GAS FLOWS IN THE TRANSITION REGION ABOVE SUNSPOTS

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ABSTRACT

Strong downflows and moderate upflows in the transition region over a sunspot have been observed with the High Resolution Telescope and Spectrograph (HRTS) on Spacelab 2 in 1985. The flows are persistent in the sense that they are seen in the same spot for 5 days. Their existence in the Spacelab 2 material confirms earlier sunspot observations with HRTS on rocket flights and supports a contention that such downflows are common. The downflows are prominent in regions of limited extent (4'-6'), and flow velocities are in the range 40-80 km s\(^{-1}\) and are thus supersonic. There are also indications of more than one characteristic flow speed in the downflows. Upward flows have smaller velocities, 5-20 km s\(^{-1}\), but may extend over a larger area. In the downflowing regions there is always an appreciable amount of gas at rest in the line of sight. Obvious changes in the flow patterns are seen over periods of 20 minutes. Flow speeds derived from the profiles of different lines formed in the transition region between 30,000 and 230,000 K are very similar implying constant downflow in this temperature range. The structured appearance and apparent coexistence of flows with gas at rest are similar to the observed properties of the Evershed effect in lower layers. Various mechanisms which may account for the observations are discussed. The most likely model appears to be flows in a filamentary structure.

Subject headings: Sun: atmospheric motions — Sun: spectra — Sun: sunspots

I. INTRODUCTION

The wavelength shifts of spectral lines observed in sunspots, i.e., the Evershed effect, is of general interest since they contain information about the interaction between gas motions and the strong magnetic field observed in sunspots. In the low-excitation lines the Doppler shifts are most likely restricted to the white light sunspot (see, e.g., Wiehr et al. 1986). The shifts are usually interpreted as evidence for a nearly horizontal flow from the umbra toward the photosphere (Evershed 1909, 1910). In the chromosphere the direction of the flow is reversed and the total extent is increased to the size of the superpenumbra. The reversed Evershed effect is generally interpreted as a flow along curved loops directed toward the sunspot (e.g., Beckers 1962, 1964; Maltby 1975). A recent review of the Evershed effect is given by Sivaraman (1984).

To observe the even higher layers above the chromosphere requires ultraviolet spectra below 2000 Å with high angular and spectral resolution. Downflows in the transition region over sunspots have been observed with the High Resolution Telescope and Spectrograph (HRTS) on rocket flights in 1975 and 1978. Brueckner (1981), Dere (1982), and Nicolas et al. (1982) have described this phenomenon where supersonic flow velocities are seen in the 100,000 K region. However, rocket flights could only give a snapshot of the sunspot transition region. Reliable information on many properties of the downflow phenomenon had to wait until satellite observations were available.

In the following we describe the observations, data reduction, and results of the new UV observations of sunspots. It is found that the sunspot observed with HRTS on Spacelab 2 always shows the downflow of gas previously noted for the sunspot transition region. A new result is the detection of an upward flow in regions close to the observed downflows. Finally the nature of the flow, its possible filamentary character and relation to waves, is discussed.

II. OBSERVATIONS

HRTS flew as a part of Spacelab 2 from 1985 July 29 to August 6. The instrument, mission, and scientific results so far have been described by Bartoe et al. (1986), Brueckner et al. (1986), and Cook (1985).

During the Spacelab mission several series of observations were made of the sunspot in active region NOAA AR 4682. Spectra were taken of this spot on seven occasions over a period of 5 days. The observing periods are listed in Table 1, which also gives information about the observing programs and pointing quality. The present investigation is based on inspection of the entire material, but quantitative measurements have been made of the spectrograms from orbits 43 and 67, program sequences 54 and 24, respectively.

The observing programs consisted either of rasters, where the slit was moved parallel to itself between exposures, or of exposure series with the slit remaining in one position on the Sun throughout the program. Two types of spectral frames were observed. The full frame (FF) and short frame (SF) options refer to whether the entire solar spectrum, 1190-1680 Å, was registered simultaneously, or just a limited band of 14 Å, which could be centered at any wavelength within the HRTS range. The pointing stability in Table 1 is given in arc seconds. It is derived from the Sun sensor data and from the TV coverage of the Hz slit jaw image. The actual resolution was determined by the performance of the Instrumental Pointing System (IPS). Thus, the resolution is usually best for the shorter exposure times.

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The two sequences from which we present quantitative measurements are both rasters. In sequence 24 in orbit 67 a raster in the short frame mode was made in C iv of an 'large region. The increment between slit positions was 2". Only one exposure time, of 8 s, was used. The raster covered the sunspot and thus maps the sunspot flow over a 20 minute time span in the active region and is repeated every 4.5 minutes. The sequence transition region at 100,000 K.

Using full frame spectra one may study the flow phenomenon been carried out in Oslo and at the Naval Research Laboratory. The stray light in the photometer is reduced by closely matching the size of the illuminated field on the film to the entrance aperture in front of the photomultiplier. An aperture size of 6 x 16 μm is used for most of the photometry.

The film grains contribute most of the noise. In the Spacelab 2 data the noise is higher than in previous HRTS spectra. The cause is probably related to the enhanced film background level (Brueckner et al. 1986). The result is a lower signal-to-noise ratio which is made more severe because the high background level also reduces the contrast of the film.

Noise has been removed by Fourier filtering. A low pass filter in two dimensions has been applied to the digitized image in the Fourier domain. The bandwidths of the filter were determined by carefully comparing the filtered and unfiltered images. The criterion was that intensity contrasts should be preserved to avoid introducing systematic errors in the measured line peak intensities and widths. This requires fairly wide filters, and some noise therefore remains after filtering. This is partly due to the size of the film grains causing the noise, the larger grains being comparable in the extent to the sharpest gradients in the spectrograms.

b) Measurements of Velocities

The determination of flow velocities requires the establishment of an accurate wavelength scale. In addition, it is necessary to measure the wavelength shifts from the reference scale caused by the flow. In the strong downflows associated with sunspots there appear to be several separate flow components resulting in a complex shape of the line profile. As will be discussed below, there is always a distinct component at or near the rest wavelength. This means that determining the velocities is more complicated than measuring a single line shift and thus is affected by additional uncertainties.

i) Wavelength Scale

The wavelength scale is obtained from the measured positions of selected lines from neutral and singly ionized atoms in the digitized spectrograms. The neutral lines have small wavelength variations along the slit. In addition, averaging is done over sections of 25"-50" in quiet solar regions. The positions agree to 2 μm. This means that velocities of transition region lines with only one velocity component in the line of sight may be determined to within 0.01 Å, corresponding to 2 km s⁻¹. A
necessary correction for a small geometrical distortion of the
spectral images does not affect this accuracy.

We have preferred lines from Si i, C i, S i and Fe ii as
reference lines for the wavelength scale. These lines are well
defined in the solar spectrum and have reasonably good labora-
tory wavelengths. As a result, all measured velocities in the
transition region are relative to the low chromosphere. For
the lines from O v and N v near the short-wavelength end of
the spectrum there are no good reference lines sufficiently close to
the transition region lines. For these wavelengths the scale has
been calibrated using the average quiet solar wavelength of the
transition zone lines in a region with no pronounced flows. The
resulting velocities may contain a small systematical error
because of the apparent net redshift of the transition region
lines (see Dere, Bartoe, and Brueckner 1984; Athay et al. 1983).

ii) Fits to the Line Profiles

Flow velocities are found by measuring the wavelength posi-
tions of Gaussian fits to the observed profiles. Two types of fits
with three, four, or five fitted parameters have been used. Pro-
files have been fitted to single Gaussians, giving good results in
cases where the entire profile is shifted. To find the flow velo-
cities for the more complex profiles in the downflow region one
needs to fit at least two Gaussians to the observed profiles. The
fitting is done using a modified version of the least-squares
method described by Bevington (1969).

The amount of noise also limits the number of parameters
which may be fitted to a profile. This means that some of the
line parameters must be preselected. In the case of fitting two
components, four or five parameters are used. The five param-
eters are the two intensities, the wavelength of the component
at rest, the wavelength shift between the components, and the
line widths, assumed to be identical for the two components.

Fits with five parameters are successful if the wavelength
shift is sufficiently large to cause a complete separation of the
two components. Where this is not the case we have used the
widths determined by the successful fits to the completely
separated components at nearby solar locations and re-
alyzed the data fitting four parameters. This gave results
which appear consistent both when regarding the angular
velocity variation along the slit and when comparing velocities
determined from different lines formed at approximately the
same temperature. Under favorable conditions we estimate
that the flow velocities may be determined to within 5 km s\(^{-1}\).

The accuracy is less for lines where the flow components are
not separated, and for the weakest lines fits can be made only
to line profiles averaged over several resolution elements along
the slit.

Fitting profiles to the C iv lines at 1550 Å encounter special
problems because of blends with lines from Si i and Fe ii.
Subtraction of the blends is not always successful owing to the
difficulty in estimating the strengths of the blended lines hidden
in the wide combined profile. An estimate may be made from
the intensity of other nearby Si i and Fe ii lines.

Fitting at most two components to the observed line profiles
assumes that only one dominant high-speed flow velocity is
present. This limitation, which is forced upon us by the amount
of noise in the data, may not correspond to the real conditions.
Some of the profiles, particularly in the earlier rocket spectra
from HRTS, but also in the Spacelab material, indicate the
presence of more than one dominant flow speed. The effect on
the measured maximum velocity of an additional flow com-
ponent may not be strong in the case where the components are
well separated.

c) Intensity Calibration

A relative intensity calibration has been obtained by compar-
ing in detail spectrums taken closely together in time,
but with different exposure times. The spectrums have been
accurately aligned to cover exactly the same wavelength range
and area on the Sun. This method assumes that the reciprocity
failure of the Kodak Eastman 101-01 film can be neglected
(Burton, Hatter, and Ridgely 1973). The individual exposure
values show considerable scatter around the resulting mean
film characteristic curve. From the scatter one derives a typical
rms uncertainty in the intensity of 30%. This high value is due
to the pronounced granularity of the film caused by the high
background levels for the Spacelab 2 HRTS data.

Absolute intensity calibration requires observations of a ref-
ence source to derive the instrument sensitivity as a function
of wavelength. For HRTS on Spacelab 2 an instrument cali-
bation using a known laboratory standard was not available.
Instead, the intensity of the quiet solar spectrum was used as
the source. Intensities of emission lines and continua on a
relative scale were compared to the solar spectrum from the
Skylab SO-82B calibration rocket (Kjeldseth Moe et al. 1976).
A more detailed description of the procedures is given by
Brekke et al. (1987).

d) Alignment of Spectrums and Sunspot

The total diameter of the sunspot in NOAA AR 4682 was
~30" with the size of the umbra being 15". A series of white
light pictures of the spot crossing the solar disk July 28 to
August 6 is shown in Figure 1 (Plate 7). We note that the
umbra on several days has a complex structure. Relating the
position of the slit to the features of the spot has been done
with the aid of Hz images, the telemetered pointing informa-
tion, and from the observed extent of the sunspot on the spec-
trograms. Here one is guided by the intensity variation along
the slit of the UV continuum and of lines from Si i.

IV. RESULTS

In the following we will assume that the observed shifts and
asymmetries in the line profiles are caused by flows. Redshifts
or red asymmetries will be regarded as downflows since the
sunspot during the time August 1–5 was very close to the
meridian. Throughout this period the cosine of the heliocentric
angle was larger than 0.8.

Clear evidence for strong downflow in the transition region
above the spot is found in all the observing sequences of the
sunspot listed in Table 1. Flow speeds seem not to change very
much over the 5 days the spot was observed. The detailed flow
pattern is, however, changing. Thus, there are clear changes in
the location of the downflows from one day to the next. Fur-
thermore, smaller changes are observed over the 20 minutes
duration of a series of rasters in orbit 67. In this section we first
describe the general properties of the downflow structure. An
extended survey of the flow pattern above and around the spot
is then shown. Finally, the variation of the flow speed with
temperature is given.

a) Spatial Scales of the Strong Downflow Region

In general, the transition zone lines show one or more
regions of limited extent where downflows are particularly

Fig. 1.—White light images of the sunspot in NOAA active region 4682 between July 28 and August 6. Courtesy L. Deszö, Debrecen, Hungary.

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prominent. Figure 2 (Plate 8) shows four successive rasters across the region with strong downflow in C IV on August 3. Only one of the C IV lines, the 1548 Å line, is included in the figure. The four sets of panels in the figure depict the spectra from each of the four rasters. The downflow associated with the sunspot is clearly visible as two to four regions of limited extent with a strongly emitting redshifted component in the C IV line. The size of the individual downflow regions is 4"–6". As one steps across the raster, the number of redshifted areas varies between two and four, and their positions along the slit also appear to change slightly. This may indicate that the individual downflow regions are components of a larger region with a complex structure.

There are some differences in the number and positions of the strong downflow regions in the four rasters. Also the total extent of the downflowing regions appears to be smaller on the last of the four rasters in Figure 2. The sharp gradients in the spatial distribution of the velocities is another typical property of the flow pattern. This is evident in the sudden appearance and disappearance of the high-velocity features as the slit rasters across the flow region. The features appear and disappear in a single 2" step.

Sharp gradients in the flow pattern is also apparent between the various features when moving along the slit. However, on closer scrutiny some of the area between the clearly demarcated downflow regions are found to contain fast gas flows. This is clearly evident in Figure 3. Here the flow velocities are plotted as a function of position along the slit for one slit position in each of the four rasters. One notes that although some of the regions between individual features show no evidence of downflow other regions have flows at lower speed. Flow speeds range between 40 and 75 km s$^{-1}$ in these regions of differing flows. All these speeds are, however, supersonic.

The reason these weaker flows are much less apparent becomes clear from Figure 4 (Plate 9). Here is shown an example of the observed and fitted line profiles at two adjacent locations along the slit in the 4" position in the third raster of Figure 2. Flow speeds in the two regions are similar, but the intensity ratio between the redshifted component and the line component at rest differs greatly. The effect may be distinguished by a close examination of the reference spectral image in the top panel. The different locations are thus characterized more by differences in downward mass flux than by different flow speeds. Judging from the observed intensity values the mass flux ratio between the two regions in Figure 4 may amount to nearly a factor 4. This assumes that the emission is

![Fig. 3.—Distribution of downflow velocities along the slit in the four rasters of Fig. 2. Panels represent slit positions 4", 6", 8", and 4" in rasters 1–4, respectively.](image-url)
Fig. 2.—Rasters of the sunspot in NOAA AR 4682 in C iv on 1985 August 3. The four panels represent four separate rasters across the spot and surrounding regions. Positions are relative nominal positions of the slits in the four rasters.

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Fig. 4.—Observed and fitted line profiles of the C\textsc{iv} lines at two positions along the slit in position 4" in raster 3 in Fig. 2. Exact positions on the slit are marked on the top panel. Markings above the line profiles give the laboratory wavelength positions of the C\textsc{iv} lines.

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b) The Presence of Multiple Velocities in the Downflow

Figure 4, and later Figure 10 below, also demonstrate another interesting property of the strong downflows over sunspots. As has been implied above, an appreciable fraction of the gas in the line of sight is nearly at rest and not participating in the strong downflow. The strength of the line component near the rest wavelength is comparable to the emission in the redshifted component. This is a general property at all locations showing downflow. It implies that along a line of sight as much or more of the gas is at rest as is flowing supersonically.

A possible explanation of this observation is that the different flows occur in an extremely filamentary structure, where the individual filaments are much smaller than the angular resolution. The hypothesis of an unresolved fine structure is similar to the currently most favored explanation for the "flag"-like line profiles seen in visual lines in the Evershed effect. The actual determination of the amount of gas in the flow relative to the gas at rest must take into account the possible effect of ionization relaxation in the flowing gas (see for instance Kjeldseth-Moe 1976; Dere et al. 1981).

c) Regions with Upflows

The observed strong downflows would imply corresponding upward flows of gas carrying the same mass flux. In the absence of an upward mass transport a coronal loop above the sunspot would be depleted of gas in a few minutes. The observations with HRTS on Spacelab 2 for the first time indicate that at least part of the required mass may be supplied from areas inside the spot itself. Evidence for this in the rasters from August 3 can be seen from some of the panels in Figure 2 where a weak and extended blueshift of the C IV line is present outside, but near the position of the strong downflow.

A blueshift indicating upflow in a region adjacent to the downflow is very prominent in Figure 5 (Plate 10), which shows the C IV lines in two locations across the spot in orbit 43 on August 1. The left panel has two typical redshifted regions in the sunspot. (The gap in the data in the lower part of the panels is due to light being blocked off by a speck of dust located on the entrance slit of the spectrograph.) The panel to the right shows the same lines from a region only 3" away. The redshift has disappeared and been replaced with a blueshift of the C IV line extending over the greater part of the spot. In this case the entire line profile seems to be shifted; i.e., there are no coexisting zero velocities. Also the blueshift seems to come from a less structured region of considerable extent.

d) Distribution of Flows in the Sunspot Region

The distribution among up- and downflows is best seen from a map of flow velocities. The rasters from August 3 in orbit 67 have been used for a complete mapping of velocities in the transition region in an extended area inside and around the sunspot. Because of the complex line profile of the C IV line, reflecting the presence of multiple velocities within one resolution element, Figure 6 (Plate 11) displays the results in three different maps. The upper left panel shows the values corresponding to the shift of the entire line profile. This has been derived from fits to a single Gaussian profile and gives the best picture of the net flow outside the typical sunspot downflow regions where the entire line profile is shifted. The profiles in the downflow regions are not well represented by this fit.

However, the lower panels give the results of fits to two components using two Gaussian profiles. The bottom left panel shows the velocities from the short-wavelength component, while the panel to the right gives the results from the redshifted component. A scale of velocities in kilometers per second is also included in the figure.

The strong downflow near the sunspot on August 3 shows clearly in the bottom right panel. On this occasion the downflow region was located near the edge of the sunspot of which the contour of the penumbra has been drawn. The three separate regions of supersonic downflows are easily distinguished. From the figure one gets the impression of matter falling out of the corona in a "sheet"-like structure in which local concentrations of the mass flow is embedded, rather than in individual tubes. The associated upflow may be localized in the bottom left panel as the blue band parallel to the downflow structure, but lying somewhat closer to the spot center. The blueshift of the entire line in this region is even more apparent from the upper left panel in Figure 6. It still remains to be investigated whether the upward mass flux in this region can fully compensate for the downflows.

Figure 6 also shows the presence of high gas velocities outside the sunspot flow region. Strong blue or red colors in the bottom panels imply that up- and downflowing gas is present. The velocity values may, however, not be accurately derived by the two-component fit to the line profile.

To illustrate these flows we have selected two regions marked with black and white crosses in Figure 6. At the black cross the redshift corresponds to a strong downflow similar to those seen at the edge of the sunspot. Figure 7a shows the profile of the C IV line at 1548 Å at this position. The component at 1548.7 Å is attributed to the blended line from Si i. There is clearly a strong downflow of gas at this location.

Figure 7b shows the profile of the C IV line at the position marked with the white cross in Figure 6. This area features upflows with velocities higher than those we have inside the sunspot and apparently associated with the downflows. From the line profile it is, however, clear that the mass flux involved is limited. This upflow region also differs from the ones associated with the sunspot in having the main part of the emission occurring at or near the rest wavelength.

A third interesting region is located in the northwest corner of the bottom panels. The maps indicate coexisting strong blue- and redshifts, but no net flow. This is the strong explosive event described by Brueckner et al. (1986), and the line profile is similar to the one presented in Figure 9 of their paper. A two-component fit results in strongly red- and blueshifted components, but the derived velocities are not representing the actual gas velocities since the two-component Gaussian fit gives a bad description of this very wide line profile.

The upper left panel in Figure 6 also reveals several regions of net downflow clustered around the edge of the penumbra. Similar patterns of flow have been observed outside sunspots in the chromospheric Mg b and Hα lines. The sunspot downflow areas join this general pattern of downflowing gas.

e) Variation of Flow Velocity with Temperature

The C IV lines in Figure 5, demonstrating the blueshift, are part of a full frame spectrum from orbit 43. These spectra have the highest photometric quality of all the HRTS data from Spacelab 2. An overview of the entire spectrum is displayed in Figure 8 (Plate 12). Figure 8 represents a view of the flow 2 days before the observations in Figures 2-4 and the map in
FIG. 5.—Down- and upflows within the sunspot in NOAA AR 4682 on 1985 August 1. The two spectra are taken with slit positions 3" apart stepping across the sunspot. Left panel shows the customary downflow in the spot in the C iv lines. In the right panel with the slit still inside the spot, an upflow (blueshift) in the line is clearly evident.

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Fig. 6.—Near vertical gas flows in the transition region in and around sunspots. Flow velocities in the upper left panel are derived from fitting the line profiles to a single Gaussian profile. Bottom panels show results from a two-component Gaussian fit. In the left panel are the velocities derived from the blue component. Bottom right panel shows the downflow (red) derived from the redshifted component. Fits have been made to the observed line profile of the C iv line at 1548 Å. The velocity color scale is given and a contour of the sunspot penumbra is drawn in the figure.

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Fig. 8.—Sunspot downflows in a number of lines formed at different temperatures in the sunspot transition region. The lines in the panels are those listed in Table 2 with their temperatures of formation.

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The spectral images in Figure 8 are from a spectrogram taken with a 60 s exposure time. The reason for using this rather long exposure was the need to display all the transition region lines in the HRTS spectral range at the same pointing. Strong downflows are located in the spot, the redshifted line component forming an archlike structure in the spectrograms covering a 15" long portion of the slit. There are clear concentrations of mass flux to be seen at two or three separate locations.

Further information on the flow is given in Figure 9, showing the velocity of the downflow measured from the redshifted component as a function the position along the slit. The figure gives results for some representative lines in the spectrum shown in Figure 8.

A complete set of velocity values derived from all the lines in Figure 8 is listed in Table 2. The velocities are average values for three selected locations. The range in position given in the table for the locations refer to the position scale in Figure 9. The listed temperatures of formation are estimated from contribution function calculations in the sunspot model of Nicolas et al. (1982). The values strictly apply only to static conditions. In a moving gas ionization conditions may be different owing to relaxation effects when the temperature and density of the gas are changing. Finally, profiles for all lines in Table 2 are drawn in Figure 10 on a uniform intensity scale. The profiles in most cases represent averages over regions with fairly uniform flow speed.

The downflows are especially prominent in the lines from C IV, N IV, O IV, Si IV, and S IV, where the velocity features look very similar within the error of measurement. A region of particularly high velocities extends over a 7" portion of the total downflow. Here the flow velocities for the lines from all these ions reaches ~85 km s\(^{-1}\), in spite of the lines being formed over a considerable range in temperature. For the same ions a search for possible weak flows from the fits to the line component near the rest wavelength give flow speeds which are often close to zero, but in other locations may amount to 10–15 km s\(^{-1}\). It should be mentioned that for O IV the 1404.77 Å line is not used because it is blended with a line from S IV. Furthermore, the 1397.2 Å line is too weak to give reliable results.

In the lines from N V and O V the maximum flow velocities are as high as in the 3 times ionized atoms, but the extent of the region of maximum flow seems less than at lower temperatures. The shifted component in the high-speed region is faint in these lines and can only be recognized because it occurs at approximately the same location in all the lines. Because they are weakly exposed, the measurements of the O V and N V lines are less reliable. It is thus difficult from the data reduced so far to decide whether the apparent differences between the flows at 100,000 K and 230,000 K are real.

Also the O III lines at 1661 and 1666 Å show the high-speed downflow, but with very faint emission in the redshifted component.

### Table 2

<table>
<thead>
<tr>
<th>Wavelength (Å)</th>
<th>Ion</th>
<th>Temperature of Formation (K)</th>
<th>Velocities in Given Ranges of Positions*</th>
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<td>265000</td>
<td>55...5...</td>
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<tr>
<td>1501.800</td>
<td>S v</td>
<td>...</td>
<td>65...68</td>
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<td>O v</td>
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<td></td>
<td>55...48</td>
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* Refer to position scale in Fig. 9. Velocities in kilometers per second.
Fig. 9.—Variation of the downflow speed across the spot for selected strong transition region lines formed at different temperatures. Different symbols denote results obtained using different lines from the same ion.
Fig. 10.—Observed and fitted line profiles of the transition region lines near the position of maximum downflow for selected lines from Table 2
V. POSSIBLE MECHANISMS CAUSING THE REDSHIFTS

So far it has been assumed that the line profiles of the transition region lines have been caused by flows. It should be noted that the flow velocities are not measured, but inferred from asymmetric line profiles. Many kinds of motions may, however, give rise to profiles of this kind. Possible origins include wave particle motion, flows within flux tubes, and bodily motion of tubes. It is important that the chosen explanation is able to describe the observed asymmetries, including the amount of gas apparently at rest and coexisting with the downflows.

Sunspot waves with periods of 120–200 s have been observed in the transition region by Gurman et al. (1982). Waves with similar periods exist in the spot chromosphere (Giovanelli 1974). The velocity amplitudes of these waves are, however, too small to explain the large redshifts observed with HRTS.

Progressive magnetoacoustic waves with periods shorter than the exposure time and/or wavelengths shorter than the angular resolution may account for line shifts and asymmetrical lines (Eriksen and Maltby 1967). The effect would depend on both the aspect angle, the relative density amplitude, and the phase velocity of the wave. The velocity of this longitudinal wave is limited to the sound speed for propagation along the magnetic field. These waves may represent the redshifts for a reasonable choice of magnetic field strength and density amplitude, but the waves would have to propagate nearly perpendicular to the magnetic lines of force to show large particle velocities. With the spot near the center of the disk, the observations, however, suggest motions along the field lines in the transition region. One would also require regions with no waves to get the strong contribution to the emission at the rest wavelength.

Compression shocks may occur in the transition between supersonic and subsonic flow in a loop (Meyer and Schmidt 1968). These might give rise to profiles showing both subsonic and supersonic velocities in a small volume. This mechanism may produce asymmetric line profiles at particular positions, but it is difficult to reconcile with the asymmetries extending over wide areas. Several traveling shocks may perhaps give rise to the extended regions, but will also lead to time changes in the observed structures. Whether these would be consistent with the rather slow changes in the flows that we observe is not clear. With this mechanism it may also be difficult to produce the large amount of gas at rest.

Motions of individual magnetic flux tubes are known to occur in the moat around sunspots (e.g., Vrabec 1974). The motion inside the spots is less well known, but moving the tubes downward with supersonic speeds seems difficult.

The observed asymmetric profiles in the Evershed flows in the photosphere and chromosphere of sunspot penumbrae are best explained by the existence of unresolved fine structures with different flow speeds in the individual fine structure tubes (Beckers 1969). The fact that spectral lines formed in the photosphere/chromosphere transition region show profiles which require both supersonic velocities and material at rest suggest that filamentary flow channels exist also in these layers. The interpretation requires channels with one dimension smaller than the spatial resolution. Larger flow channels would require a wide range of flow speeds within each channel to account for the observations.

Observationally the last model discussed appears to be the most likely for explaining the profiles of the UV lines. Possible influence from some of the other mechanisms cannot be excluded but is unlikely to be the main origin of the asymmetric lines.

The model is complex and may have difficulties not touched upon in this brief exposition. It must obviously be a dynamical model where the flow in the fine-structure tubes are constantly changing. Individual flows might be of comparably brief duration since the time to empty a particular flow channel would be short. The material would spend part of the time in the channels at rest before the start and after the end of the motions. A connection may exist between the origin of the filamentation and the flow. One should also investigate connections to the light bridges in the sunspots observed by HRTS both from rockets and from SpaceLab 2 (see also Fig. 1).

VI. CONCLUDING REMARKS

The downflow in the transition region over sunspots first detected on HRTS rocket flights seems to be a general phenomenon. Although details in the flow pattern appear to change over a period of 5 minutes and obvious changes are seen over 20 minutes, the phenomenon itself persists for days.

The downflows extend over a large fraction of the sunspot. Flow speeds are supersonic with typical values ranging between 40 and 80 km s\(^{-1}\). Coinciding with the downflows are large amounts of gas at or close to rest along the same line of sight. This is a general and important property of the supersonic downflows in the transition region. It results in “flag”-like line profiles similar to those observed in the photospheric Evershed effect. While generally known, the implications of such line profiles have not been much discussed.

The flow speed seems to be nearly constant with temperature when studied in lines formed between 30,000 and 250,000 K. However, the amount of gas flowing downward relative to the amount of gas at rest varies. At low temperatures the relative amount of flowing gas is much smaller.

The spectrograms also contain evidence for an upflow
TRANSITION REGION ABOVE SUNSPOTS

The described properties of the transition region flows above sunspots are similar to the general properties of Evershed flows in the photosphere and chromosphere. One may point to the structured appearance, suggesting flows along the magnetic structures in the spot and to the appearance of the line profiles indicating the coexistence of strong flows with gas at rest within very small volumes. However, the observations in the transition region cannot be explained by any of the existing models for Evershed effect, including the recent model by Spruit (1981).

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