become well established that most of the solar wind and most of the "open" solar magnetic field lines of interplanetary space emanate from a few evolving regions on the solar disk whose total area varies from perhaps 5 to 20% of the solar surface. In the inner corona above such regions the density is low, and the intensities of emission lines characteristic of these higher temperatures are much reduced relative to the quiet corona. Low density, open magnetic regions had long been known to exist in high heliographic latitudes, especially near the minimum of the sunspot cycle, but the understanding that these coronal holes also commonly occur at low latitudes and that they are the source of the high speed solar wind streams was not established until the mid 1970s. The fact that the high speed solar wind originates within coronal holes has placed severe demands on theories of solar wind acceleration, but it has also focused and clarified the problem. Certainly an important constraint on theory would be measurements of flow velocity and mass flux as a function of height in the inner corona.

In 1973 during the Skylab mission Cushman and Rense flew an EUV rocket experiment and found a region on the solar disk where the coronal emission line λ303 Si XI was very faint and also shifted to shorter wavelength with respect to the rest of the solar disk. They suggested that the region was a coronal hole, and interpreted the blueshift (which corresponded to 13 km s^{-1}) as evidence for plasma outflow from it. It subsequently turned out that this region did not fall within one of the coronal holes catalogued by the Skylab experimenters based on the ATM soft X-ray and He II solar images. This observation is considered in more detail below.

More recently a new stable high resolution EUV spectrometer has been developed at the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado to study motions in the inner corona. This rocket-borne normal incidence Rowland mount spectrometer forms a spectrum on a multi-element linear array detector consisting of a micro-channel plate using the CODACON readout scheme developed by G. Lawrence of LASP. The 1024 channels of this array are aligned along the dispersion direction with 28 mÅ per channel in second order. As presently configured, the instrument is optimized for efficiency and resolution near 600Å and covers the region λ605-λ635 in second order with the first order spectrum superposed on it.

We have flown this experiment three times. On each flight the solar pointing system (SPARCS) was programmed to scan back and forth along a chord on the Sun's disk throughout the flight. The scan line was chosen to cross a coronal hole as defined by λ10830 He I spectroheliograms from Kitt Peak. Each scan took about 30 sec and 9 or 10 scans were completed on each flight. The effective spatial resolution was reduced to 1 x 1 arcmin by motion of the slit along the scan line during the 0.4 second readout time of the detector. On each flight, where the scan crossed the coronal hole, emission lines formed in the corona and transition region were shifted to shorter wavelengths relative to the rest of the disk. No significant shift was seen in the chromospheric lines of Si II.

In this paper we summarize the results of these three recent LASP rocket flights and some pertinent results by other investigators. We discuss the implication that these measurements have for solar wind flow at the base of coronal holes down to the transition region.

Observations

The target for the first flight (June 5, 1979) of the LASP experiment was a rather small low latitude hole near Sun center just south of an active region (McMath 16046). The relative Doppler displacement of the transition region line λ629 OV ($T \sim 10^{5.4}$K) (Rottman, Orrall and Klimchuk, 1981) is shown in Figure 1.

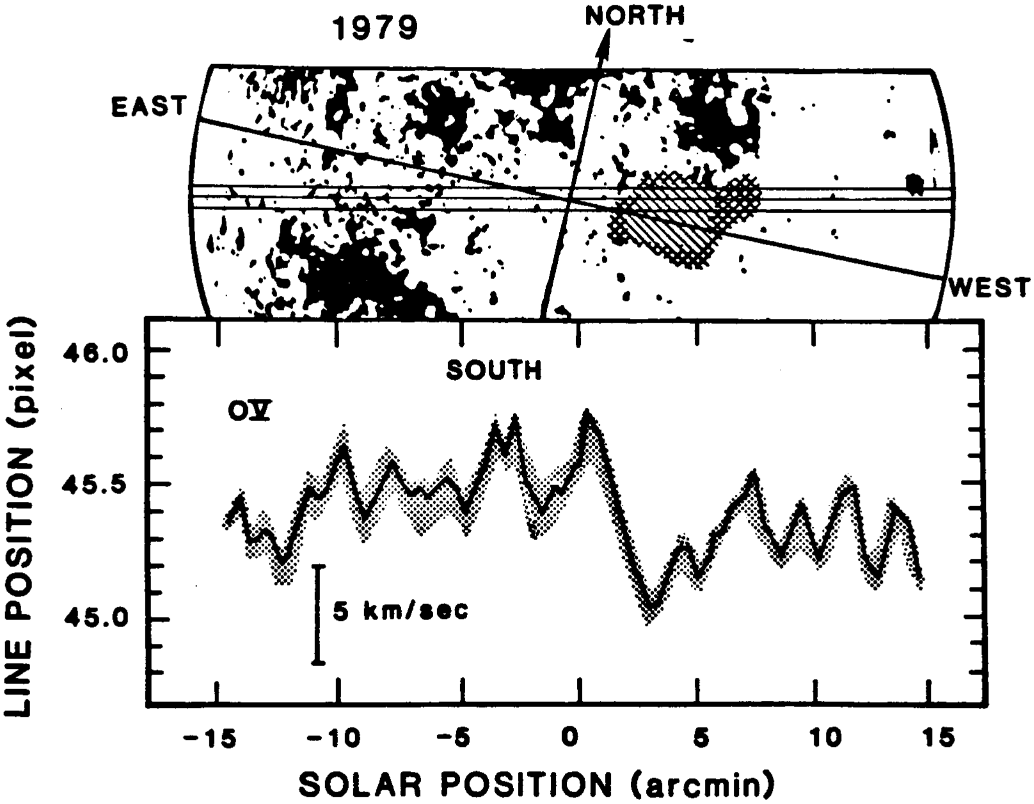

Figure 1. Mean line position of OV λ629 as measured along a solar diameter during the rocket flight of June 5, 1979. The shaded band represents ±1 standard deviation of the mean. In the top panel the dark markings indicate regions bright in the K-line (Ca II) and the crosshatched region is the coronal hole observed in λ10830 He I.

The shading represents one standard deviation of the mean of 9 scans across the solar disk. The top panel of the figure is a schematic representation of active regions bright in Ca II emission (dark areas) and the coronal hole from the λ10830 He I spectroheliogram (cross hatched). There is a clear relative blueshift where the scan crosses the hole. On this first flight, internally scattered Lyman-alpha radiation made measurements of the coronal lines such as λ625 Mg X uncertain within the hole where coronal emission is very weak.

On the second flight (July 15, 1980) the scan line crossed a very compact low latitude hole near Sun-center very closely associated with active region HL 16974 (Rottman, Orrall and Klimchuk, 1982). Figure 2 presents line position

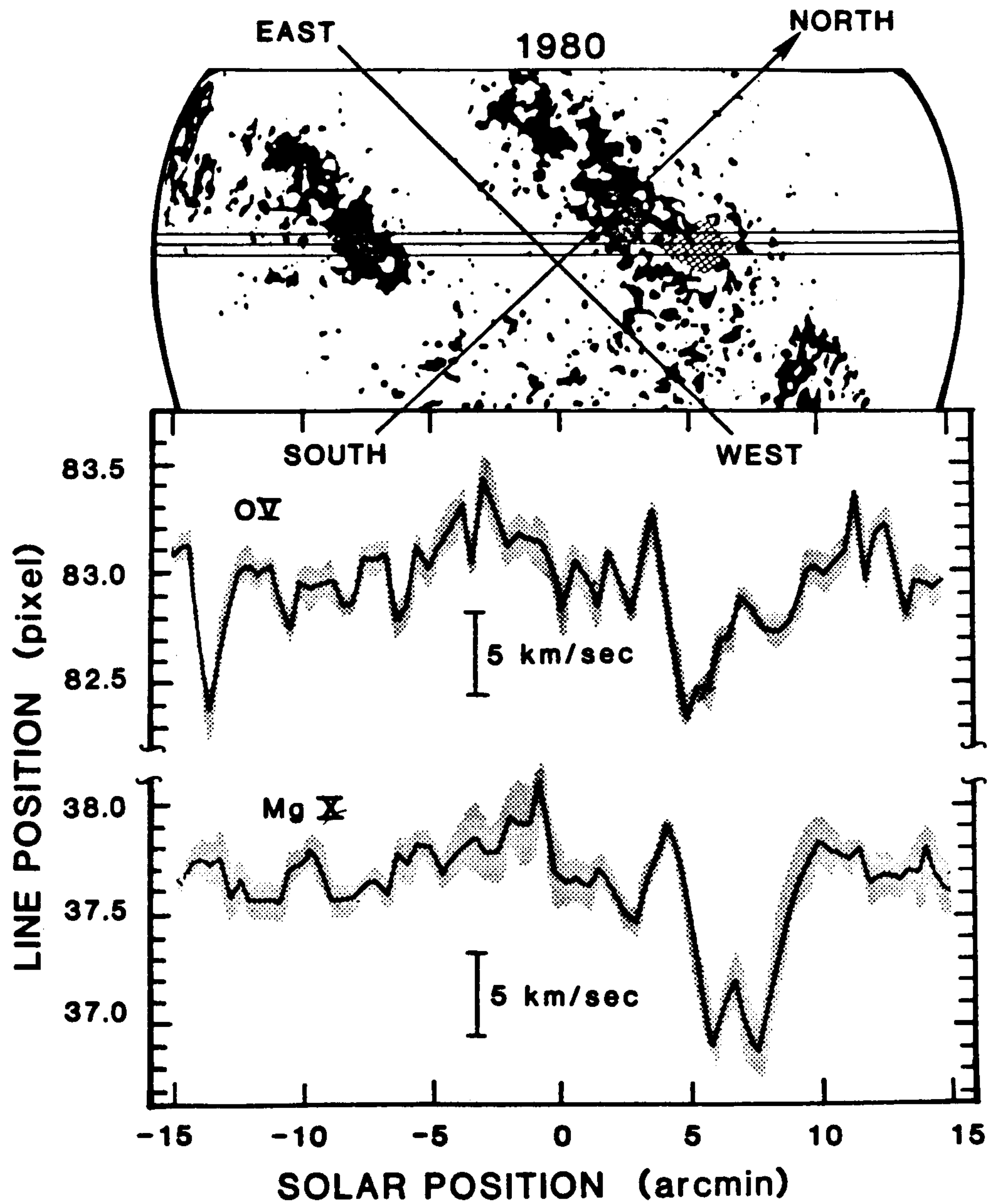

Figure 2. Mean line positions of the OV λ 629 and MgX λ 625 measured along a chord of the solar disk during the rocket flight of July 15, 1980. The format of the figure is similar to Figure 1.

data for the λ629 OV line and also the coronal line λ625 Mg X. Here the signature is clear in both lines and is larger in the coronal line than in the transition region line. The shape of this "blueshift" signature is different in the two lines, an effect that may be due in part to the inclusion of closed magnetic field regions within the hole or from surrounding plages. This contamination probably also reduces the observed blueshift. There is another striking feature, also an apparent outflow seen here only in OV. This is a real feature and is associated with a prominence or filament that crosses the scan line. Such filament-associated outflows were occasionally seen by the OSO-8 observers (Lites et al. 1976 and Lites 1980).

These first two flights occurred on either side of sunspot maximum of solar cycle 21, a time when polar holes were not prominent. At the time of the third flight on November 12, 1981 the polar holes were becoming stronger and the north polar hole had a well developed low latitude extension. The scan line was chosen to cross this north polar hole and also a compact low latitude hole near Sun-center which is surrounded on three sides by plage emission from active region HL 18031. Intensity and line position data for the coronal line (Mg X) and the transition region line (OV) are shown in Figure 3 (Orrall, Rottman and Klimchuk, 1983). There is again a blueshift associated with a filament, this time visible in Mg X and not in OV. The partial reversal of the blueshift within the polar hole may be the result of the intrusion of non-hole emission into the scan line, which passed quite close to the hole boundary near that point. The area of the low latitude extension of the hole is comparable to the smaller low latitude holes of the Skylab era. The polar portion (above 60° latitude) has only 1/3 to 1/2 the area of the great polar holes observed in the declining phase of solar cycle 20.

Our experience on three rocket flights is that wherever the scan of the spectrometer crosses a coronal hole as defined in λ10830 He I we see a clear blueshift in both the transition region and corona. We have not seen this signature where there is not enhanced λ10830 emission indicating a coronal hole. (The occasional blueshifts seen above filaments are a distinct and different phenomenon.) Thus our data support the conjecture that relative blueshifts in EUV coronal and transition region lines are a common and perhaps universal signature of coronal holes.

We are aware of two other sets of pertinent data that bear on this question. One is that of Cushman and Rense (1976) mentioned earlier. In Figure 4 we have replotted their data in a format similar to our own. The top panel is a λ284 Fe XV intensity contour map obtained with the GSFC spectrometer on OSO-7 (published in Solar Geophysical Data 1973) and rotated to the time of the rocket observation. Only the faintest contours on the disk are plotted. The horizontal line represents the slit of Cushman and Rense's stigmatic spectrograph, and it is clear that their blueshifted region coincides with the faint contour. It seems likely that this open magnetic region would have appeared as a hole on a λ10830 spectroheliogram had one been available. Skylab coronal hole No. 4 appeared nearby within this same open magnetic region on the next rotation (see Rottman, Orrall and Klimchuk, 1982).

Another similar outflow was observed by Brueckner, Bartoe and Van Hoosier (1977) on the first flight of the NRL High Resolution Telescope and Spectrograph (HRTS) on July 21, 1975. The slit of their stigmatic spectrograph crossed one small region which showed a systematic outflow of about 12 km s^{-1} in the forbidden coronal line λ1349 Fe XII. They describe the region as a "magnetic weak region" and do not suggest that it was a coronal hole. There is no low

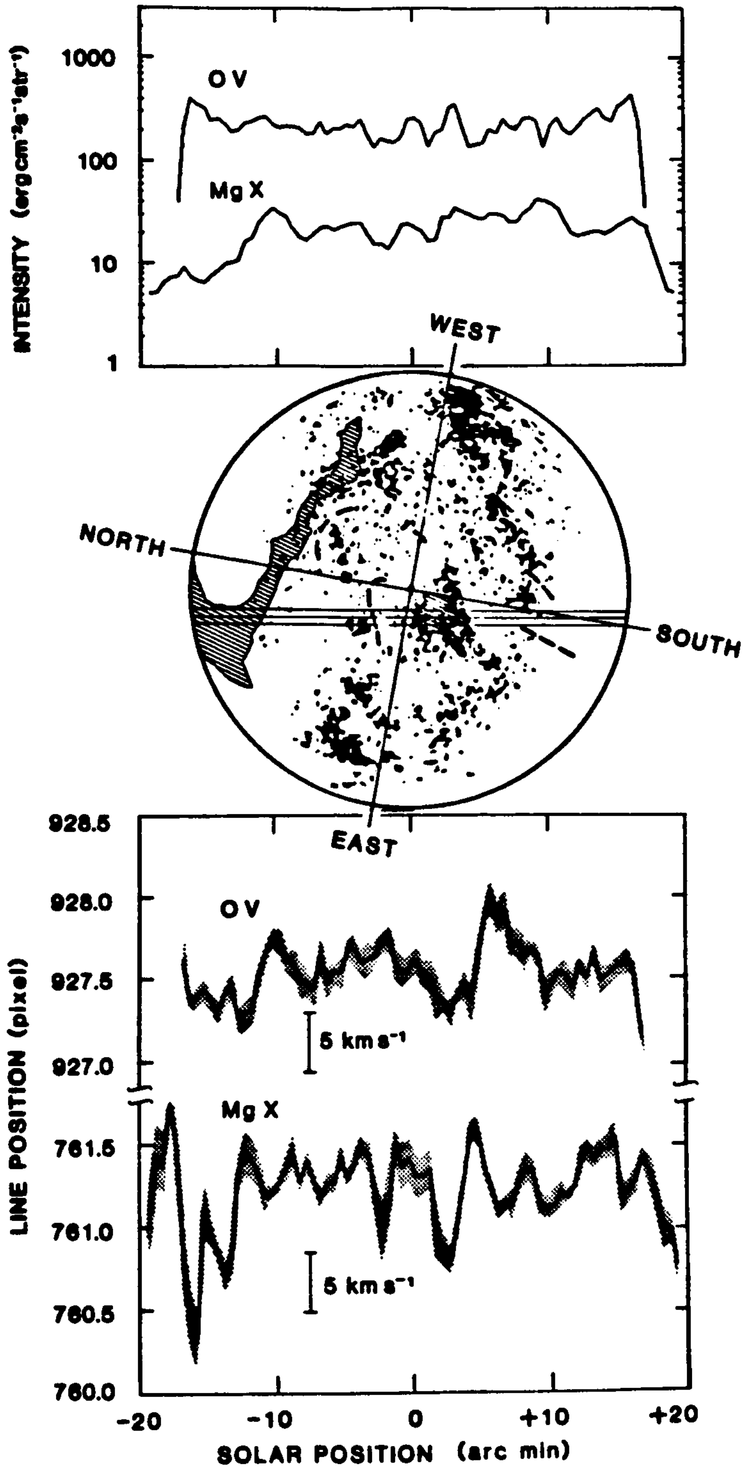

Figure 3. The mean line positions of OV λ629 and MgX λ625 measured along the North/South chord of the solar disk during the rocket flight of November 23, 1981. The format of the figure is similar to Figure 1 with the addition of the top panel giving the absolute total intensities of the two lines.

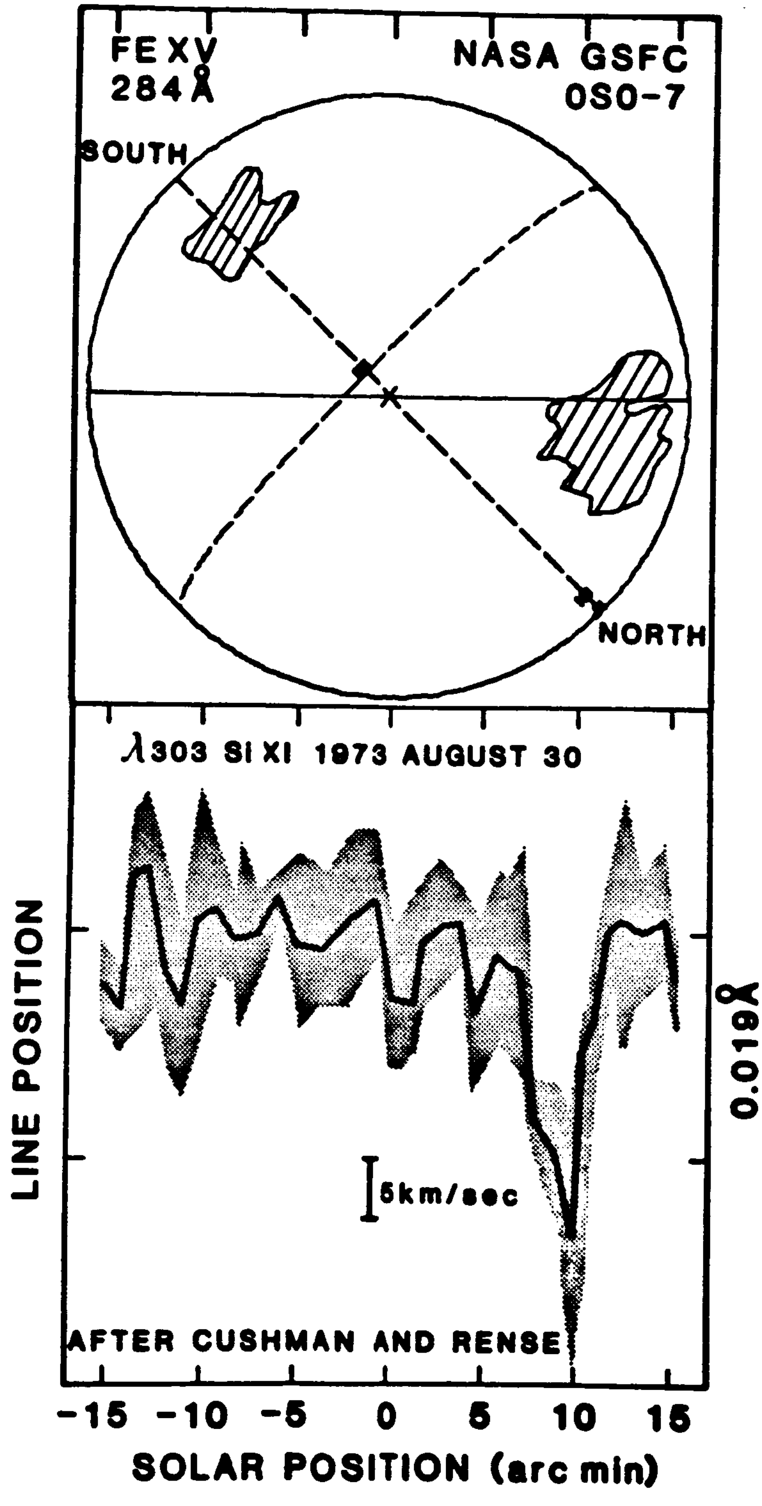

Figure 4. The relative displacement of the Si XI λ303 line along a diameter of the solar disk as measured by Cushman and Rense on August 30, 1973. The top panel shows low density contours of the corresponding Fe XV λ284 spectroheliogram from OSO 7.

latitude λ10830 coronal hole near this longitude on this rotation listed in the compilation of Sheeley, Harvey and Feldman (1976), but during 1975 holes less than 13° in extent were not listed. We have examined a Kitt Peak λ10830 spectroheliogram for the day of the HRTS-I flight provided to us by J.W. Harvey. The outflow region lay about 4 arcmin to the southeast of a large active region (McM 13766) and within 1.5 arcmin of a small short-lived active region (McM 13779). At the region of observed outflow, the slit crossed a small region 1 to 2 $arcmin^2$ in area where the He I network elements were absent or weakened. This is a primary indicator of coronal holes (Harvey and Sheeley 1977), although the quality of the spectroheliogram for that day was relatively poor. It is certainly possible that this outflow region was a compact hole similar to the small holes that we have observed. This is consistent with the weakness of the λ1349 Fe XII emission in the region of outflow. This observation is of special interest because the shifts of the coronal line were measured with respect to lines of CI which are formed in the low chromosphere.

Discussion

Basic parameters of the observed outflows within compact low latitude holes discussed above are summarized in Table I. The implied velocities are the

TABLE I

OBSERVATIONS OF LOW LATITUDE HOLES

Date	Position B	Position L	Associated Active Region	Area $arcmin^2$	Area % of Solar Surface	Lifetime (Rotations)	Apparent Velocity ($km\ s^{-1}$) Transition Region	Apparent Velocity ($km\ s^{-1}$) Corona
11/23/81	-5°	157°	HL 10831	2	0.06	3	4	7
07/15/80	+21°	239°	HL 16974	3	0.09	> 4	7	12
06/05/79	+2°	205°	McM 16046	11	0.33	> 7	5	-
07/21/75	-10°	185°	McM 13779	-	-	-	-	12
08/30/73	+30°	210°	McM 12508	-	-	-	-	13

maximum measured blueshifts uncorrected for projection. All of the outflows were quite close to active regions. The close association of low latitude coronal holes and active regions was noted by Bohlin and Sheeley (1978). They also found evidence on λ284 Fe XV Skylab spectroheliograms for very small coronal holes within active regions, similar to the small holes that we observed in

1980 and 1981 which are almost engulfed by their adjacent active regions. Examination of rocket X-ray spectroheliograms and λ10830 data (Kahler, et al. 1983) indicate that weak low-latitude holes as determined by λ10830 data do not correspond to obvious and deep X-ray holes.

The most straightforward and least contrived explanation for these negative wavelength shifts associated with coronal holes is that they are a direct manifestation of systematic mass flow from the base of coronal holes, and moreover that the apparent velocities (multiplied by the local density) are a rather direct measure of the mass flux into interplanetary space. The observed velocities are consistent with this hypothesis and with the equation of continuity for the interplanetary mass flux to within the uncertainties in coronal density and the effective fraction of the solar surface that contributes to the solar wind (Rottman, Orrall and Klimchuk, 1982).

The wavelength shifts measured so far are relative and are not absolute with respect to the rest frame of the photosphere. Pneuman and Kopp (1978) have suggested that coronal lines might be systematically redshifted relative to the photosphere due to the downflow of condensing spicular material returning to the photosphere. If so, then the apparent blueshifts in holes might be due to a difference in downflow speeds. We have recently incorporated a platinum hollow cathode lamp in our spectrometer as an absolute wavelength standard that should be capable of testing this possibility. But existing observations at least suggest that any such systematic shift in coronal wavelengths is too small to account for the blueshift signature in holes. We discussed above the HRTS measurements of Brueckner, Bartoe and Van Hoosier (1977) which show no large systematic displacement of the coronal line λ 1349 Fe XII relative to CI lines formed in the low chromosphere, over most of the quiet solar surface covered by their slit. In another experiment Behring, Cohen, Feldman and Doschek (1976) found an upper limit of 4 km s^{-1} for any systematic displacement of coronal lines relative to lines of the low transition region from spectra of the entire solar disc between 160 and 770 angstroms.

Finally we stress that even with absolute wavelength measurements, the relationship between the actual mass flux and the observed Doppler shift is to some extent model-dependent in the presence of unresolved structures and flows, and in particular will depend on the density structure of the transition region and inner corona.

Summary and Future Observations

As discussed above, all of the existing observations suggest that apparent or relative coronal outflows are a common signature of coronal holes. A similar signature of smaller amplitude is also observed in lines formed in the transition region. The observed magnitudes of these outflows are consistent with the conjecture that they are a direct manifestation of the high speed solar wind flow from coronal holes to within present uncertainties in coronal density and geometry. Evidently EUV observations of coronal emission lines made with high spectroscopic resolution and stability can supply information about the acceleration and heating of coronal plasma in open magnetic regions deep in the inner corona that can be obtained in no other way. Few such observations have been made below 1200 Å, where most of the abundant coronal ionic species have their resonance lines. In a continuing program of EUV spectroscopy we hope to address a number of problems of coronal dynamics. In what follows we outline some studies that are direct extensions of current work that will contribute to understanding the inner corona as the source of the solar wind.

High priority should be given to making absolute measurements of Doppler displacements of coronal lines. During the 1981 November 23 flight of the spectrometer we obtained comparison spectra from an on-board hollow cathode platinum lamp. Since the motion of the rocket with respect to the Sun's center of mass is accurately known, absolute wavelengths can be inferred. We are not yet confident that we have anticipated all important sources of systematic error in these measurements, especially those that arise from the changing thermal environment of the spectrometer within the sounding rocket. But absolute measurements are certainly attainable and an improved system has been incorporated in the payload for the next flight. Such measurements are needed to infer the mass flux and to test the conjecture of Pneuman and Kopp (1978) mentioned earlier.

Coronal emission lines are broadened primarily by the combined effects of thermal, wave and turbulent motions, and probably also by the ordered motion of unresolved structures. Line width measurements are therefore an important diagnostic. Numerous line width observations have been made in EUV lines formed in the underlying transition region, and in visible coronal forbidden lines observed well above the Sun's limb at eclipse or with the ground based coronographs. But very few line widths have been measured in EUV coronal lines directly against the Sun's disk, which arise at the very base of the corona. We are making center-to-limb measurements of line widths that may make it possible to separate the vertical and horizontal components of the small scale non-thermal velocity field, and to compare these motions in open and closed magnetic regions. The on-board standard lamp provides an inflight determination of the spectrograph instrumental profile.

It is feasible within the limited duration of a sounding rocket flight to obtain spectra over a small raster. This would make it possible for example to map the outflow within a hole and thus infer the geometry of flow. It is also feasible to obtain time series of spectra from a limited region of the disk to search for direct evidence of waves in both open and closed magnetic regions. The ability to carry out either of these experiments on a sounding rocket will be enhanced by the use of a two dimensional array detector. One such detector for the EUV has been developed at LASP also using the CODACON readout scheme and is presently being flight tested.

It is clear that longer periods of observation are needed to explore the origin of the solar wind in the inner corona than can be provided by sounding rockets. One opportunity for obtaining such observations would be the planned Solar Corona Diagnostic Mission (formerly called the Solar Corona Explorer). With an extended observing period it will be readily feasible to map systematic coronal velocity fields over the entire disk on a synoptic basis. Such observations will supply essential data for modeling coronal holes as the source of the solar wind. They will establish how solar wind outflow evolves with the evolution of a coronal hole or more broadly with the evolution of an open magnetic region.

Finally, the observations of coronal outflow described here strongly complement the indirect method of inferring outflow velocities at greater heights (1.5 to 8 solar radii) from observations of Doppler-dimmed resonantly scattered EUV emission lines made above the Sun's limb (Kohl and Withbroe 1982, Kohl 1983).

Acknowledgements

This research is supported by the National Aeronautics and Space Administration under grant NSG-5178. We aknowledge the assistance provided by J.A. Klimchuk of the High Altitude Observatory in analyzing the data from the three LASP rocket flights. J. Harvey of Kitt Peak and GSFC Southwest Solar Station has kindly provided the λ10830 spectroheliograms. A portion of the work of F.Q. Orrall was supported under NASA grant NSG12-001-011.

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