MEASUREMENTS OF CORONAL KINETIC TEMPERATURES FROM 1.5 TO 3 SOLAR RADII

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ABSTRACT

A rocket-borne Lα coronagraph has been used to make the first measurements of the spectral line profile of resonantly scattered hydrogen Lα coronal radiation between 1.5 and 3 solar radii. These data provide, for the first time, direct measurements of coronal temperatures above 1.5 solar radii. Data were obtained in a coronal hole, quiet region, and streamer. The widths of the profiles from the quiet region decrease with height and correspond to a steady decrease in hydrogen kinetic temperature, with increasing radius, from about 2.5×10^6 K at $r \approx 2\,R_\odot$ to about 10^6 K at $r \approx 4\,R_\odot$. In the coronal hole the measured line widths indicate a kinetic temperature of 1.8×10^6 K at $r \approx 2.5\,R_\odot$.

Subject headings: line profiles — Sun: corona — Sun: solar wind

I. INTRODUCTION

The absence of empirical data on temperatures and mass flow velocities in the solar corona above 1.5 solar radii ($R_\odot$) from Sun center has resulted in significant gaps in the understanding of the physical nature of the solar corona. Of particular concern is the lack of information regarding the processes whereby energy is supplied to heat the corona and accelerate the solar wind. The discovery of resonantly scattered hydrogen Lα radiation from the solar corona during the 1970 solar eclipse (Gabriel *et al.* 1971) revealed a means of determining temperatures and mass flow velocities in this critical region of the solar atmosphere. The method depends upon measurement of the profiles and intensities of coronal resonance lines such as hydrogen Lα with simultaneous and cospatial measurements of the polarization and intensity of coronal visible light. To perform these measurements independently of solar eclipses, a Lα coronagraph with reflecting optics has been developed at the Harvard-Smithsonian Center for Astrophysics. This *Letter* describes preliminary results of the first rocket flight of this instrument which was flown jointly with a companion white-light coronagraph from the High Altitude Observatory.

II. INSTRUMENTATION

The Lα coronagraph instrument (Kohl, Reeves, and Kirkham 1978; Kohl *et al.* 1980) 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 occulting system which employs a rectangular entrance aperture with knife edges and an internal straight-edge occulter. The primary mirror is rotated in the direction of

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dispersion to select $0\rlap{.}''6 \times 4\rlap{.}''0$ spatial elements of the corona between 1.5 and 3.5 $R_\odot$ along a solar radial direction which is determined by the roll angle of the solar pointing control. The spectral resolution (FWHM) is 0.34 Å. The white-light coronagraph is designed to provide pictures of the white-light coronal structure at the time of the flight and measurements of the intensity and polarization of the electron-scattered visible radiation at the same positions observed by the UV instrument.

III. OBSERVATIONS

The primary objectives during the first flight on 1979 April 13, were the verification of the Lα coronagraph design and performance, including stray-light rejection and the measurement for the first time of the profile of resonantly scattered Lα radiation out to several solar radii from Sun center. All of these objectives were accomplished. The instrument performed flawlessly. Line profiles were measured at 1.5, 1.8, 2.0, 2.5, 3.0, and 3.5 $R_\odot$ in a quiet region, at 1.8 and 2.0 $R_\odot$ in a polar coronal hole and 1.5 $R_\odot$ in a streamer. In addition, measurements made at 3.5 $R_\odot$ in the coronal hole indicated that the stray-light level was extremely low, with an upper limit of 2×10^{-7} the intensity of the chromospheric Lα line measured on the disk. The intensity and profile of chromospheric Lα radiation were measured also. The data from all three coronal regions are of excellent quality; however, for this brief report we restrict our discussion to the measurements from the coronal hole and quiet region. Further details of the instrument, its calibration, and stray-light rejection properties are discussed by Kohl *et al.* (1980).

Figure 1 shows on the right the empirical Lα profile measured at $\rho = 1.8$ in a large coronal hole located at the south pole. (The parameter ρ is the distance in solar

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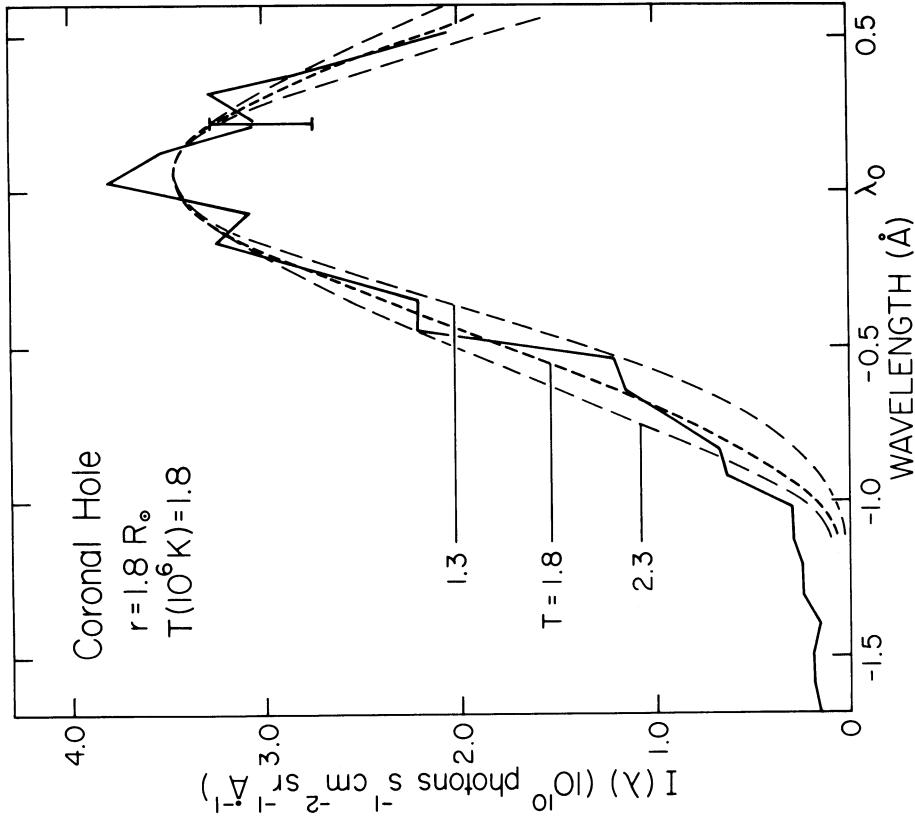FIG. 1.—Empirical Lα profile (*heavy line*) measured at ρ = 1.8 at the position indicated by small rectangles in the eclipse photograph (*upper left*) and a photograph from the HAO rocket white-light coronagraph (*lower left*). The dashed lines are theoretical profiles corresponding to coronal hydrogen temperatures of 1.3, 1.8, and 2.3 × 10⁶ K. The instrument terminated the scans at approximately halfway down the red wing of the line. 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 rectangle and the circle showing the location of the solar disk are artifacts caused by stray light.
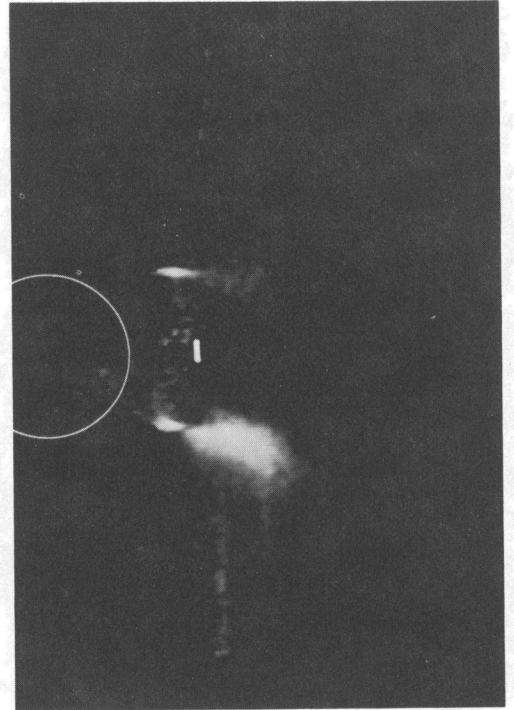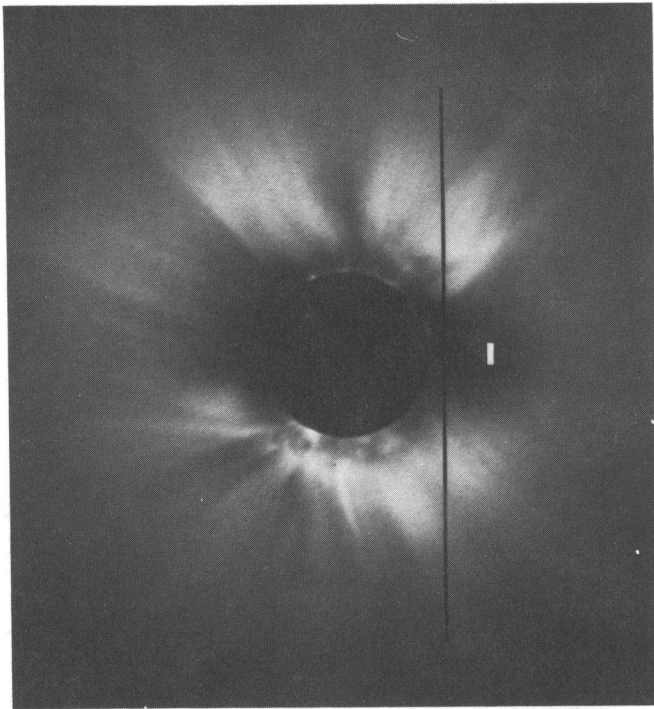
radii from Sun center to the point where the line of sight intersects the plane of the solar disk.) On the upper left is a white-light picture of the 1979 February 26 eclipse provided by C. F. Keller, Jr., from the Los Alamos Scientific Laboratory. Because the rocket flight occurred approximately 1.5 solar rotations after the eclipse, this picture can be used as an approximate illustration of some of the more stable features in the corona at the time of our observations. The small white rectangle in this photograph marks the projection of the spectrometer slit for the observation at 1.8 $R_\odot$; and the straight line extending from left to right, the corresponding position of the primary occulting edge of the UV instrument. In the lower left is a picture 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 Lα instrument, it observes only that portion of the corona beyond the occulting edge. The pointing coordinates for the rocket flight were chosen by using data from the Naval Research Laboratory white-light coronagraph on the US Air Force satellite *P78-1* (see Sheeley *et al.* 1980) and from ground-based observations made with the HAO coronal emission-line polarimeter (KELP) at the Sacramento Peak Observatory.

The shape of the Lα profile depends on the velocity distribution of the hydrogen atoms along the line of sight and, hence, provides information on the hydrogen kinetic temperature of the coronal plasma. The profile measured in the coronal hole at $\rho = 1.8$ is very nearly Gaussian. A least-squares fit of a Gaussian curve to the measured profile yields a halfwidth $(1/e)$ of 0.64 Å (corrected for instrumental broadening of 0.03 Å). If we ignore the effect on the profile due to details of the resonant scattering process (which makes the profile narrower than a profile whose shape is controlled only by the velocity distribution of coronal hydrogen atoms, see Beckers and Chipman 1974) and possible variations in temperature along the line of sight, the above width corresponds to a kinetic temperature of 1.5×10^6 K. Inclusion of the effects of the resonant scattering process (assuming a spherically symmetric corona) results in a 20% correction to this temperature raising it to a value of 1.8×10^6 K. Curves for $\pm 0.5 \times 10^6$ K are also shown. The fitting errors are about 2.5×10^5 K. A similar analysis of the profile measured at $\rho = 2.0$ in the coronal hole yields nearly the same temperature (within the fitting errors), 1.9×10^6 K.

The above kinetic temperatures as defined here include the effects of thermal motions, turbulent motions, and outflow of coronal plasma into the solar wind. Since the thermal velocity of hydrogen atoms in a 1.8×10^6 K plasma is 170 km s^{-1}, while measured turbulent velocities in the low corona typically have values of the order of 25–30 km s^{-1}, the effects of turbulent broadening are likely to be small. However, outflow of coronal plasma could introduce significant broadening of profiles in a coronal hole where the outflow velocities can be large even close to the solar surface (e.g., Kopp and Orrall 1976; Munro and Jackson 1977). For a radially directed flow, the plasma

in the line of sight on the observer's side of the plane that is through Sun center and perpendicular to the line of sight will have a velocity component toward the observer, while the plasma on the opposite side of this plane will have a velocity component directed away from the observer. This tends to broaden the profile with the magnitude of the broadening depending on the details of the resonant scattering process (see Beckers and Chipman 1974). For this reason, the temperature determined above, 1.8×10^6 K, is the maximum proton thermal temperature. Correction for the presence of turbulent and/or outflow velocities will yield lower temperatures. For example, in the Kopp and Orrall (1976) model the outflow velocities over the range of heights where the Lα line is formed (for a line of sight with $\rho = 1.8$) fall between 10 and 100 km s^{-1}. If we take the upper limit of these values, 100 km s^{-1}, we find that the proton thermal temperature, derived from the Lα profile, is reduced to 1.4×10^6 K. A hydrogen temperature between 1.4 and 1.8×10^6 K at distances near 2.0 $R_\odot$ is significantly higher than the "ionization" temperatures (1.0 to 1.1×10^6 K) typically found near the base ($r \approx 1.1 R_\odot$) of coronal holes from measurements of EUV spectral line intensities (which yield temperatures depending primarily on the ionization balance, see Munro and Withbroe 1972; Withbroe and Wang 1972; Mariska 1978). This suggests that there may be significant coronal heating between 1.1 and 2.0 $R_\odot$ in these regions.

It is of interest to compare the Lα measurements with the semiempirical model for a polar coronal hole derived by Munro and Jackson (1977) from measurements made in 1973 by the *Skylab* white-light coronagraph. The white-light data were used to determine the electron density as a function of height in the coronal hole. Using these densities and an assumed outward mass flux driven by *thermal pressure only*, Munro and Jackson deduced the variation of proton kinetic temperature with height for a series of models with different assumed gas pressures at the upper boundary. This yielded a family of curves with temperatures between 2.4 and 3.1×10^6 K at the distance ($r = 2.3$ to 2.6 $R_\odot$) corresponding to the mean distance over which the Lα line is formed for lines of sight corresponding to $\rho = 1.8$ and 2.0. The maximum temperatures (calculated assuming no nonthermal broadening) deduced from the Lα profiles, 1.8×10^6 K at $\rho = 1.8$ and 1.9×10^6 K at $\rho = 2.0$, are lower than those of the model by 0.6 to 1.2×10^6 K. If the effects of the large outflow velocities in the Munro-Jackson model are included, the difference is even larger, since, for example, the Lα width calculated with the Munro-Jackson model for $\rho = 2.0$ is 0.8 Å, a value substantially larger than the 0.65 Å width observed. This suggests that either (*a*) the temperatures in the Munro-Jackson model are too high because there exist accelerating forces in the solar wind other than those due to gas pressure and gravitational forces (e.g., momentum transfer by mechanisms such as wave-pressure gradients), or (*b*) the outflow velocities in the model are too high, or (*c*) the polar hole observed in the 1979 April rocket flight has lower temperatures and outflow
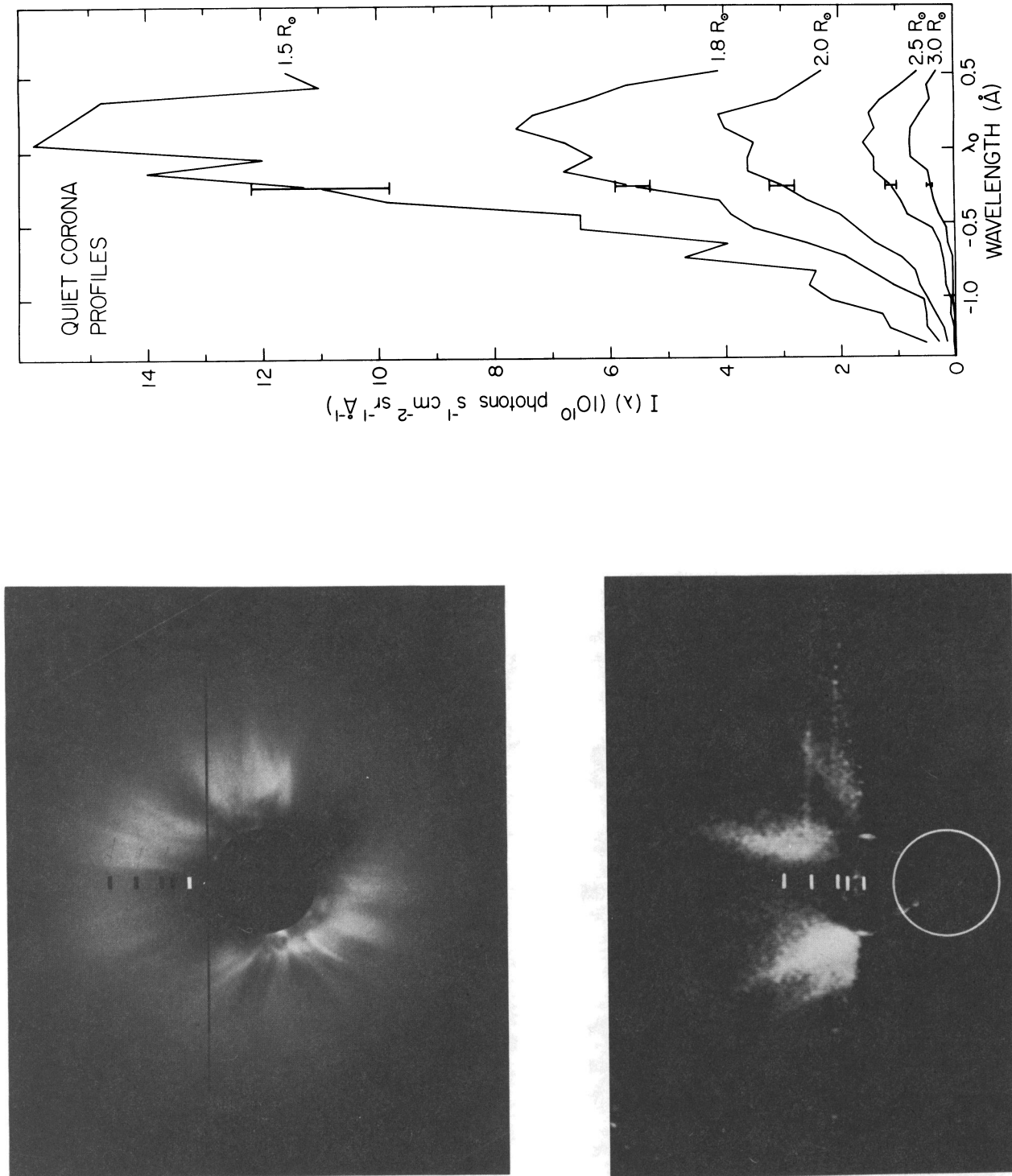
QUIET CORONA
PROFILES

1.5 R⊙

1.8 R⊙

2.0 R⊙

2.5 R⊙
3.0 R⊙

I (λ) (10¹⁰ photons s⁻¹ cm⁻² sr⁻¹ Å⁻¹)

WAVELENGTH (Å)

FIG. 2.—Empirical Lα profiles measured in a quiet region at the positions indicated by the small rectangles in the eclipse photograph (*upper left*) and in the rocket white-light picture (*lower left*).

velocities than the 1973 polar hole modeled by Munro and Jackson. We are developing an empirical model based on the measurements of the Lα profiles and intensities. The results of this work will be reported in a future paper.

One of the unexplained features of the empirical Lα profiles is that they appear to have extended non-Gaussian wings (see Fig. 1). At the present time we have been unable to attribute this to any known instrumental effect. It is much too intense to be due to electron scattering of the chromospheric Lα radiation. However, it is premature to attribute this feature to a high-velocity tail in the hydrogen velocity distribution because of the possibility that it may be due to un-explained low-level noise in the telemetry data. One of the objectives of the second flight of the rocket pay-load, which was flown successfully on 1980 February 16, was to obtain improved measurements of the Lα line wings. The data from this flight are presently being processed.

Figure 2 shows profiles measured at several radial positions in a quiet region. The locations of these positions with respect to the coronal structure are illustrated approximately by the white-light eclipse and rocket coronagraph pictures on the left. A least-squares fit of Gaussian curves to these profiles yielded line widths ($1/e$ halfwidth) of 0.71, 0.67, 0.65, 0.51, and 0.45 Å at, respectively, $\rho = 1.5, 1.8, 2.0, 2.5$, and 3.0. (Because the profile measured at $\rho = 3.5$ is less reliable than the others because of increased statistical fluctuations and contamination by emission from the geocorona, it has not been used in this analysis.) A preliminary analysis of these profiles, taking into account the effects of the contribution of the geocoronal emission (which slightly increases the central intensities of the profiles at $\rho = 2.5$ and 3.0 $R_\odot$), indicates that the decrease in line width corresponds to a steady decrease of the coronal temperature with increasing radius from about 2.5×10^6 K at $r \approx 2$ $R_\odot$ to about 10^6 K at $r \approx 4$ $R_\odot$. This suggests that there is a temperature maximum in the quiet corona located at or below 2.0 $R_\odot$. Theoretical studies (see review by Hollweg

1978) indicate that the proton temperature (which is obtained from the Lα profile) may decrease more rapidly with increasing distance from the Sun than the electron temperature (which controls the hydrogen ionization balance and hence affects the Lα intensities). A more detailed investigation of the Lα profiles and intensities should yield some insights concerning possible differences in these two temperatures.

It is interesting to note that a detailed study of EUV emission gradients by Mariska and Withbroe (1978) provided evidence for a positive temperature gradient between 1.0 and 1.4 $R_\odot$, with the "ionization" temperature reaching about 2.5×10^6 K at $r = 1.4$ $R_\odot$. This result, combined with the information provided by the measurements of the Lα profiles, suggests that the maximum hydrogen temperature in the inner quiet corona ($r \lesssim 4$ $R_\odot$) has a value of about 2.5×10^6 K and that it is located between 1.5 and 2.0 $R_\odot$ from Sun center. If this hypothesis is confirmed by more detailed analysis of the Lα profiles and intensities, it indicates that most of the nonradiative energy heating the inner quiet coronal plasma is released within about one solar radius of the surface.

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