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## V. DYNAMICS OF THE CHROMOSPHERE AND TRANSITION REGION

(R. Grant Athay)

One of the more interesting aspects of the chromosphere-corona transition region is its tendency to exhibit large Doppler shifts. Both the non-thermal velocity component of line widths and the velocity displacement of line positions tend to maximize at temperatures near $10^5$ K. The increase in velocity amplitudes with increasing temperatures below $10^5$ K is readily understood in terms of the increasing sound speed and decreasing densities associated with the outwardly increasing temperature. Why the observed velocity amplitudes should decrease at still higher temperatures is not at all clear, however, and it seems very likely that this phenomenon is indicative of fundamental differences in the dynamics of the upper transition region and corona from those in the lower transition region and chromosphere.

The possibility remains, of course, that the apparent velocity decrease at high temperatures is only partially a solar effect. At temperatures above $10^5$ K, increases in temperature, in general, are associated with increasing amounts of radiating material as a result of the decreasing temperature gradients. The resulting increase in path length over which a given spectral line forms tends to blend together regions of differing Doppler shift. As a result, the lines are broadened in preference to overall wavelength displacements. The apparent decrease in Doppler shifts very likely is due partially to this effect. However, since no marked increase in the non-thermal component of line broadening has been observed for temperatures above $10^5$ K, it is evident that the steady increase in velocity amplitude up to $10^5$ K does not continue at the same rate into the $10^6$ K regime of the corona. Thus, at least part of the effect appears to be of solar origin.

A further unusual property of the temperature regime below about $10^5$ K is the tendency for the solar plasma to exhibit large scale systematic flows as well as both periodic and highly transient localized flows. This review concentrates on the observational aspects of these flows as reported from 1981 to mid-1984.

*Vertical Flow.*

A number of observers have continued to report systematic downflows observed in spectral lines formed in the lower transition region and chromosphere. Gebbie *et al.* (1981) report average downflow velocities for the quiet sun ranging from 1.4 km $s^{-1}$ in C II to 4.2 km $s^{-1}$ in C IV, which is consistent with momentum conservation. Roussel-Dupre and Shine (1982) find mean redshifts of 12 km $s^{-1}$ in C IV and Si IV at disk center, and Dere (1982a) finds an average red shift of 5.4 km $s^{-1}$ for the quiet sun in C IV.

In active regions, Feldman, Cohen and Doschek (1982) find mean red shifts ranging from 4 to 17 km $s^{-1}$ in ions formed at different temperatures with the maximum occurring between $5\times10^4$ and $10^5$ K and decreasing to 2 km $s^{-1}$ in lines of Si II, S II and C II formed in the upper chromosphere, and Brueckner (1981) finds downflows of 10-60 km $s^{-1}$ in C IV.

Over sunspot umbrae the situation is less clear. Several authors (Brueckner 1981, Nicholas *et al.* 1982, Dere 1982b and Athay et al. 1982) have reported downflows in C IV generally exceeding those in the quiet sun. However, in subsequent studies Athay, Gurman and Henze (1983) found several spots with upflow and Gurman and Athay (1983) found from a study of 8 sunspots a small net average upflow. Also, Mein *et al.* (1982) found strong upflow in C IV in three sunspots;

Kingston *et al.* (1982) found only a weak net downflow in two sunspots; and Henze *et al.* (1984) found both upflow and downflow in different portions of a single spot. It seems clear that some sunspots have downflow, but that perhaps an equal number have upflow at transition region temperatures. Within a given spot the flow direction may well be time dependent.

Evidence that the downflows in the quiet sun are associated at least partially with the network seems quite conclusive. Positive correlations between red shift amplitude and intensity of C IV have been found by Gebbie *et al.* (1981), and Athay *et al.* (1983). Similar correlations have been found in active regions by Mein *et al.* (1982), Simon *et al.* (1982), and Athay *et al.* (1982, 1983). On the other hand, Dere (1982a) found no correlation between velocity and intensity and Athay *et al.* (1982, 1983) found that the correlation in C IV was often restricted to intermediate intensities. Furthermore, the latter authors noted that whereas the network features tended to have a red shift the reverse correlation was much weaker. Much of the red shifted areas are near to or below average brightness. Thus, it appears that the red shifted areas include most of the network but, in addition, include much of the supergranule cell interior. Also, the very brightest features in active regions often show blue shifts (Athay et al. 1983). This is consistent with high resolution observations reported by Brueckner (1981) and Dere (1982a, 1982b) that show many bright blue shifted features in C IV.

Although the preponderant downflow at transition region temperatures seems well established in both the quiet and active sun, the form of the downflow is unclear. In both low resolution and high resolution data C IV lines show a variety of profile types ranging from asymmetric profiles composed of a a strong unshifted component and weaker Doppler shifted components in the red wing (Dere 1982), to symmetric profiles with notable Doppler shift (Athay *et al.* 1983). It seems probable, therefore, that the Doppler shifted areas have scale sizes ranging from sub-arcsecond to many arcseconds.

An attempt by Rottman, Orrall and Klimchuk (1981) to measure the radial flow velocity in a coronal hole in OV showed a blue shift of 3 km $s^{-1}$ in the coronal hole relative to the average of the observed area outside the coronal hole. Since the average sun is very probably redshifted in OV, as in other lines formed at similar temperatures, it is unclear whether, in fact, the observed coronal hole had a net outflow in OV or just a reduced redshift.

The high spatial resolution HRTS data from the U.S. Naval Research Laboratory reveal a complex array of moving features including small blue shifted jets of relatively short lifetime. Brueckner (1981), Dere (1982a, 1982b) and Brueckner and Bartoe (1983) identify "chromospheric jets" as a class of objects with blue shifts at 10-20 km $s^{-1}$ and "coronal jets" as a second class with blue shifts up to 400 km $s^{-1}$. Little is known about the morphology and the associations of these jets with other solar features due to the limited spatial sampling in the HRTS data. The discovery of these interesting high speed jets together with the unanswered questions about the structure of the downflows underscores the need to pursue high resolution studies of the highly dynamic transition region.

*Horizontal Flow.*

As is clear on general physical grounds and supported for some time by observations, flows with dominant horizontal components play an important role in the dynamics of the solar atmosphere. The difficulty of observing such flows has notably restricted what is known concerning them. Again, however, recent transition region studies have provided interesting new results.

Nicholas and Kjeldseth-Moe (1981) and Athay *et al.* (1982, 1983) report flow patterns observed in C IV around large sunspots indicative of a reverse Evershed effect. On the sun-center sides of the spots, the gas is red shifted, and on the limbward side it is blue shifted. The red shifted area is usually larger in size than the blue shifted area and the red shift amplitude usually exceeds the blue shift amplitude, which suggests that the flow follows a pronounced Wilson depression.

At transition region temperatures, active regions show horizontal flow patterns that are coherent over large spatial domains and that are closely associated with the overall magnetic field structure of the active region (Athay *et al.* 1982, Athay, Gurman and Henze 1983). Near the magnetic neutral line separating strong field regions of opposite polarity the flow is usually divergent with opposite sign either side of the neutral line. However, near the neutral lines separating the weaker field areas of opposite polarity bordering the strong field areas the flow is often convergent

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towards the neutral line. In many cases the local flow around individual spots appears to be a coherent part of the large scale pattern, but in other cases the flow appears to be peculiar to the spot itself.

*Oscillations.*

Periodic oscillations in a sunspot umbra were reported by Zhugzhda and Makarov (1982). Brightness fluctuations observed in the Hα and K lines show series of wave trains lasting for 1.5 to 2 hours. Individual wave trains start at periods near 200 s and decrease to about 150 s as the train dies out. The wave trains are somewhat less pronounced in Hα than in the K line, but otherwise they are very similar in the two lines. The authors interpret the pulses of wave trains and the changing wave period in terms of an alternate compression and expansion of the chromospheric resonant cavity.

Umbral oscillations in C IV have been reported by Gurman *et al.* (1982) and Henze *et al.* (1984). Of the eight sunspots studied by Gurman et al., all showed velocity and brightness oscillations. Periods ranged from 130 to 170 s and velocity amplitudes from 0.8 to 3.5 km $s^{-1}$. For four of the spots, maximum velocity and maximum blue shift were in phase, consistent with adiabatic acoustic waves. In the one spot studied by Henze *et al.* different umbral pixels showed oscillatory periods from 110 to 200 s in both brightness and velocity. The pixel with the best defined period showed peak intensity leading peak blue shift approximately 45°.

Successful attempts to construct quiet sun $k - \omega$ diagrams in the chromospheric components of the K line have been reported by Kneer and von Uexküll (1983) and by Dame, Gouttebroze and Malherbe (1984). Both sets of observations show modal structure in the approximate wave number ranges 0.25 to 2.5 $Mm^{-1}$ and at frequencies beginning near 15 mHz ($P \approx 420$ s). Modal structure is resolved up to frequencies of approximately 30 mHz ($P \approx 210$ s) in the observations of Kneer and von Uexküll and to approximately 45 mHz (140 s) in those of Dame, Gouttebroze and Malherbe. The latter authors also find faint but inconclusive evidence for longer period waves in the gravity wave regime.

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## VI. THE PHYSICS OF CORONAL FLUX TUBES

(B. Roberts)

Recent texts dealing with background aspects of this topic include Priest (1982), Noyes (1982) and Giovanelli (1984). Here we concentrate on the equilibrium structure of coronal loops, their oscillations and instabilities, and their heating.

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