OBSERVED REDSHIFTS IN THE SOLAR TRANSITION REGION
ABOVE ACTIVE AND QUIET REGIONS

H. ACHOUR, P. BREKKE, O. KJELDSETH-MOE, AND P. MALTRY
Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029, Blindern, N-0315 Oslo, Norway
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ABSTRACT

Solar UV spectral observations show a redshifted emission at temperatures between the chromosphere and the corona. We have measured the magnitude of the redshift as a function of the temperature using solar spectrograms from the High Resolution Telescope and Spectrograph—HRTS. The velocity derived from the average redshift is found to increase up to a temperature \( T \approx 1.35 \times 10^5 \) K in both quiet and active regions, then decrease with increasing temperature, with the rate of decrease depending critically on the laboratory wavelengths adopted for the transition region lines. This result illustrates the need for improved laboratory measurements.

We find that the differential redshift between an active region and the surroundings increases smoothly with temperature, reaches a maximum velocity difference of 7 km s\(^{-1}\) at 1.35 \( \times 10^5 \) K and falls abruptly to zero at 2.3 \( \times 10^5 \) K. This observation is independent of the laboratory wavelengths. Suggestions regarding the origin of the redshift are confronted with the results.

Subject headings: Sun: activity — Sun: transition region — Sun: UV radiation

1. INTRODUCTION

Ultraviolet observations of the Sun show a net redshift in the emission lines formed in the transition region, i.e., between the chromosphere and the corona (see, e.g., Doschek, Feldman, & Bohlin 1976; Roussel-Dupré et al. 1976; Gebbie et al. 1981; Athay, Gurman, & Henze 1983; Dere, Bartoe, & Brueckner 1984, 1986; Klimchuk 1987, 1989; Hassler, Rottman, & Orrall 1991; Henze & Engvold 1992; Brekke 1993; Brekke & Hassler 1995). Systematic redshifts have also been observed in stellar spectra of late-type stars, first with the International Ultraviolet Explorer (see, e.g., Ayres et al. 1983; Ayres, Jensen, & Engvold 1988; Engvold et al. 1988) and recently by the Hubble Space Telescope (Linsky, Wood, & Andrusil 1994).

Solar observations of quiet regions have been reviewed by Mariska (1992), who emphasized that the wavelength shift varies widely from point to point on the solar disk. Thus, interpretations of the redshift must take into account that a deduced net redshift is of a statistical nature. His Table 5.1 summarizes previous quiet region measurements of the net redshift and shows values that range from 7 to 10 km s\(^{-1}\) for lines formed near \( T = 10^5 \) K. The redshift at temperatures below 7 \( \times 10^4 \) K and above 10\(^5\) K is less well known both for the quiet Sun and for active regions. Presently it is unclear how far toward coronal temperatures the redshift phenomenon extends. Results by Dere (1982) indicate a weak coronal extension in active regions, whereas no quiet-Sun redshifts at coronal temperatures have been reported (Hassler, Rottman, & Orrall 1991). Conflicting results have been presented at transition region temperatures above 10\(^5\) K.

Consider first quiet-Sun observations. Measurements of the O v lines 1371 and 1218 Å from HRTS spectrograms led Brekke (1993) to suggest that the redshift extends to temperatures above 2.3 \( \times 10^5 \) K and that a significant discrepancy between his results for the O v lines was caused by an error in the laboratory wavelength of the 1218 Å line. Further evidence for an extension of the redshift to high temperatures was presented by Brekke & Hassler (1995), based on data from the Laboratory for Astrophysics and Space Physics (LASP) rocket flight on 1988 March 12.

These results disagree with the commonly quoted lack of redshift in the Skylab observations of the O v 1218 Å line by Doschek et al. (1976). These authors established the wavelength of the 1218 Å line from measurements outside the limb, where they expected no systematic shifts. However, their measurements on the disk may be affected by the strong Ly\( \alpha \) wing, which was not subtracted before the position of the O v line was determined. The difference between the results by Doschek et al. (1976) and by Brekke (1993) is important since some numerical simulation models of the flows in transition region loops assume that the redshifted emission may be replaced by blueshifted emission at temperatures above 2.5 \( \times 10^5 \) K (see, e.g., McClymont & Craig 1987; Mariska 1988; Spadaro, Antiochos, & Mariska 1991).

Consider next redshift observed in solar active regions (see, e.g., Lites et al. 1976; Brueckner, Bartoe, & Van Hoosier 1978; Brueckner 1981; Dere 1982; Feldman, Cohen, & Doschek 1982; Kjeldseth-Moe et al. 1984; Mariska & Dowdy 1992; Brekke 1993). Based on Skylab observations with a spatial resolution of 2º \( \times 60' \) Feldman et al. (1982) found redshifts to be largest for lines formed between 5 \( \times 10^4 \) K and 10\(^5\) K, while redshifts were distinctly smaller for lines formed above 10\(^5\) K. The line-of-sight velocities derived by Dere (1982) from observations with high spatial resolution also showed a maximum close to 10\(^5\) K. In a recent publication Mariska & Dowdy (1992) argue that the difference in line-of-sight velocity between 10\(^5\) K and 2 \( \times 10^5 \) K found by Feldman et al. (1982) was within the errors of measurements. Assuming mass conservation with no area change with height they found that the observed line shift at 10\(^5\) K should imply velocities of 65 km s\(^{-1}\) at 5 \( \times 10^6 \) K in agreement with their Skylab observations of velocities up to 70 km s\(^{-1}\) in the 465 Å line from Ne vii. Hence, it seems to be of value to study the temperature variation of the line-of-sight velocity with higher accuracy than previously.
In this paper we present wavelength measurements of a number of transition region lines from observations obtained during the two first rocket flights of HRTS, referred to as HRTS 1 and HRTS 2. Since exposure times as long as 51 s were used during the HRTS 1 flight we are able to include measurements of the wavelength shifts for lines formed at temperatures ranging from the chromosphere to the corona.

In solar-quiet regions we find that the line-of-sight velocity increases monotonically with temperature, up to $T \approx 1.35 \times 10^5$ K, then decreases at a rate that depends critically on the laboratory wavelengths adopted for the transition region lines. The active region shows a similar behavior, but the magnitude of the line-of-sight velocity is larger. Particular attention is given to the difference in flow velocity between an active region and the surrounding quiet-Sun regions. The velocity difference increases smoothly with temperature, reaches a maximum at $1.35 \times 10^5$ K and falls abruptly to zero at $2.3 \times 10^5$ K. It should be pointed out that this result does not depend on uncertainties in the laboratory wavelengths. Instead the velocity difference is related to the difference in physical condition between the two regions, most probably controlled by the magnetic field.

2. OBSERVATIONS

HRTS—the High Resolution Telescope and Spectrograph (Bartoe & Brueckner 1975)—may simultaneously observe the wavelength range 1175–1730 Å with an angular coverage of $950'' \times 1''$. The instrument combines this extensive wavelength and spatial coverage with high angular (1''), spectral (0.05 Å), and time resolution (5'' s for the strongest lines). We have used data from the two first HRTS rocket flights, HRTS 1 and HRTS 2, flown in 1975 July 21 and 1978 February 13, respectively. The rocket data have better signal-to-noise levels than the more extensive observations obtained during the Spacelab mission in 1985. Furthermore, HRTS 1 contains a sufficiently long exposure, 51 s, to permit accurate measurements also of the nitrogen N v lines formed at $2.0 \times 10^5$ K, which are otherwise too weak to be measured in most quiet regions in the HRTS 2 data.

During the HRTS 1 flight the slit extended from the solar center to the southwest limb, crossing a sunspot and the surrounding active McMath region 13766 and a prominence outside the solar limb. Exposure times were 1.0, 2.8, 20.0, and 51.0 s. The spatial resolution of these spectrograms, 08' (Basri et al. 1979), remains among the highest yet achieved with the HRTS instrument, and is constant with wavelength. Pointing jitter did not exceed 0.2'. During the second HRTS flight the slit was oriented radially from the solar disk center through the active region McMath 15139, including a sunspot, and extending across the solar limb.

3. DATA REDUCTION AND CALIBRATION

The HRTS spectrograms were registered on photographic film. The various steps in the reduction process of these spectrograms have been described by Kjeldseth-Moe et al. (1988, 1993), Brekke (1992, 1993), Brekke et al. (1991), and Brekke & Kjeldseth-Moe (1994). They include microphotometry, resampling to correct for geometrical distortion, noise filtering, and intensity and wavelength calibration. Thus, in the following we describe only additional reduction procedures of particular relevance to the accurate determination of the wavelengths, and thus the redshifts, of the transition region lines.

The standard wavelength calibration procedures allows a wavelength scale accurate to 0.01 Å, or 2 km s$^{-1}$ in velocity units, to be established relative to the line emission from the chromospheric gas (see Brekke 1992, 1993). The absolute velocity of the chromospheric gas relative to the Sun appears to be small, 1 km s$^{-1}$ according to Samain (1991). The method, however, suffers uncertainties at wavelengths below 1300 Å, since fairly few chromospheric reference lines at these wavelengths are sufficiently strong to register in most available HRTS exposures.

However, the long HRTS 1 exposure offered the opportunity to check the wavelength scale, particularly for the measurements of the N v lines. Thus, we selected 10 additional chromospheric lines close to the N v 1238 Å and 1242 Å lines and determined the average deviation in wavelength to be 0.0035 Å. This corresponds to an accuracy in the velocity determination of 0.9 km s$^{-1}$. Hence, the positioning of our wavelength scale is confirmed by these additional measurements.

The position of the transition region lines may furthermore be affected by blends. Particular attention was given to the resonance lines of C iv. Provided the lines are optically thin, the 1548 Å line should have twice the intensity of the 1550 Å line. The difference between the intensity profiles of the 1548 Å line and twice the 1550 Å line will then reveal blends in the two lines. An optical thin condition for the C iv lines is confirmed from the average measured intensity ratio over the entire length of the HRTS 2 slit of 2.05 $\pm$ 0.33. Our measurements furthermore confirm the results of Dere, Bartoe, & Brueckner (1984) for the wavelength positions of the blends. In addition we find one unidentified blend at 1548.228 Å with an intensity slightly larger than the Si i 150.959 Å line (Achour 1994). Most of the blends in the C iv lines are identified as Si i lines. None of the other lines studied appears to be as seriously affected by blends as the C iv lines.

Flow velocities are determined from Gaussian fits to the observed line profiles, using the least-squares method described by Bevington (1969). This gives values for wavelength, line width and intensity. The line positions were also measured using a centroid technique and no significant differences were found between the two methods. The contribution from the blended lines is subtracted from the observed profiles before fitting to Gaussians. Widths and intensities of the Si i blends inside the C iv lines were estimated from a study of several other Si i lines in the same wavelength region. The background continuum emission was also subtracted before fitting the profiles. Below 1440 Å the solar UV continuum is too weak to be registered with the HRTS instrument. Its value was estimated from measurements at longer wavelengths and in the wing of the Lyman-α line, applying measured ratios from the SUSIM irradiance monitor. (For a description of the relation between spectra from HRTS and SUSIM, see Brekke & Kjeldseth-Moe 1994 and references therein.) The results of the wavelength measurement are not strongly dependent on an accurate determination of the continuum background. Thus, throughout the reduction procedure the accuracy of the wavelength determination is preserved and remains at the value 2 km s$^{-1}$.

4. RESULTS

Transition region line profiles observed with HRTS show the presence of several distinct flow velocities within the same resolution element of $1'' \times 1''$, leading to the multiple flow concept (Kjeldseth-Moe et al. 1988, 1993, 1994). Observations
from HRTS 1, HRTS 2, and HRTS on Spacelab 2 demonstrate that multiple velocities are not limited to sunspots, where they were first detected, but are also present in quiet solar regions. In the observations presented below we consider only the strongest line component with relatively small wavelength shifts relative to the rest wavelength. Thus, neither the blue-shifted nor the redshifted high-velocity components are included in this study.

4.1. Center-to-Limb Variation and the Downflow Hypothesis

The pervasive redshift is often interpreted as a predominantly vertical gas motion, i.e., a downflow. At the center of the solar disk vertical motions may be observed without projection effects, while close to the limb only horizontal flows are observable as Doppler shifts. Hence, it is of interest to consider possible systematic variations in the Doppler shift along the slit from the disk center to the limb.

Several observers have reported an increase in redshift from limb to disk center (see, e.g., Roussel-Dupré & Shine 1982; Rottman et al. 1990; Hassler et al. 1991). Dere et al. (1984) reported redshifts at and above the limb for several slit positions in a raster sequence observed during the third HRTS flight. We do not intend to present a complete discussion of the center-to-limb variation, but to draw attention to the following two aspects of the observed line-of-sight velocity in the N v 1238 Å line along the slit (see Fig. 1). First, we note the considerable local variation in the line-of-sight velocity (see also Kjeldseth-Moe et al. 1984; Brekke 1993). These variations in fact dominate over any average center-to-limb variation, even when we consider a running mean curve averaging over 50°. Second, Figure 1 shows that the redshift persists nearly to the solar limb. This may be interpreted as the presence of a strong horizontal component in the flow field or alternatively point to a mechanism different from persistent gas downflow for producing the redshift. Hence, as stressed by Dorsch et al. (1976), care should be taken before interpreting the redshift as caused by a net downflow of mass. Also the observation by Feldman et al. (1982) that the redshift in active regions is nearly independent of the position on the solar disk suggests a closer examination of the commonly accepted interpretation. Based on high spatial resolution observations of lines formed in the temperature range $10^4 - 10^5$ K, Athay & Dere (1989) found that the flow does not appear to be continuous. Thus, one could argue that the observed center-to-limb behavior does not really support predominantly vertical gas motion. However, since we cannot completely exclude the vertical downflow hypothesis, we prefer to argue that alternative explanations for the redshift of the transition region lines should be seriously considered.

4.2. The Wavelength Shift in Quiet Regions

In regions close to the center of the solar disk the vertical flow may be observed without projection effects. During both rocket flights the Sun had quiet regions close to the disk center. For temperatures up to $1.35 \times 10^5$ K these regions show practically the same redshift values and accordingly the same monotonic increase in downflow with increasing temperature for HRTS 1 and HRTS 2.

![Fig. 1. — HRTS 1 observation of the spatial variation of the line-of-sight velocity in the N v line 1238 Å. In this figure the laboratory wavelength of Hallin (1966) is used. The chromospheric reference line (C i 1364.164 Å) is shown for comparison. A section of the spectrogram showing the N v from disk center to the limb is shown to the left and the position of the active region McMath 13760 is marked. The position along the slit is given in pixel units, where 1 pixel corresponds approximately to 0.5.](image-url)
The long exposure of HRTS 1 also allows precise wavelength measurements in the quiet Sun of the ‘’hotter’’ N v and O v lines. We present the results for HRTS 1 for a quiet region located close to disk center. Figure 2 (top) shows the derived vertical flows for HRTS 1 for a series of lines formed in the transition region. The line-of-sight velocities have been averaged over 90°. The laboratory wavelengths of the observed lines, the average vertical flow velocities in the 1° × 90° quiet region close to disk center as well as estimates of the temperatures of line formation are given in Table 1. The temperature values given for the various ions in this paper are based on the ionization equilibrium calculations of Nicolais et al. (1982). Flows in the transition region can change these values by approximately 20% (see, e.g., Joselyn, Munro, & Holzer 1979; Hansteen 1993).

Other quiet regions along the slit were also measured, but only minor deviations from the results presented in Figure 2 or Table 1 were found. In particular the quiet region adjacent to the active region on the center side showed the same redshift values as the quiet region close to disk center. The measured vertical flows in O v are very similar to the HRTS 1 results presented and discussed in detail by Brekke (1993; see also Brekke & Hassler 1995).

4.3. Sensitivity of the Result to Laboratory Wavelengths

The laboratory wavelengths of the N v and O v lines are critical to the determination of the redshift at high temperatures. This is apparent from the quiet region results in Figure 2 (top), which indicate the presence of two inconsistencies. The first is the large difference in the average vertical flow velocity measured in the two O v lines (1.5 km s⁻¹ and 9.0 km s⁻¹ for 1218 and 1371 Å, respectively). Brekke (1993) suggested that the measurement using the 1371 Å line was the most reliable since its laboratory wavelength is best determined. However, this makes it difficult to understand the derived vertical flows of 2.2 and 2.0 km s⁻¹ in the N v lines (filled stars in Fig. 2), based on the laboratory wavelengths, 1238.821 and 1242.804 Å, of Hallin (1966). This result for the N v lines may be taken in support to the O v 1218 Å result of 1.5 km s⁻¹.

However, if we instead use the laboratory wavelengths of Edlén (1934), (open stars in Fig. 1) the velocity values are 7.3 and 8.3 km s⁻¹. This is comparable to the vertical flow of 9.0 km s⁻¹ derived for the O v 1371 Å line as well as the N v results from Skylab (Doschek et al. 1976), calibrated by off-limb measurements of the transition region line. Since the Skylab measurements are independent of uncertainties in the laboratory wavelengths, they favor the laboratory values of Edlén (1934). A third option is to use the laboratory wavelengths of Bockasten, Hallin, & Hughes (1963). We tend to give less weight to this work since it would give a larger difference between the results for the two N v lines (6.1 and 2.2 km s⁻¹).

In conclusion one may state that the detailed results at high temperatures are still undecided. Improved, new measurements of the laboratory wavelengths are required. This uncertainty also applies to the active region measurements discussed in the next section.

4.4. Redshift in an Active Region

The 51 s long exposure of HRTS 1 also permits us to measure the wavelength shifts in an active region just below the sunspot (see Fig. 1). Table 1 and Figure 2 (middle) give the average line-of-sight velocity for the raster lines 560–670, corresponding to averaging over an area of 1° × 55° of the active region. The set of spectral lines is nearly identical to the set of lines studied for the quiet region, with the addition of two coronal lines from Fe xii, which become sufficiently strong to be registered.

Also for the active region the line-of-sight velocity increases with temperature, reaches a maximum in the temperature region where the O iv lines are formed (T = 1.35 × 10⁴ K), and decreases again for higher temperatures. The values derived for the N v and O v lines are noticeably less than the average value (17.6 km s⁻¹) measured in the O iv 1401 Å line. With the exception of the O v lines the flow velocities are significantly higher in the active than in the quiet region for all transition region lines. One also notes that no significant differences are detected between any two lines from the same element in the same stage of ionization, again with exception of the O v lines.

The coronal lines in the HRTS spectral range include Fe xii 1242.00 and 1349.40 Å. The Fe xii 1242.00 Å, formed at a temperature of 1.4 × 10⁵ K, is partly blended with chromospheric lines of Si i, Ca ii, and C i. However, in the active region the Fe xii 1242 Å is much stronger than the chromospheric lines. An average Doppler shift of 1.2 km s⁻¹ was derived for a set of 100 raster lines, corresponding approximately to 50°.

The Fe xii 1349.40 Å line is more suitable for determining coronal velocities since it is less blended with chromospheric lines. The measured wavelength positions above the limb in the HRTS 2 data are in excellent agreement with the rest wavelength of 1349.40 Å determined from Skylab spectra (Sandlin, Brueckner, & Tousey 1977). We find that the velocity varies with position within the active region, and derive an average value of 4.3 ± 3 km s⁻¹. We confirm a maximum velocity value of 15 km s⁻¹ as derived by Brekke (1993).

It is of interest to compare the derived line-of-sight velocities with other active region measurements. The study of Feldman et al. (1982) of two active regions during their passage over the solar disk included several of the same lines, i.e., Si iv 1393 Å, O iv 1401 Å, N v 1238 and 1242 Å, and O v 1218 Å. Considering that Feldman et al. (1982) averaged over a somewhat larger region (2° × 60°) and lacked the supporting high spatial resolution observations, it seems reasonable to compare our results with the higher of their values, several of which were observed close to disk center. For heliocentric angles θ < 30° Feldman et al. (1982) gave line-of-sight velocities for O iv and

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**Table 1**

<table>
<thead>
<tr>
<th>Ion</th>
<th>λ (Å)</th>
<th>Quiet (ν₁) (km s⁻¹)</th>
<th>Active (ν₂) (km s⁻¹)</th>
<th>T (10⁴ K)</th>
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<td>11.0</td>
<td>0.7</td>
</tr>
<tr>
<td>C iv</td>
<td>1548.202</td>
<td>6.2</td>
<td>13.0</td>
<td>1.0</td>
</tr>
<tr>
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<td>15.0</td>
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<td>17.6</td>
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<td>7.1</td>
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<tr>
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<td>8.5</td>
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<td>1349.40</td>
<td>4.3</td>
<td>14.5</td>
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</table>

a Hallin 1966.
b Edlén 1934.
Fig. 2.—Observed redshift for a series of transition region lines in the quiet region (top) and the active region McMath 13766 (middle). Two values are shown for each of the \( \text{N} \text{ v} \) lines, based on laboratory wavelengths of Hallin (1966) and Edlén (1934), marked as filled and open stars, respectively. The redshifts are converted to line-of-sight velocities and the difference between the active region and the quiet region is shown (bottom). One value of the line formation temperature is assigned to each transition region line.
Si iv ranging from 10 km s$^{-1}$ to 18 km s$^{-1}$, comparable to our results of 11 km s$^{-1}$ and 17.6 km s$^{-1}$ for the active region with $\theta = 18^\circ$.

A more detailed comparison of the results have to take into account that different laboratory reference wavelengths may have been used. Feldman et al. (1982) used the wavelength position of the transition region lines outside the limb as reference wavelength, while we have used laboratory wavelengths. For the N v and O v lines Feldman et al. (1982) derived velocities between 6 km s$^{-1}$ and 10 km s$^{-1}$ for $\theta < 30^\circ$. Using the laboratory wavelengths of Hallin we obtain similar results, 7.1 km s$^{-1}$ and 8.5 km s$^{-1}$ for the N v lines, but somewhat higher values, 12.2 km s$^{-1}$ and 14.8 km s$^{-1}$, if we use the laboratory wavelengths of Edlén (1934). We find a smaller velocity for the O v 1218 Å line than Feldman et al. (1982). However, both measurements are uncertain owing to the proximity of the hydrogen Ly$\alpha$ line. We conclude that our results for the active region are compatible with those of Feldman et al. (1982). Including our result for the O v line 1371 Å, both studies indicate that the redshift phenomenon extends to temperatures above 2.3 \times 10^{5} K in active regions.

The line-of-sight velocity is not uniform within the active region. This variation with position may be significant when discussing the extension of the redshift to higher temperatures. Whereas the coronal lines show small average shifts, velocities up to 15 km s$^{-1}$ are observed in a small region for the Fe xii 1349 Å line. Also the 70 km s$^{-1}$ velocity derived by Mariaska & Dowdy (1992) for the Ne vii 465 Å line formed at 5 \times 10^{5} K was limited to a small region.

4.5. Differential Redshift

As mentioned previously no significant differences were found between the wavelength shifts in several quiet regions along the slit in the HRTS 1 observations. Hence, the results in Table 1 and Figure 2 for the active and quiet regions may be directly compared, allowing us to study the difference in redshift between "two atmospheres, placed side by side".

The reason for directly comparing active and quiet regions is to present a new, supplementary way of comparing theoretical predictions with observations. An obvious advantage is that this approach is independent of laboratory wavelengths. Provided we have sufficient additional information a comparison of this kind could be of value for most regions on the Sun. In our case, it appears from the discussion above that we may regard the active region studied as typical for active regions lying close to disk center. In the next section we will attempt to include this comparison in the confrontation between theory and observations.

The difference in line-of-sight velocity between the active and quiet region is shown in the lower panel of Figure 2. The velocity difference increases with increasing temperature, reaching a maximum of 7 km s$^{-1}$ at temperatures of 1.0–1.35 \times 10^{5} K, where the N iv 1486 Å and the O iv 1401 Å lines are formed. Above this temperature the velocity difference decreases abruptly with increasing temperature. As was pointed out above the velocity difference results, plotted in Figure 2, are not affected by the uncertainty in the laboratory wavelengths.

5. DISCUSSION

The presence of the solar wind requires a net outflow at all heights in the solar atmosphere. However, it is generally believed that the solar wind mainly occurs in open magnetic field regions where emission from transition region lines are very weak. Hence, it is tempting to assume that the redshift phenomenon is limited to regions in the solar atmosphere with relatively strong UV emission, originating from gas probably contained in closed magnetic field structures.

If the observed redshifts in the transition region lines are interpreted as net downflows the resulting mass flux would empty most loops in the solar corona in minutes (see, e.g., Brueckner 1981). Since this is much shorter than timescales for observed changes in the corona, and since a comparable upflow has so far not been detected, we are faced with a puzzle that still awaits a commonly accepted explanation.

In the following we discuss proposed models for the observed redshifts. In Figure 2 the redshifts have been converted to velocities, since this gives a good measure of the magnitude of the effect. This does not mean that we restrict ourselves to gas flow from the corona to the chromosphere. In fact, we will also discuss a possible interpretation of the redshift that involves downward propagation of disturbances from the corona.

The observations show the following characteristics of the redshift phenomenon:

1. The redshift phenomenon is of a statistical nature, with strong local variations in the observed redshift for all the transition region lines studied.
2. The net redshift is larger in the active region than in the quiet regions.
3. A weak extension of the redshift into the corona may occur in active regions.
4. The difference in line-of-sight velocity between the active region and its surroundings increases with increasing temperature to a maximum at $T \sim 1.35 \times 10^{5} K$, then decreasing abruptly at higher temperatures and may cease to exist at $T = 2.3 \times 10^{5} K$.

The active region differs from the quiet region in several aspects. We venture to suggest that the key parameter is the magnetic field. In fact, a recent study of the connection between red- and blueshifted emission lines and the photospheric magnetic field demonstrates a marked tendency for the C iv 1548 Å line to increase in strength and also to be redshifted as the magnetic flux density increases (Brynildsen, Kjeldseth-Moe, & Maltby 1994).

5.1. Model Classification

Different starting points have been adopted in the numerous papers that have presented possible explanations for the observed redshifts:

1. Unidirectional flow along the whole loop; upflow in one leg and downflow in the other;
2. Upflows and subsequent downflows along the same lines of force;
3. Episodic heating in the corona creating disturbances that propagate along magnetic field lines toward the chromosphere.

This scheme does not include the idea of Roumeliotis (1991) that most of the Sun's lower transition region is contained in sheared magnetic boundary layers separating adjacent flux loops, where it is heated by the Joule dissipation of intense, field aligned electric currents. He finds that by increasing the electric current in his model the atmosphere evolves from a "cool" equilibrium to a "hot" equilibrium and a strong downflow is initiated, which is not compensated by a comparable
upflow when the atmosphere cools. Further development of this idea, including a scheme for the heating sequence is required before a meaningful comparison with observations can be done.

Bray et al. (1991) and Mariska (1992) have reviewed the first two classes of models. In order to explain the observed redshifts with the unidirectional flow model a strong asymmetry in the heating of the loop is required, with energy mainly deposited in a small part of the loop (see, e.g., Boris & Mariska 1982; Mariska & Boris 1983; McClymont & Craig 1987; Mariska 1988; Spadaro, Antiochos, & Mariska 1991). The most promising models are obtained with the flow restricted to cool loops (Klimchuk & Mariska 1988; McClymont 1989).

The second class of models attributes the redshift to downflowing gas caused by the return of spicular material (see, e.g., Pneuman & Kopp 1978; Athay & Holzer 1982; Athay 1987). One possibility is to include episodic heating in small areas, followed by radiative cooling (Sturrock et al. 1990; Raymond 1990). Recent work by Cheng (1992) gave support to the idea that the redshift was caused by the return of spicular material. Working with a rebound shock model for the spicule, Cheng (1992) showed that the rebound shock front could give rise to an average downward directed velocity in the transition region. However, taking into account that the line emission varies with time and position, Hansteen & Wikstol (1994) showed that the resulting hydrodynamic evolution leads to a perceived upflow and blueshift in transition region spectral lines, even though the average velocity in the line-forming region is directed downward.

A new interpretation of the net redshift in the transition region was presented by Hansteen (1993), see also Hansteen & Maltby (1994). Hansteen considered episodic disturbances generated by several nanoflare bursts in the corona and investigated the resulting conduction-modified, acoustic disturbances.

He found that two effects contributed to the redshift, namely the particle motion in the acoustic wave coupled with the line emission and the physical displacement of the transition region itself by the wave pulse. This model may be extended to include other MHD disturbances, such as Alfvén waves (Hansteen & Maltby 1992). Since the Alfvén wave is noncompressive its main effect is to increase the magnitude of the wave pulse and accordingly to increase the physical displacement of the transition region.

5.2. Confrontation with the Observations

Consider next the confrontation between these models and the observations presented above. With the latter model we predict that the redshift increases with an increase in the Alfvén wave pulse. Hence, with this model it seems likely that redshifts will be larger in the active region than in the quiet region, in agreement with the observations (point 2 above). The observations also suggest (point 4 above) that one should add the requirement that the displacement of the transition region increases with temperature up to $1.3 \times 10^5$ K, then decreases and becomes independent of the magnetic field value for a temperature of $2.3 \times 10^5$ K. Hansteen (1993) predicted a change in redshift with temperature that promises to give agreement with the observations. However, the model calculations have to be extended to include Alfvén waves before a satisfactory comparison can be done. In passing we note that Maltby (1994) has suggested that the combination of acoustic and Alfvén wave disturbances may explain the tendency for the observed line profiles to show more than one distinct line-of-sight velocity.

Finally, let us consider the two classes of models with flows within magnetic flux tubes. For a steady flow the velocity $v$, density $\rho$, cross section $\sigma$ and magnetic flux density $B$ are related by $\rho v = c_\alpha = c_r$ and $B\sigma = c_\beta = c_r$. Eliminating $\sigma$ from these equations gives

$$\frac{\rho v}{B} = \frac{c_\alpha}{c_\beta} = c_r,$$

where $c_r$ is the ratio between the mass flux and the magnetic flux. It is likely that the average value of $c_r$ is different in active and quiet regions. Therefore, we introduce a quantity, $\psi$, defined as the ratio between $c_r$ values in active and quiet areas. Hence,

$$v = \frac{v_{q}}{q} \frac{B_{q}}{B_{a}} \rho_{a},$$

where the indices $a$ and $q$ represent active and quiet regions. In order for the velocity $v_{q}$ in the active region to be larger than $v_{q}$ in the quiet region $\psi B_{a} \rho_{a}$ must be larger than $B_{q} \rho_{a}$. Taking into account the fact that the transition line intensity, $I$, varies proportional to the square of the density $\rho$, we may write

$$v = \frac{v_{q}}{q} \left(\frac{B_{a}}{B_{q}}\right) \left(\frac{I_{a}}{I_{q}}\right)^{1/2}.$$

Inserting observed values for the O iv line, i.e., $v_{q} = 17.6$ km s$^{-1}$, $v_{a} = 10.5$ km s$^{-1}$, and $(I_{a}/I_{q})^{1/2} = 0.40$, we find that $\psi B_{a}/B_{q} = 4.2$. We do not have observations of $\psi B_{a}/B_{q}$ in the transition zone, but the predicted value appears to be reasonable. Here we have tacitly assumed that the area filling factor is the same in active and quiet regions. It should be noted that nearly the same average intensity is found in upflows and downflows, whereas the average downflow is nearly twice the average upflow (see, e.g., Brynildsen et al. 1994). Hence, for the flow model to work it seems necessary to require an area filling factor that depends on the flow direction.

Again the observations suggest (point 4 above) that one should add the requirement that the displacement of the transition region increases with temperature up to $1.3 \times 10^5$ K, then decreases and becomes independent of the magnetic field value for a temperature of $2.3 \times 10^5$ K. Although the observations suggest a weak extension of the redshift phenomenon into the corona (point 3 above), the best option for the flow models appears to be loops with maximum temperatures less than, say, $2.5 \times 10^5$ K, heated more in one leg than in the other. Taking into account the statistical nature of the observed redshift as well as the tendency for the line profiles to show more than one distinct line-of-sight velocity one is tempted to follow the suggestion by Kjeldseth-Moe et al. (1993), who suggested a filamentary structure, where a loop consists of a number of thin fibrils, each with its own flow field. In order to maintain the flow for a sufficient amount of time one may think of new fibrils replacing the old ones.

6. CONCLUDING REMARKS

We have studied the redshift of spectral lines formed in the transition region between the chromosphere and the corona as a function of temperature, both for active and quiet regions. With the spectrometers soon to be flown on the Solar and Heliospheric Observatory (SOHO) we should be able to...
extend the investigation to several active regions and to improve our understanding of the high-temperature region. It is apparent that determination of improved laboratory wavelength is needed for a number of transition region lines.

In this paper we have drawn attention to the difference in observed line-of-sight velocity between an active region and the adjacent quiet regions as a function of temperature. This difference is independent of laboratory wavelength values and may be used as a test of theoretical models. The observed velocity difference increases with increasing temperature, reaching a maximum at temperatures of $1.0 - 1.35 \times 10^5 \text{ K}$, and then decreases abruptly with increasing temperature. Apparently the $\pi$ v lines, formed at $2.3 \times 10^5 \text{ K}$ and $2.4 \times 10^5 \text{ K}$, differ from the other transition region lines by not showing any significant change in the line-of-sight velocity between the active region and the surrounding quiet regions. We should aim for further observations of this velocity difference in order to compare different active regions and also to study the variation with position within active regions.

Both the observations presented here as well as those given in a recent study of the connection between redshift and photospheric magnetic field (Brynildsen et al. 1994) point to the magnetic field as the key parameter in determining the magnitude of the redshift. Although the present observations cannot immediately point to the most probable origin of the transition region redshift phenomenon, new requirements to theoretical models for the redshift are presented. For the flow models the best option appears to occur for loops consisting of a number of thin fibrils and with maximum temperatures of less than $2.5 \times 10^5 \text{ K}$. It is possible that further calculations will show that disturbances originating in the corona and propagating into the transition region may explain the observations presented here, without any limitation regarding the maximum temperature in the flux tube. Finally, it should be noted that the discussion above is based on the assumption that the temperature varies monotonically along field lines, reaching up to coronal temperatures. Since observations of loops as seen in light of different ions do not give clear support to this view (see, e.g., Feldman 1993) alternative interpretations cannot be excluded.

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