ANALYSIS OF CORONAL H I LYMAN ALPHA MEASUREMENTS FROM A ROCKET FLIGHT ON 1979 APRIL 13

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ABSTRACT

Measurements of the profiles of resonantly scattered hydrogen Lyman-alpha coronal radiation have
been used to determine hydrogen kinetic temperatures from 1.5 to 4 $R_\odot$ from Sun center in a quiet
region of the corona. Proton temperatures derived from the line widths decrease with height from
2.6 x 10^6 K at $r = 1.5$ $R_\odot$ to 1.2 x 10^6 K at $r = 4$ $R_\odot$. These measurements combined with temperatures
for lower heights determined from earlier Skylab and eclipse data suggest that there is a
maximum in the quiet coronal proton temperature at about 1.5 $R_\odot$. Comparison of measured
Lyman-alpha intensities with those calculated using a representative model for the radial variation of the
coronal electron density provides information on the magnitude of the electron temperature gradient
and suggests that the solar wind flow was subsonic for $r < 4$ $R_\odot$ in the observed region. Comparison of the
measured kinetic temperatures to the predictions of a simple two fluid model suggests that there is
a small amount of proton heating and/or a nonthermal contribution to the motions of coronal protons
between 1.5 and 4 $R_\odot$.

Subject headings: line profiles — Sun: corona — Sun: spectra — ultraviolet: spectra

I. INTRODUCTION

Resonantly scattered coronal hydrogen Lyman-alpha radiation can be used as a means of spectroscopically probing
temperatures, densities, and flow velocities in the solar wind acceleration region where presently available em-
pirical information is very limited. The first measurements out to several solar radii of the H I 1216 spectral
line profile were acquired during a flight of the Rocket Lyman Alpha Coronagraph on 1979 April 13. Kohl et al.
(1980), hereafter referred to as Paper I, presented preliminary results of this first flight. Among these was the
finding that the proton kinetic temperature derived from the widths of Lyman-alpha profiles measured in a “quiet”
unstructured region of the corona decreased with increasing solar radius from 1.5 to 4 $R_\odot$. In the present paper
we report results of a detailed analysis of the measurements of the Lyman-alpha line profiles and intensities made
in this “quiet” region.

II. OBSERVATIONS

The Lyman-alpha measurements were obtained with a coronagraphic instrument carried above the UV absorbing
region of the terrestrial atmosphere by a Nike boosted Black Brandt V sounding rocket. The instrument consists of
a 75 cm Fastie-Ebert scanning spectrometer with a photoelectric detection system, an off-axis parabolic primary
mirror with 47.4 cm focal length, and an occcluding system which employs a rectangular entrance aperture with
knife edges and an internal straight edge occulter. The spectra resolution (FWHM) is 0.34 Å as determined from
laboratory measurements of the instrumental profile before and after the rocket flight. Further information on
the instrument is given by Kohl, Reeves, and Kirkham (1978) and Kohl et al. (1982). A companion white light coronagraph flown on the same payload provided pictures of the white light coronal structure at the
time of the flight.

Figure 1 shows the observed region of the corona. The lower picture was obtained with the HAO white light coronagraph during the rocket flight. Since this instrument used a linear occulter with the same orientation as the occulter in the Lyman-alpha instrument, it observes only that portion of the corona beyond the occulting edge. The small white rectangles in this photograph mark the projection of the spectrometer slit for the observations at
1.5, 1.8, 2.0, 2.5, and 3.0 $R_\odot$. For comparison the upper part of Figure 1 contains a white light picture of the 1979
February 26 eclipse provided by C. F. Keller, Jr. from the Los Alamos Scientific Laboratory. Because the rocket flight occurred approximately 1.5 solar rotations after the
eclipse, this picture can be used as an approximate illustration of the more stable features in the corona at the
time of our observations. The small rectangles mark the position of the spectrometer slit, and the straight line extending from left to right marks the corresponding
Fig. 1.—The small rectangles in the white light eclipse photograph (upper) and in the rocket white light picture (lower) indicate positions where Lyman-α measurements were acquired. The eclipse photograph, which was taken approximately 1.5 solar rotations prior to the rocket flight, has been reversed so that long lived solar features will have the same orientation in both white light pictures. In the coronagraph picture, the linear streaks and emission between the lowest rectangle and circle, showing the location of the solar disk, are artifacts caused by stray light.
position of the primary occulting edge of the UV experiment.

Figure 2 shows Lyman-\(\alpha\) profiles (points) measured for 0.6 \(\times\) 4.0 spatial elements at \(p = 1.5, 1.8, 2.0, 2.5, 3.0,\) and 3.5 solar radii (R\(_0\)). The parameter \(p\) is the distance measured in solar radii from sun center to the point where the line of sight intersects the plane of the solar disk. The instrument terminated the spectral scans approximately halfway down the red wing of the profiles. Because only a single scan was acquired at 3.5 R\(_0\), the Lyman-\(\alpha\) profile for this position is of significantly lower reliability than the others. On the first rocket flight the objective was to acquire scans in several coronal regions in order to prove the instrumental concept and evaluate instrumental performance for observations at different positions in various types of coronal structures; consequently, short integration times were used. A second flight in 1980 acquired profiles with substantially better statistical accuracy over a longer wavelength range, but at fewer spatial positions (Weiser et al. 1981).

Table 1 gives the number of spectral scans made at each spatial position, and the Lyman-\(\alpha\) intensities and widths (1/e half width, i.e., about 0.6 FWHM). The intensities were integrated across the line profile under the assumption that the missing portion of the red wing of the spectral line (see Fig. 2) has the same shape as the blue wing. These intensities have been corrected for the effects of the geocorona. For \(p < 2\) R\(_0\), the geocorona produces a narrow (\(\approx 0.03\) \(\AA\)) absorption feature at line center, while for \(p > 2\) R\(_0\), the geocorona produces a narrow emission feature at line center. The amount of the geocoronal contribution was determined using Jacchia's (1977) model for the terrestrial atmosphere. The exospheric temperature calculated for the time of the rocket flight was 1340 K, which yielded an optical depth of 2.3 at line center and geocoronal emission of \(1.2 \times 10^9\) photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). This predicted value for the geocoronal emission is in excellent agreement with the intensity measured by the rocket experiment at 3.5 R\(_0\) in a polar coronal hole, \(1.3 \times 10^9\) photons cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). Because the observed profile in this feature had the same shape and width as the instrumental profile (FWHM = 0.34 \(\AA\)) and the coronal hole intensity at that height was expected to be weak, the measured intensity was assumed to be due to the geocorona. The observations in the polar coronal hole were made on the same flight as the quiet region observations discussed in the present paper (Kohl et al. 1980). Using the above optical depth and geocoronal emission, the geocoronal contribution to the line profiles could be determined.

![Figure 2](https://example.com/figure2.png)

**Fig. 2.**—Comparison of measured (points) and calculated Lyman-\(\alpha\) profiles. The solid lines are calculated profiles which include the geocoronal absorption/emission and have been convolved with the instrumental profile (FWHM = 0.34 \(\AA\)). The dashed lines are the calculated profiles assuming there is no geocoronal absorption/emission. The calculated profiles were computed using the hydrogen temperatures given in Fig. 4 (see § IV). The error bars give the statistical accuracy of the measurements.
The widths of the Lyman-α line were determined by a least-squares fit of Gaussian curves to the measured profiles. Three different widths are given in Table 1 for each spatial position: (1) the width determined from the measured profiles, (2) the width determined after correction for the effects of the geocoronal emission/absorption, and (3) the width determined ignoring the line center. These widths have been corrected for the instrumental broadening of 0.03 to 0.04 Å depending on the line width. Since the line wings $\lambda - \lambda_0 > 0.34$ Å are unaffected by the geocoronal absorption/emission (which has a measured FWHM = ~0.34 Å due to the instrumental broadening), they provide a reliable measurement of the line width (see Fig. 2). The empirical widths are plotted in Figure 3. The uncertainty in the widths is comparable to the scatter of the plotted points (~0.04 Å). In § IV we will discuss the implications of the decrease of the widths with increasing $\rho$.

### III. FORMATION OF CORONAL H I LYMAN-α RADIATION

Gabriel (1971), Beckers and Chipman (1974), and Withbroe et al. (1981) have discussed the formation of resonantly scattered hydrogen Lyman-α coronal radiation. (At the heights considered here, the collisionally excited component can be ignored.) If we employ a rectangular coordinate system with the observer’s line of sight being the x-axis, the intensity scattered at frequency $v$ is given by (Withbroe et al. 1981),

$$I_s(v) = \frac{0.8 h B_{12}}{48 \pi} \int_{-\infty}^{\infty} \frac{N_e R(T_e)}{(\pi \sigma)^{1/2}} \times \exp \left\{ - \frac{\left[ (v - v_0)^2 - V_x^2 \right]}{\sigma^2} \right\} dx \times \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(v', \omega) \delta \times (v' - v_0 - \frac{V_x}{c} \cdot \hat{n}')dv', dv_x,$$

where $B_{12}$ is the Einstein coefficient, $h$ is Planck’s constant, $N_e$ is the electron density (cm$^{-3}$), $R(T_e) = N_{H_1}/N_P$, $N_{H_1}$ is the neutral hydrogen density, $N_P$ is the proton density, $v_0$ is the central frequency of the Lyman-α transition, $V_x$ is the velocity of the x-component of the solar wind, $\omega$ is the angular direction of the incident chromospheric radiation, $I(v', \omega)$ is the intensity of the chromospheric radiation at frequency $v'$, $[11 + 3(\mathbf{n} \cdot \mathbf{n'})^2]/12$ is the angular dependence of the Lyman-α scattering process, $\mathbf{n}'$ is a unit vector in the direction of the incident chromospheric radiation, $\mathbf{n}$ is a unit vector in the direction of the scattered beam of radiation, and the Dirac delta function is used to account for the fact that the only photons that can be scattered by...
a hydrogen atom moving with velocity \( v \) are those with \( v' = v_0 + v_0/c \cdot \mathbf{v}' \). We assume \( N_\alpha = 0.8N_e \), as expected for a fully ionized plasma \( (N_\alpha \ll N_e) \) with 10% helium.

For the velocity distribution in the calculations discussed below we used a Maxwellian function for the hydrogen distribution

\[
f(v)dv = \frac{1}{(\alpha \pi)^{3/2}} \times \exp \left[ -\frac{(v_x - v_x')^2}{\alpha} - \frac{(v_y - v_y')^2}{\alpha} - \frac{(v_z - v_z')^2}{\alpha} \right] \\
\times dv_x dv_y dv_z ,
\]

where \( \alpha = 2kT_H/m_H \). We have not included nonthermal motions as a separable effect. If such motions are present, are isotropic, and have a Maxwellian distribution (as is often assumed in lower regions of the solar atmosphere), we assume that \( T_H \) includes the combined effects of thermal and nonthermal motions. The ionization balance term \( R(T_e) \) is assumed to depend only on the electron temperature and to be given by Gabriel's (1971) relationship. The assumption that the ionization temperature for hydrogen is equal to the electron temperature appears to be a good approximation for the heights considered here, \( r < 5 R_\odot \) (cf. Holzer 1977).

As equation (1) illustrates, the resonant scattering of Lyman-\( \alpha \) radiation is a fairly complex function of the temperature and density distributions along the line of sight and also the geometry of the scattering process. The essential physics can be shown via an approximate form for the emission per unit volume,

\[
E(\Delta \nu) = \text{const} \times R(T_e) N_e \exp \left[ -\left( \frac{\Delta \nu}{\Delta \nu_0} \right)^2 \right] \\
\times \int_{-\infty}^{\infty} J_\nu \phi(v' - v)dv' ,
\]

where \( \Delta \nu = \nu - \nu_0, \Delta \nu_0 = \alpha^{1/2} v_0/c \) is the Doppler width, \( J_\nu \) is the mean intensity of the chromospheric Lyman-\( \alpha \) radiation, \( \phi \) is the normalized coronal absorption profile, and \( v_0 = v_0 V/c \) is the Doppler shift introduced by the solar wind moving with a velocity \( V \). If the outflow velocities are sufficiently high that \( V \gtrsim (c/v_0) \Delta \nu_0/2 \), then the intensity of the resonantly scattered radiation is reduced due to the difference in the central frequency of the coronal absorption profile and that of the chromospheric Lyman-\( \alpha \) line (see Withbroe et al. 1981). This diminution of intensity is called Doppler dimming (Hyder and Lites 1970; Beckers and Chipman 1974).

The shape of the line profile of the scattered radiation is very nearly a Gaussian with a width \( (1/e \text{ half width}) \Delta \nu_0 \); however, the details of the scattering process lead to slightly smaller widths than \( \Delta \nu_0 \) (see Withbroe et al. 1981). Hence, we see that the shape of the resonantly scattered profile depends primarily on the hydrogen temperature \( T_H \), while from equation (3) the integrated intensity \( J_\nu(v)dv \) depends on the electron density, electron temperature, and the flow velocity. For sufficiently large flow velocities, the shape of the profile can also be influenced by the solar wind flow velocity (also see Beckers and Chipman 1974; Withbroe et al. 1981).

In the results discussed below we calculated Lyman-\( \alpha \) profiles using equations (1) and (2). For the profile of the incident chromospheric radiation we used the measurements of Gouttlebroze et al. (1978). We assumed that the intensity and shape of the chromospheric profile are constant across the solar disk. The chromospheric Lyman-\( \alpha \) line shows little center-to-limb variation (Prinz 1974; Basri et al. 1979, and unpublished data from the Harvard Skylab experiment). For the absolute scale, we used the Lyman-\( \alpha \) flux determined from the relationship given by Vidal-Madjar (1979), a relationship between the Lyman-\( \alpha \) flux and sunspot number based on numerous measurements of the solar Lyman-\( \alpha \) flux by rockets and spacecraft. For the relevant sunspot numbers we used values given in NOAA Solar Geophysical Data. The adopted Lyman-\( \alpha \)-d line intensity is \( 5.3 \times 10^{15} \) photons \( \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \).

IV. ANALYSIS

Because the shape of the Lyman-\( \alpha \) profile depends on the temperature and density variations along the line of sight, it is necessary to make use of a model in order that these line-of-sight effects can be taken into consideration. The simplest type of coronal model is one with spherical symmetry in which the temperature and density vary monotonically with radius. We assume that the electron and proton temperatures, which need not be equal, are simple functions of the radius \( r \) (see below). For the electron density we used the model given by Allen (1963) for solar maximum. The density gradients, \( d(\log N_e)/dr \), in this model are nearly identical to those in Allen's equatorial model for solar minimum. Most coronal features appear to have similar density gradients (cf. Newkirk 1967; Saito 1970), except for coronal holes which have somewhat steeper gradients similar to those in Allen's polar model (cf. Munro and Jackson 1977; Munro and Mariska 1977).

In order to fit the measured line widths (which vary as \( T_H^{-1/2} \)) we used the expression

\[
\log T_H = a + b \log (r/R_\odot) ,
\]

where the constants \( a \) and \( b \) are constants to be derived from the measured widths (see Fig. 3). For the initial calculations, we assumed that the electron temperature (which controls the hydrogen ionization balance) was constant, independent of radius, and thus that \( N_H/N_e = \) constant. The solid line in Figure 3 gives the predicted widths for a temperature \( (T_H) \) model with \( a = 6.55 \) and \( b = -0.75 \). The corresponding variation of \( T_H(r) \) is given by the heavy solid line in Figure 4. The rapid decline of the hydrogen temperature (and therefore the proton temperature, since the strong coupling between hydrogen atoms and protons keeps \( T_p \approx T_e \); see Holzer 1977) implies that the heating of protons between 1.5 and \( 4 R_\odot \) is not large. We will discuss further in § V the implications of the decline of the hydrogen (and proton) temperature. The hydrogen temperatures presented in Figure 4 are relatively insensitive to the assumed model whose pri-
Mary function is to provide information concerning the mean heights of formation for the Lyman-α profiles. For a spherically symmetric atmosphere we find that the mean radius of formation (in units of \( R_0 \)) for a profile measured at a position \( r \) is approximately \( r = r + H \) where \( H \) is the density scale height. For typical density models \( H \) increases from about 0.3 \( R_0 \) at \( r = 1.5 R_0 \) to about 1 \( R_0 \) at \( r = 3.5 R_0 \).

Also shown in Figure 4 are temperatures derived from 1965 eclipse measurements (points) of the width of the Fe \( \text{xiv} \) \( \lambda 5303 \) line (Liebenberg, Bessey, and Watson 1975) and temperatures deduced from 1973 Skylab measurements (dashed lines) of EUV emission gradients (Mariska and Withbroe 1978). The Fe \( \text{xiv} \) measurements were made in a quiet equatorial region and assume that the Fe \( \text{xiv} \) line is broadened only by thermal motions. Because iron is much heavier than hydrogen, the Fe \( \text{xiv} \) line is much more sensitive to broadening by nonthermal motions than the hydrogen line. Thus it is interesting that the Fe \( \text{xiv} \) kinetic temperatures are in good agreement with the derived hydrogen temperatures in the low corona where the two sets of measurements overlap. The kinetic temperature is defined here as a temperature which is due to the thermal and nonthermal velocities in the line of sight.

The radial temperature variation between 1.0 and 1.4 \( R_0 \) (dashed lines in Fig. 4) obtained by Mariska and Withbroe was derived from intensities of the O \( \text{vi} \) \( \lambda 1032 \) and Mg \( \text{x} \) \( \lambda 625 \) lines measured in an equatorial region of the corona that was typical of quiet regions of the atmosphere. Their temperatures are based on measurements of emission gradients which depend upon the coronal ionization equilibrium and the electron density gradient. In the low corona these temperatures should be close to the electron temperature because the equal energy partition time is short compared to other changes in plasma properties.

We see that the three diverse sets of data (Lyman-α profiles, Fe \( \text{xiv} \) profiles, and EUV emission gradients) are all consistent with the hypothesis that the temperature maximum for protons in the quiet corona (for the region \( r < 4 R_0 \)) is located at about 1.5 \( R_0 \) from sun-center and has a value of approximately \( 2.5 \times 10^6 \) K.

Figures 5 compares the empirical Lyman-α intensities (points) with those calculated using an empirical static coronal model (solid line) which uses electron densities from Allen's model for the solar maximum and the proton temperatures derived from the Lyman-α line widths and which assumes \( T_e(r) = \text{constant} \). In order to bring the computed and observed intensities into good agreement, it was necessary to assume \( T_e = 2.7 \times 10^6 \) K. Use of a coronal model with lower (or higher) densities would give a lower (or higher) temperature. For example, use of the densities in Allen's model for the equator at solar minimum in the above calculation yields \( T_e = 1.7 \times 10^6 \) K. A lower electron temperature is needed in order to increase the Lyman-α intensity by increasing the ratio \( N_{\text{H}}/N_e \) to

\[
\frac{N_{\text{H}}}{N_e} \approx \frac{T_e}{T_\text{H}} \approx \frac{T_\text{H}(r)}{T(r)}
\]
compensate for the lower densities in the minimum model, since

\[ I_{\text{Ly}\alpha} \sim \int N_{\text{H}1} \, dx = \int \frac{N_{\text{H}1}}{N_e} \, N_e \, dx. \]  

(5)

Use of a coronal model with \( T_e = 2.4 \times 10^6 \) K, a model we will be considering in § V, requires densities approximately 15% smaller than those in Allen’s model for solar maximum, densities nearly equal to those in Saito’s (1970) model for the quiet Sun. Because the Lyman-\( \alpha \) intensity is relatively insensitive to the assumed electron temperature, a comparison of the computed and observed Lyman-\( \alpha \) intensities places only a loose constraint on the absolute value of \( T_e \). One requires a more direct measurement of \( T_e \) such as can be done using the profile of the broad (~50 Å) electron scattered component of Lyman-\( \alpha \) (see Hughes 1965; Withbroe et al. 1981).

In order to assess the effect of changing the assumed variation of electron temperature with radius, we calculated Lyman-\( \alpha \) intensities using a model having

\[ T_e(r) = T_p(r/r_0)^n, \]  

(6)

where \( n \) is a constant and \( r_0 = 1.5 R_\odot \). For a coronal model whose electron temperature structure is controlled by the outward flow of energy carried by electron thermal conduction \( n \approx -0.3 \) close to the sun (e.g., Hundhausen 1972). (The factor of 0.3 is obtained for constant conductive flux \( F_c = r^3 \frac{dT}{dr} \), which yields \( T_e \propto r^{-2/3} \) with the sign of the exponent depending whether \( F_c \) is directed outward or inward.) For a static atmosphere where the primary coronal heating occurs at large distances from the Sun \( (r > R_\odot) \), the electron temperature will be nearly constant over the range of heights of interest here with a value of \( n \approx 0.3 \). For an expanding corona in a diverging geometrical configuration with energy deposition throughout the solar wind acceleration region, \( n \) can be larger. For example Munro and Jackson (1977) and Munro and Mariska (1978) inferred that \( n \approx 1 \) for \( 1 < r < 4 R_\odot \) in the polar coronal hole they studied.

The dashed lines in Figure 5 illustrate the effect on the Lyman-\( \alpha \) intensities of using models with different gradients for the electron temperature as specified by equation (6) for different values of \( n \). The magnitude of \( T_p \) was selected so as to force all curves through the observed intensity at \( \rho = 2.0 \). Curves with \(-0.3 \leq n \leq 0.0 \) give the best fit indicating that the Lyman-\( \alpha \) intensities are consistent with a nearly constant value for the electron temperature from about 1.5 to 4 \( R_\odot \).

However, the curves plotted in Figure 5 are for static models with no solar wind flow and thus do not include any effects of Doppler dimming. In order to illustrate the effects of Doppler dimming, we have plotted in Figure 6 intensities calculated with Allen’s density model and with \( T_e = T_p(r/r_0)^{-0.3} \); that is, a model in which the electron temperature falls off as predicted for a corona in which the outward conductive flux is approximately constant. For simplicity, we assumed that the solar wind velocity is determined by the conservation of particle flux, \( \lambda = (N_e + N_p)^2 V = \text{constant} \). We see that the curves for

\[ V_w(4 R_\odot) \lesssim 85 \text{ km s}^{-1} \]

give good agreement with the observations. These models correspond to particle fluxes \( \lambda \lesssim 2 \times 10^{35} \) particles s\(^{-1}\). Typical values deduced from solar wind observations at the orbit of the earth are \( 1 \) to \( 2 \times 10^{35} \) particles s\(^{-1}\) (Feldman et al. 1977). Thus a model with electron densities given by Allen (1963) and a radial electron temperature variation corresponding to \( n = -0.3 \) is consistent with the measured radial variation of the Lyman-\( \alpha \) intensities and measurements of the solar wind particle flux measured at 1 AU. A comparison of Figures 5 and 6 indicates that values of \( n < -0.3 \) require higher mass fluxes. For example, in order to have \( T_e(r) = T_p(r) \), which corresponds to \( n \approx -0.8 \), a particle flux of \( 3 \times 10^{35} \) particles s\(^{-1}\) is required. This corresponds to \( V(4 R_\odot) = 130 \text{ km s}^{-1} \).

The above results suggest that the solar wind flow in the observed region is subsonic for \( r < 4 R_\odot \). Given the relative insensitivity of the Lyman-\( \alpha \)-Doppler dimming to subsonic flows (and the uncertainty as to the actual electron temperature and density gradients in the observed region), this evidence for subsonic flow is not conclusive. However, it does demonstrate the need for a spectroscopic diagnostic technique for measuring low velocity flows. Observations of the intensities of the O \( \text{vi} \) resonance lines could provide a means for accomplishing this because of their sensitivity (due to Doppler dimming) to flows in the 25–100 km s\(^{-1}\) range (Kohl and Withbroe 1982). The next flight (in early 1982) of the Rocket Lyman-Alpha Coronagraph is designed to evaluate the feasibility of coronagraphic observations of the O \( \text{vi} \) \( \lambda 1032 \) and \( \lambda 1037 \) lines.

Note that Doppler dimming reduces the intensities at larger values of \( \rho \) compared to those at smaller values. If
we reexamine Figure 5, we see that the fall off with increasing $\rho$ of the Lyman-$\alpha$ intensities computed for the models with $n > 0.3$ is steeper than observed. Introduction of Doppler dimming would increase the disagreement. Hence we conclude that $n < 0.3$. Since we found that it was possible to obtain a good fit to the observed intensities for values of $n$ between 0.3 and -0.8 for reasonable values of the assumed solar wind velocities and outward particle flux, the data do not enable us to determine whether or not there is significant heating of electrons throughout the region where the observed Lyman-$\alpha$ emission was produced (from about 1.5 to 4.5 $R_\odot$). That will require measurements which are more sensitive to $T_e$, such as measurements of the electron scattered component of Lyman-$\alpha$ as mentioned earlier.

V. THEORETICAL MODELS

In order to explore the implications of the empirical results we compare them with the predictions of a simple two fluid model (cf. Hartle and Sturrock 1968; Nerney and Barnes 1977; Hollweg 1978 and references therein). This model provides a means for calculating $T_e(r)$ and $T_p(r)$ as a function of assumed boundary conditions. In order to study the effects of heating we used a model based on mass continuity, the equation of motion

$$N m_p V \frac{dV}{dr} = - \frac{d}{dr} \left[ N k (T_e + T_p) \right] - \frac{GM_\odot m_p N}{r^2}, \quad (7)$$

and the specialized energy equations (see Hartle and Sturrock 1968)

$$\frac{3}{2} N V k \frac{dT_e}{dr} - V k T_e \frac{dN}{dr} = \frac{1}{r^2} \frac{d}{dr} \left[ r^2 \kappa_e \frac{dT_e}{dr} \right]$$

$$- \frac{1}{r^2} \frac{d}{dr} \left[ R_\odot^2 F_e \exp \left[ \frac{- (r - R_\odot)}{H_e} \right] \right]$$

$$= - \frac{3}{2} v_e N k (T_e - T_p), \quad (8)$$

and

$$\frac{3}{2} N V k \frac{dT_p}{dr} - V k T_p \frac{dN}{dr} = \frac{1}{r^2} \frac{d}{dr} \left[ r^2 \kappa_p \frac{dT_p}{dr} \right]$$

$$- \frac{1}{r^2} \frac{d}{dr} \left[ R_\odot^2 F_p \exp \left[ \frac{- (r - R_\odot)}{H_p} \right] \right]$$

$$= \frac{3}{2} v_e N k (T_e - T_p), \quad (9)$$

where $N = N_e = N_p$, $V$ is the flow velocity, $v_e$ is the energy exchange rate between electrons and protons, and $\kappa_e$ and $\kappa_p$ are the thermal conductivities. Hartle and Sturrock employed a model in which all heating occurred at the base of the corona. We have included in the energy equations an ad hoc mechanical heating term similar to that employed by Kopp and Orrall (1976) in their single fluid model. It is assumed that the mechanical heating decreases exponentially with characteristic scale heights $H_e$ and $H_p$ respectively for electrons and protons. The constants $F_e$ and $F_p$ determine the amount of energy delivered respectively to the electrons and protons. Since $v_e$ varies as $N T_e^{-1.5}$, the energy exchange terms on the right hand sides of equations (8) and (9) vary as $N^2$ and therefore decrease rapidly with increasing height in the corona. For typical coronal densities the electrons and protons are strongly coupled in the low corona (within a few tenths $R_\odot$ of the surface) which means that $T_e \approx T_p$ there. However, beyond $r = 1.5 R_\odot$ the electron-proton coupling rapidly decreases because of the decreasing density allowing the proton and electron temperatures to diverge. Because of the high thermal conductivity of electrons, the electron temperature gradient is shallow in the height range of interest here (1.5-4.0 $R_\odot$). For protons, the thermal conductivity is sufficiently low that protons are inefficient at transferring energy from one region of the atmosphere to another. Consequently, unless they are heated directly by a mechanical heating mechanism or indirectly by transfer of energy from the electrons, the proton temperature decreases rapidly with height, falling off adiabatically (as $N^{2/3}$) in a region with outflow of solar wind.

Equations 7-9 were used to calculate two fluid models. The density variation $N(r)$ was assumed to be given by Allen's model for solar maximum, the same density model used in § IV above. This enabled us to calculate $T_e(r)$ and $T_p(r)$ by specifying the outward particle flux $\lambda = 2 N r V$, the parameters controlling the heating function, namely, $F_e$, $F_p$, $H_e$, and $H_p$, and the temperature at the base of the corona, $T_e = T_p = 10^6$ K. An additional boundary condition was that the electron temperature approach zero as the radius approaches infinity (which gives electron temperatures of the right order of magnitude at 1 AU). Because the density variation was assumed, it was not necessary to integrate the mass, momentum, and energy equations simultaneously as is normally done in deriving two fluid models.

In the initial calculations we assumed that there was no mechanical heating of protons ($F_p = 0$). The results are shown in Figure 7 for $\lambda = 0.25, 0.5, 1.0$, and $2.0 \times 10^{35}$ particles s$^{-1}$. As indicated earlier the observed Lyman-$\alpha$ intensities suggest that $\lambda \approx 2 \times 10^{35}$. The assumed value of $H_e$ was 0.4 $R_\odot$. In order to match the measured temperatures at $r = 1.5 R_\odot$ (where $T_e \approx T_p \approx 2.6 \times 10^6$ K; see Fig. 4), a value of $F_e = 1.3 \times 10^6$ ergs cm$^{-2}$ s$^{-1}$ was required. A comparison of the empirical and theoretical curves indicates that the theoretical proton temperatures have a steeper gradient than the proton temperatures derived from the Lyman-$\alpha$ measurements. Use of models with different values for the energy deposition scale height $H_e$ (and with $F_p = 0$) yielded nearly identical results.

The difference between the predicted and observed temperature gradients indicates that the model is inadequate. One possibility is that the Lyman-$\alpha$ line is broadened by nonthermal motions due to upward propagating waves (e.g., review by Hollweg 1978). If we assume that the proton thermal velocity is given by the two fluid models (see Fig. 7), then the required nonthermal velocity between 3.5 and 4.0 $R_\odot$ (where the observed and calculated temperatures have the largest differences) is 100 km s$^{-1}$ for the model with the lowest proton temperatures (model with $\lambda = 2.0 \times 10^{35}$ particles s$^{-1}$). The
models with smaller values of $\lambda$ require lower velocities due to the smaller differences between the calculated and measured temperatures. The limiting value of 100 km s$^{-1}$ is approximately two-thirds the value suggested by Hollweg (1978) for these heights.

An alternative explanation for the difference between the calculated and empirical proton temperatures in Figure 7 is that there is some extended proton heating. We considered theoretical models with direct heating of the protons and found that such models could yield proton temperatures equal to those observed if a sufficiently large value for the energy deposition scale height was used. The required amount of heating is not large, for example a model having $F_p = 1.2 \times 10^4$ ergs cm$^{-2}$ s$^{-1}$ and $H_p = 4 \, R_\odot$ for protons (see eq. [9]) gave proton temperatures that track the empirical temperatures within the accuracy of the curve plotted in Figure 7.

As has been discussed by a number of authors (see review by Hollweg 1978), proton heating is needed at some point in the solar wind acceleration region or beyond in order to raise the proton temperature sufficiently to account for the values measured at 1 AU. The Lyman-$\alpha$ data suggest that this proton heating may begin in the solar wind acceleration region between 1.5 and 4 $R_\odot$.

When observations of a number of spectral lines besides hydrogen Lyman-$\alpha$ become available (see Kohl et al. 1981), it should be possible to separate out the effects of heating and nonthermal line broadening through comparison of the profiles of spectral lines from atoms or ions of different masses.

The observed decline of proton temperature with increasing radius has an additional significance. In a spherically symmetric static corona with steady state heating where there is no outflow of solar wind, the electron and proton temperatures will be equal for the densities considered here and vary as $r^n$ where $-0.3 < n < 0.3$. Hence the more rapid ($n \approx -0.8$) decrease of the proton temperature with height is evidence for the presence of solar wind outflow in the observed region of the corona.

VI. SUMMARY

Measurements of the profiles of resonantly scattered hydrogen Lyman-$\alpha$ radiation have been used to determine hydrogen kinetic temperatures from 1.5 to 4 $R_\odot$ in a quiet region of the solar corona. Since the shape of the Lyman-$\alpha$ profile is controlled by the velocity distribution of the hydrogen atoms in the line of sight, it provides a direct measurement of the hydrogen kinetic temperature. The hydrogen temperatures derived from the line widths decrease with height from $2.6 \times 10^6$ K at $r = 1.5 \, R_\odot$ to $1.2 \times 10^6$ K at $r = 4 \, R_\odot$. These measurements combined with temperatures derived by other methods for lower heights suggest that there is a maximum in the quiet coronal proton temperature at about 1.5 $R_\odot$.

The intensity of the $H \alpha$ Lyman-$\alpha$ line also contains information about the physical conditions in the solar corona. The Lyman-$\alpha$ intensity depends on the electron temperature, electron density, and solar wind velocity. Measured Lyman-$\alpha$ intensities were compared with intensities calculated using a representative model for the radial variation of the coronal electron density. We found that it was possible to obtain a good fit to the measured intensities for a range of electron temperature gradients (characterized by $-0.8 \leq n \leq 0.3$, where $T_e(r) \propto r^n$) for reasonable values of the assumed outward particle flux. The comparison with the model also suggests that the solar wind flow in the observed region was subsonic for $r < 4 \, R_\odot$. © American Astronomical Society • Provided by the NASA Astrophysics Data System
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The comparison between the Lyman-α observations and the predictions of a simple two fluid theoretical model provides some evidence for proton heating and/or a nonthermal contribution to the motions of coronal protons between 1.5 and 4 R\(_{\odot}\). Given the limitations of the simple two fluid model (e.g., spherically symmetric, homogeneous), this evidence is not conclusive; however, the results do suggest that the amount of proton heating, if present, is not large. Coronal observations, such as those presented here, place empirical constraints on models for the solar wind acceleration region. Determinations of basic plasma parameters of this region can provide, through detailed modeling, constraints on the magnitude and location of coronal heating and thereby place constraints on possible coronal heating and solar wind acceleration mechanisms.

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