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THE RADIAL GRADIENTS AND COLLISIONAL PROPERTIES
OF SOLAR WIND ELECTRONS

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ABSTRACT

The plasma instrument on Mariner 10 carried out measurements of electron density and temperature in the interplanetary medium between heliocentric distances of 0.85 and 0.45 AU. Due to the stable coronal configuration and low solar activity during the period of observation [January 9 to March 30, 1974], the radial variations of these quantities could be obtained. The power-law exponent of the core temperature was measured to be -0.3 ± 0.04 , and the halo temperature was found to be almost independent of heliocentric distance. The exponent of the power law for the density variation was 2.5 ± 0.2 and the extrapolated value at 1 AU was consistent with measured values during the same period. Calculations of the core electron self-collision time, and the core-halo equipartition time were made as a function of radial distance. These measurements indicate a macroscale picture of a Coulomb-collisional core and a collisionless isothermal halo. Extrapolating back to the sun, core and halo temperatures become equal at a radial distance of $\sim 2-15$ solar radii. Temperature variations were observed at the time of passage of high speed streams, and at the time of observation of stream interfaces, where the density falls before the temperature, Coulomb collisions in the core become much less important and the halo density is observed to decrease by more than an order of magnitude.

INTRODUCTION

In this paper we discuss the properties of the solar wind electrons measured by the electron spectrometer on Mariner 10. These observations were made continuously during a period of 80 days, or about $2\frac{1}{2}$ solar rotation periods, during which the spacecraft moved from a heliocentric distance of 0.85 to 0.45 AU. There were well-marked repetitive corotating high speed streams and rarefactions during this time, and the characteristic density variations (Burlaga et al., 1978) were observed. The electron distribution function observed for electrons propagating toward the sun almost always has a suprathermal (halo) population distinguishable from the thermal (core) population, as has been observed on other satellites in earth orbit for some years (Montgomery et al., 1968).

Variations in both core and halo "temperatures", of amplitude greater than 50% of their nominal values, were observed superimposed upon the corresponding heliocentric radial variations.

These observations bear on the nature of the solar wind electron distribution function, especially the relationship between the core and halo components. The radial dependences of density and "temperature", the variations associated with streams on the macroscale, and some information on smaller scale properties, will be discussed. The broad picture is of a collisional core distribution, whose heliocentric "temperature" variation approximates $r^{-2/7}$, coexisting with an approximately isothermal Coulomb-collisionless halo distribution. Both components exist at all radial distances and show stream-associated variations, which may be either induced by boundary condition changes or dynamical effects.

Since Parker's (1963) discussion it has been generally assumed that solar wind electrons are collisional. In some theories (Hollweg, 1970; Jockers, 1970 models 2, 3 and 4) the electrons are treated as a fluid everywhere and the protons are collisionless above some level in the corona; in others the solar wind is considered as consisting of two components which are collisionless above a baropause (Lemaire and Scherrer, 1971). The collision-dominated region for electrons then extends to a greater radial distance R than the collision-dominated region for protons. In addition to Coulomb collisions, instabilities and wave particle interactions are often invoked to reduce the electron temperature anisotropy to the observed value of between one or two. The present observations show quantitatively that the core of the electron distribution function can be described as collisional at least for radial distances within 1 AU, since, with a very few well-marked exceptions associated with high speed streams, the Coulomb collisional relaxation length is less than the density scale height at all times and all radial distances, R , at which data were obtained. It is found that Coulomb collisions between the core and the (test) halo population are negligible, and there is an observable tendency for both core-core and core-halo collisions to become less important with increasing radial distance.

OBSERVATIONS

The plasma electron detector on Mariner 10 has been described before (Bridge et al., 1974); its energy range (13 eV to 700 eV) was divided into 15 differential channels which were sampled cyclically at a rate

of one every 0.4 seconds, a spectrum of electrons being acquired every six seconds. The "temperatures" together with values of density, speed, and spacecraft potential, were obtained by a self-consistent method to be described elsewhere. The core "temperatures", T_c , were deduced from least square fits of $\text{Log}(f_{\text{obs}}) = A - E/kT_c$, over the energy range 13 eV to 40 eV. The halo "temperatures", T_H , were obtained from similar fits over the range 94 eV to the energy at which the counting rate of the detector fell to zero, generally about 400 eV, thus avoiding the region of changing slope for all values of break point energy below 95 eV (Feldman et al., 1975). The present discussion is based upon hourly averages of these six-minute self-consistent estimates, each of which is derived from at least three scanning cycles of the instrument.

Hourly average values of the spacecraft potential are shown in the top panel of Figure 1. We note that it has been shown that such a positive potential should not affect values of temperature derived from measurements of an isotropic Maxwellian velocity distribution for energies numerically above this potential (Mott-Smith and Langmuir, 1927). We see that the spacecraft potential remained constant within $\pm 0.5\text{v}$ at about 22 volts for the first part of the mission, followed by a discontinuous reduction to values in the range of 8.5 to 12 volts, depending upon conditions in the interplanetary medium; potentials in this lower range persisted for the rest of the flight. The discontinuous change occurred at the same time as an engineering change on the spacecraft.

Besides the spacecraft potential, Figure 1 shows hourly average values of the total density, core temperature and halo temperature, as a function of R. Time goes from right to left in Figure 1, and the decimal

day numbers of year 1974 are shown at the top. The positions of sector boundaries are also indicated by vertical broken lines, and solid vertical lines are used to draw attention to the times when T_H/T_C becomes small.

RADIAL VARIATION OF ELECTRON DENSITIES AND TEMPERATURES

In making determinations of the radial dependence of a quantity, especially from observations taken with a single spacecraft, it is difficult to separate the required spatial variation from competing temporal variations. It is usually assumed that the major temporal variations are introduced as a result of solar rotation, which causes periodic changes in the quantity measured at a given radius due to the effects of co-rotating streams. Averages of quantities over solar rotations, referred to the mean position of the spacecraft, are sometimes used (Gringauz, 1975), or the quantities are examined at approximately the same solar longitude but different distances. Unless the stream structure remains strictly constant however, these procedures remove only some of the systematic, non-radial, variations so that the resultant radial variation is hard to determine with precision. Furthermore, to use averages over solar rotations, the rate of change of R with time should be small enough for the range in R associated with a given solar rotation to be a small fraction of the total range in R covered by the measurements. This condition was not met on Mariner 10. The use of two spacecraft at different radial distances is, even when possible, subject to the necessity of making co-rotational and delay corrections, which may involve latitudinal complications (Schwenn et al.,

1977). It is therefore not immediately clear that this procedure is superior to the single spacecraft method. For the present measurements, a power law was assumed to describe the mean radial dependences of the two temperatures and the density, and the exponents were determined using several methods of data analysis.

During the time period November 1973 through January 1974, just preceding these observations, there was low solar activity and a relatively stable and simple coronal configuration, as determined by the Skylab experiments. Figure 2 shows the situation during Carrington rotations, 1608, 1609 and 1610, November 14 to February 1, 1974. with three coronal holes, labeled 7, 4 and 2, 7 and 2 being associated with the polar coronal hole structures. Behannon (1976) has discussed the characteristics of the interplanetary magnetic field at this time, also finding a very stable configuration with two sectors. The average magnetic field azimuth direction ϕ varied during the whole mission from $\sim 315^\circ$ at 1 AU to $\sim 350^\circ$ at 0.45 AU in one sector, and from $\sim 135^\circ$ at 1 AU to $\sim 150^\circ$ at 0.45 AU in the other. The sector structure remained the same for the second part of our observation period, from February 1 to April 1, 1974. The C9 index, as illustrated by Burlaga and Lepping (1978), showed no discontinuities during this period, justifying the assumption made here that the coronal structures, and by inference interplanetary streams, remained largely unchanged for the whole period of observation.

In view of this unusually stable situation, attempts were made to fit all the more than 1600 hourly average determinations to a relation of the form $\text{Log } x = \alpha \text{ Log } R + \beta$ by the method of linear least squares.

The results are listed in Table 1. The errors quoted are the standard deviations, and we see from the first column that the derived exponent for the density is within three standard deviations of the expected value of -2, that the exponent of the core temperature is, -0.3 ± 0.04 only slightly exceeding $-2/7$ ($=0.286$), predicted for a spherically-symmetric Coulomb-conduction dominated expansion, and that there seems to be a tendency for the halo temperature to increase slightly as R increases. The restricted data set referred to in the second column of Table 1 differs from the full set only in having the measurements made during the high speed streams at $R = 0.77, 0.71, 0.66$ and 0.48 arbitrarily removed. The three periods of restricted data leading to the exponents quoted in the third column of Table 2 are the most widely separated corresponding 100 degree intervals of solar rotation available in the data. These were chosen to give the maximum separation in radius, to be used in the same way as solar rotation averages, and were centered at $R = 0.79, 0.66,$ and 0.49 respectively. Although all three methods of analysis yield consistent results, the most reliable determination will be taken to be that for the full data set. Analysis of each half of this set separately produces results consistent with, but of lower precision than, analysis of the full set. Thus the core temperature, T_c is characterized by a radial variation with an exponent of -0.3 , while the halo temperature, T_H , increases with radius with exponent $+0.17$. The different radial variation of core and halo temperatures emphasizes the normally weak local coupling on the macroscale between these components of the electron population. The predicted values of T_c and T_H at 1 AU are $0.97 \pm 0.2 \times 10^{50}$ K and $6.7 \pm 0.5 \times 10^{50}$ K respectively. The measure-

ments of Feldman et al. (1975) show the average value of T_c to vary with bulk speed over the range 1.25 to 0.9×10^{50} K; with a time average of $1.24 \pm 0.3 \times 10^{50}$ K. Agreement is satisfactory, especially since the bulk speeds measured during the period of observation are, on the average, high.

The observed positive exponent relating the slope of the distribution of the halo electrons to the radial distance is particularly interesting, because, if real, it indicates that a substantial modification of the characteristics of these electrons may be taking place in the interplanetary medium itself. There is an indication, however, that the apparent mean rise in T_H might simply be due to there having been fewer downward excursions at the larger radii, and the fact that the spacecraft spent more time there, rather than to a radial dependence of the average halo temperature.

If we accept the experimentally determined radial variation of T_H and T_c , and project back towards the sun from 1 AU with a slope of -0.3, the two temperatures become equal at a radial distance of a few solar radii. This fact is consistent with both components having a common origin as a distribution having a single temperature in the corona, but of course does not prove this assertion. As the spacecraft moves from 1 AU inwards the mean temperature over the instrumental scan has a tendency to increase as a result of including more measurements taken near the direction of $T_{||}$, and less near the direction of T_{\perp} . Thus, the measured exponent is systematically biased to be larger than the "real"

exponent; estimates based on an ellipsoidal temperature distribution indicate that this effect might be as large as 5%, out of a total effect of 25%.

The best-fit predicted density at 1 AU is $5 \pm 2 \text{ cm}^3$. The density measured at 1 AU averaged over the entire year 1974 was $7.8 \text{ cm}^3 \pm 1$ (J. King, private communication). The time interval of Mariner 10 was characterized by higher than average bulk speed; density and speed are usually anti-correlated, leading one to expect values lower than the corresponding yearly averages. Furthermore, density calibrations are rarely more accurate than 20%; typically, instruments on the same spacecraft disagree at this level of precision. Given the size of the spacecraft potential corrections to this data the level of external corroboration is quite satisfactory.

Figure 3 shows T_c , T_H and T_H/T_c plotted against degrees of solar rotation, and these observations have a number of interesting smaller scale features besides the periodicity to which we have previously referred. The halo temperature T_H , shows fluctuations as large as the core temperature, T_c . We see from Figure 3 that in the high density precursors of streams the halo temperature is reduced to $T_H \approx 4 \times 10^{50} \text{ K}$ or below, whereas between them it relaxes back up to $T_H \approx 8 \times 10^{50} \text{ K}$; nevertheless, T_H/T_c remains remarkably more constant than either T_H or T_c . Although these variations are approximately in phase with one another, there are multiple examples (at C1, etc.) when T_H/T_c becomes small. Since we will show that collisions between core and halo, and between halo electrons themselves, are negligible, any local coupling indicated by these observations must be attributed to wave-particle

interactions in the solar wind. These are associated with the streams (see below for further discussion) rather than with the large scale solar wind expansion, however, since they do not succeed in equalizing the radial variations of the temperatures of the two components. There is no great systematic change in amplitude of the fluctuations of either T_H or T_c over the heliocentric radial range studied.

There are generally small changes in N , T_c , and T_H at the times of passage past the spacecraft of sector boundaries, shown as dotted lines in Figures 1 and 3. However, these changes do not exceed the general level of fluctuation; the large changes at $R = 0.778$ appear to be coincidental. This is in agreement with the identification of sector boundaries as the lines of demarcation between regions in the interplanetary medium, connected to coronal regions of opposite polarity, across which there may or may not be differences in the plasma parameters.

Figure 4 shows a plot of N , T_d/T_c and T_H for three successive rotations of an individual high-speed stream, observed when the spacecraft was at 0.775 AU (A), 0.63 AU (B), and 0.485 AU (C) respectively. In panel A (0.775 AU), we note that while T_c , like the proton temperature maximizes between the density and bulk speed maxima, T_H maximizes at the leading edge of the density compression. This behavior has been noted at 1 AU by Feldman et al. (1975). Panels B and C, showing observations of the same long-lived stream, indicate a change in the behavior of T_H closer to the sun: after the sharp maximum in T_H there is a very marked drop below the ambient value, so that T_H/T_c approaches unity for a few hours, after the density compression. Instances when T_H/T_c suddenly

decreased to values close to unity were associated with co-rotating streams [in stream interface regions, Ogilvie and Scudder 1976, Gosling *et al.* (1977)] of which there were two per solar rotation. These are numbered A1, A2; B1, B2; C2, in Figure 3; number 1 is the least pronounced and disappears between rotations B and C. Both numbers 1 and 2 appear in the negative sector, and we associate flows from coronal hole 2 with feature 2 in Figure 3 because of the negative magnetic polarity and its time of occurrence; feature 1 is then probably associated with the material from the polar coronal hole.

Figure 5 shows two electron distribution functions, observed at $R = 0.6338$ AU, corresponding to B2 in Figure 1, and at $R = 0.4580$ AU, corresponding to C2 in Figure 1, compared to a "normal" solar wind distribution function which shows a pronounced break at ≈ 70 eV, separating the core from the halo. The "unusual" distribution functions are typical of those observed at times when T_H/T_C tended towards unity. Figure 5 indicates that the apparent change in T_H/T_C during these times is mainly due to a very marked change in the break-point energy, which increases to ≈ 200 eV. A halo with a temperature of $6-7 \times 10^5$ K still exists at these times, but its density is apparently reduced by at least an order of magnitude. Electrons with energies between ~ 70 eV and ~ 200 eV, which were formally part of the halo, now have the same temperature as the lower energy core electrons, and the distribution functions are also less good fits to maxwellians than the 'usual' distributions. Thus during these events when T_H/T_C apparently tends towards unity what is really happening is that as the core temperature increases

the halo density decreases. We must keep in mind that all the electrons observed by this experiment were moving in the anti-solar direction; observations at angles up to 70° to this direction show the same qualitative result, but large temperature anisotropy exists in the core. We cannot make a distinction between a local and a coronal cause without measurements in at least the solar and anti-solar directions.

The initial results of the plasma experiment on the Helios mission (Rosenbauer, 1977) indicated an occasional distortion of the distribution function in the energy region ≈ 100 eV along the direction of the magnetic field. This has been ascribed to electrons flowing away from the sun and having the effect of filling in the break in the distribution function. This effect occurs predominantly at the front of high speed streams, and it has been suggested that electrons forming this 'strahl' have arrived at the point of observation without collisions, reflections, or pitch-angle scattering; anti-strahl electrons have occasionally been observed (Phillip, private communication). Since the present experiment observes electrons in motion towards the sun, direct observation of the strahl would require a re-entrant magnetic field configuration, which is expected to be a rare occurrence; nonetheless we do observe at times that the electron distribution function is characterized by a single temperature up to energies of ~ 200 eV. An anti-strahl could, of course, have been observed; Behannon (1976) showed that the elevation angle θ of the magnetic field remained sufficiently small that an appreciable portion of a re-entrant strahl of width greater than $\pm 30^{\circ}$ would have been detected within the sensitive angle of the instrument (± 13.5 degrees) for essentially all of the mission.

RADIAL VARIATION OF COLLISIONAL PROPERTIES OF ELECTRONS

In order to examine the importance of Coulomb interactions in the core of the electron distribution and between the core and the halo, we have calculated two quantities of the form

$$\xi = W \cdot t/L$$

For each of these the value of L , the density scale height, is taken to be equal to $R/2$, corresponding to inverse square density variation.

For ξ_{CORE} , W represents the thermal speed of core electrons and $t = t_c$ the self-collision time (Spitzer, 1962). For ξ_{Hc} , W represents the thermal speed of a halo electron and $t = t_{\text{eq}}$, the time required for energy equipartition to take place between two Maxwellian distributions of electrons with temperatures equal to those of the core and halo respectively. A value of $\xi < 1$ characterizes a population in which Coulomb interactions are important in determining the properties, especially the transport properties, of the population. The calculated values of the two quantities for the duration of the mission are plotted in Figure 6. The center panel indicates a rising trend for ξ_{CORE} , but its absolute value is such that the core population remains collisional at all the radial distances at which the measurements were made. There is thus no problem in accounting for the low value of temperature anisotropy observed for the core electrons, since the distribution is presumably Maxwellian in the corona. One might anticipate a radical change in the electron distribution function beyond 2 or 3 AU, but no relevant measurements are currently available. Figure 6 shows a

peak in the value of ξ_{CORE} associated with our events A1 etc., during which the value of ξ_{CORE} rises considerably above unity. At the leading edge of high-speed streams the electron temperature rises and remains high even after the density has dropped following the density spike. Since $\xi \propto T^2/n$, ξ_{CORE} increases during this interval, indicating that the Coulomb collisions become less important in the region of the stream interface, as suggested by Ogilvie and Scudder (1976), and is implicit in the results of Gosling et al. (1977). As expected, Coulomb interactions between the core and the 'test' halo electrons are unimportant at all radial distances and during all the variable solar wind conditions sampled by Mariner 10. There appears to be a trend for ξ_{HC} to increase with increasing heliocentric radius. Taking $\xi_{\text{HC}} = 20.0$ at $R = 110$ solar radii and using the estimated radial dependencies of T_c and n , ξ_{HC} would approximate unity at ~ 13 solar radii. At smaller radii a single collision-dominated velocity distribution function for electrons should exist.

CONCLUSIONS

We have presented direct and indirect evidence of the radial variation of solar wind electrons by Mariner 10 in the radial range from 0.45 to 1.0 AU. For the present study we have used the core-halo, two-component, description of the distribution function to facilitate comparison with 1 AU data. Due to the well-documented, regular stream structure throughout the interval of these measurements, we believe that we can separate the two effects sufficiently well to present a picture in which the core, between members of which Coulomb collisions are almost always important, shows a radial temperature variation described by a

power law with an exponent ≈ -0.3 . This variation is very nearly that expected for a Coulomb conduction dominated spherically symmetric solar wind solution $2/7 = 0.286$. The halo, always collisionless, has a temperature which remains constant or rises slightly as a function of heliocentric distance. Simple extrapolation leads to the conclusion that this two-component distribution likely originates from one characterized by a single temperature at a distance of between 2 and $\sim 15 R_{\odot}$. Independent support for the results of the radial variation measurements is provided by the direct calculations of the importance of Coulomb collisions in the two populations. The core population is generally strongly influenced by Coulomb collisions, as indicated, for example, by their participation in stream interactions while the halo has little local Coulomb interaction with the core. The existence of correlated variations in core and halo temperatures, taken together with the typical value of ξ_{HC} , shows that wave-particle coupling or temporal coronal source variations connect the properties of halo and core electrons. We find that the presence of streams and changes in coronal boundary conditions introduce large fluctuations in the temperatures of both components. These fluctuations are, however, superimposed and upon and may mask characteristic radial variations. The signatures of the stream-associated temperature and density fluctuations are similar at 1 AU to those described by Feldman et al. (1975) and Gosling et al. (1977), but closer to the sun the density enhancements are followed by periods when the distribution function approximates a single Maxwellian form more closely, and the halo shows a drop in density by more than an order of magnitude. At these times, at the passage of the stream interface, the importance of local Coulomb collisions between

core electrons is greatly diminished. The radial temperature variation of the core appears from our measurements to be consistent with a picture in which solar wind electrons make a transition from conduction-dominated expansion $T \propto r^{-2/7}$ close to the sun to adiabatic expansion far from the sun. Measurements in the radial range 1.0 to 1.5 AU carried out by Gringauz and Verigin (1975), giving an exponent of -0.5, are consistent with the present measurements and place the adiabatic region at least beyond the orbit of Mars.

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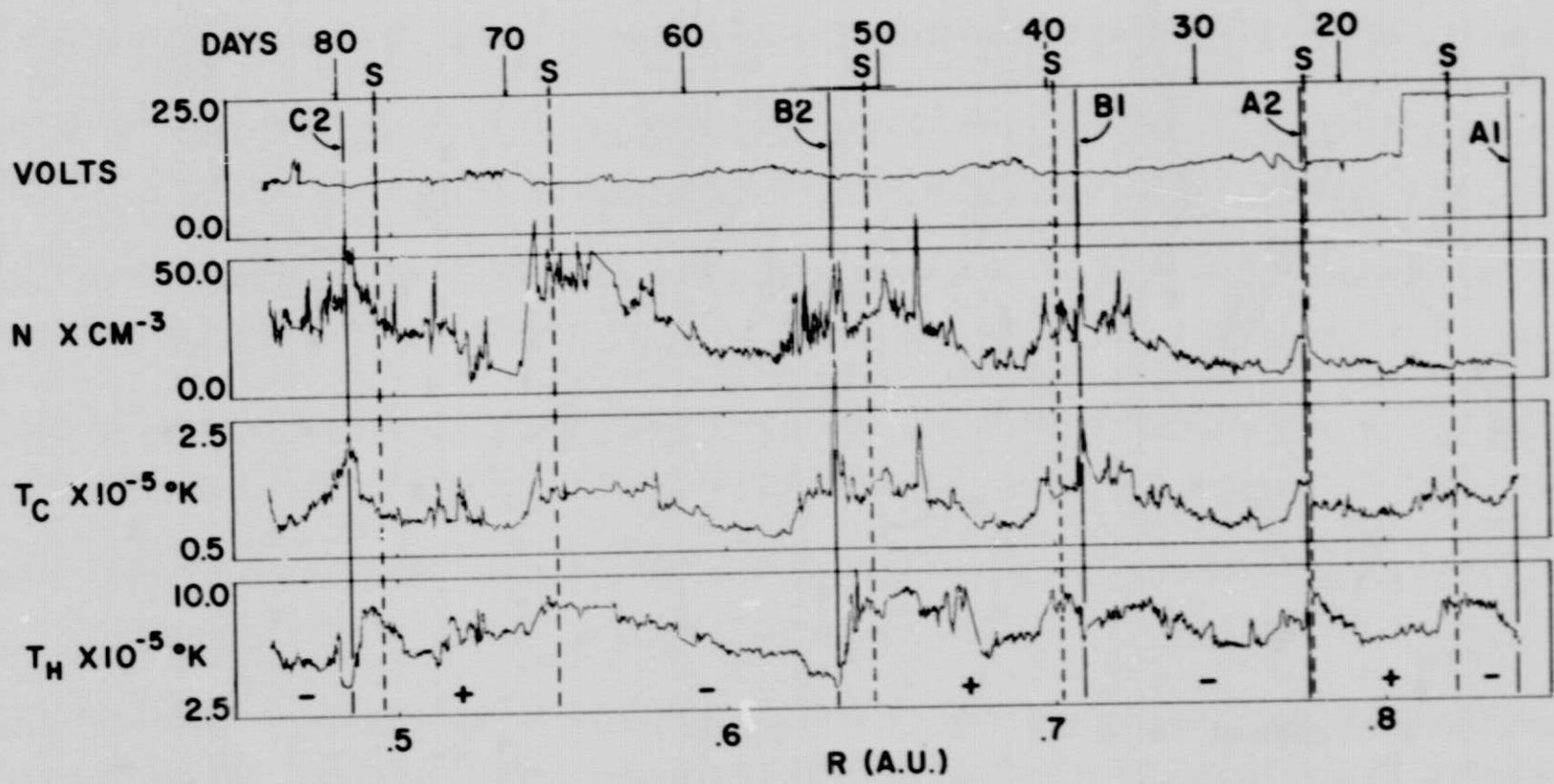
TABLE 1

RADIAL VARIATIONS--EXPONENTS

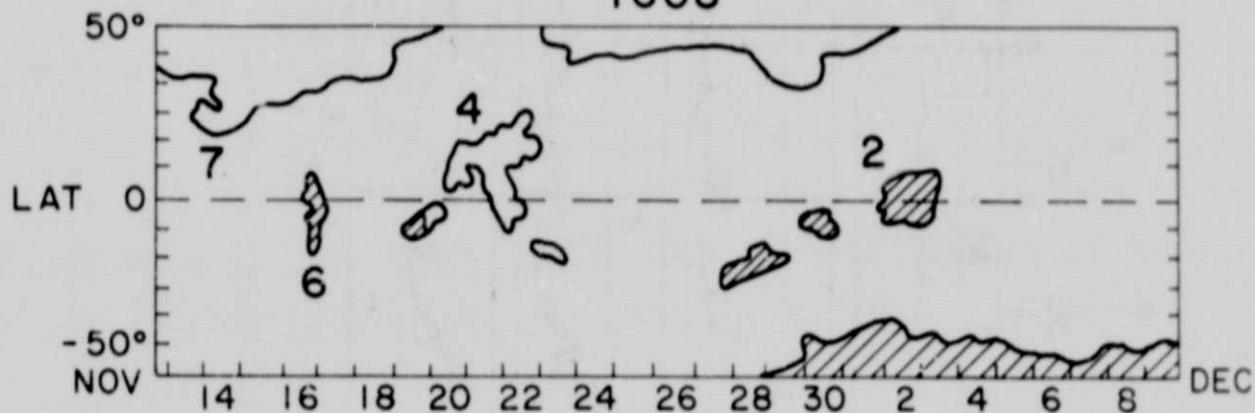
| <u>Quantity</u> | <u>All Data vs. R Directly</u> | <u>Restricted Data vs. R</u> | <u>Restricted Data for 3 periods vs. R</u> |
|---------------------|------------------------------------|----------------------------------|--|
| Electron Density | -2.5 ± 0.15 | -1.75 ± 0.12 | -2.5 ± 0.5 |
| Electron Core Temp. | -0.3 ± .04 | -.21 ± 0.04 | -0.52 ± 0.17 |
| Electron Halo Temp. | +0.15 ± 0.05 | +0.08 ± .03 | +0.22 ± 0.16 |

FIGURE CAPTIONS

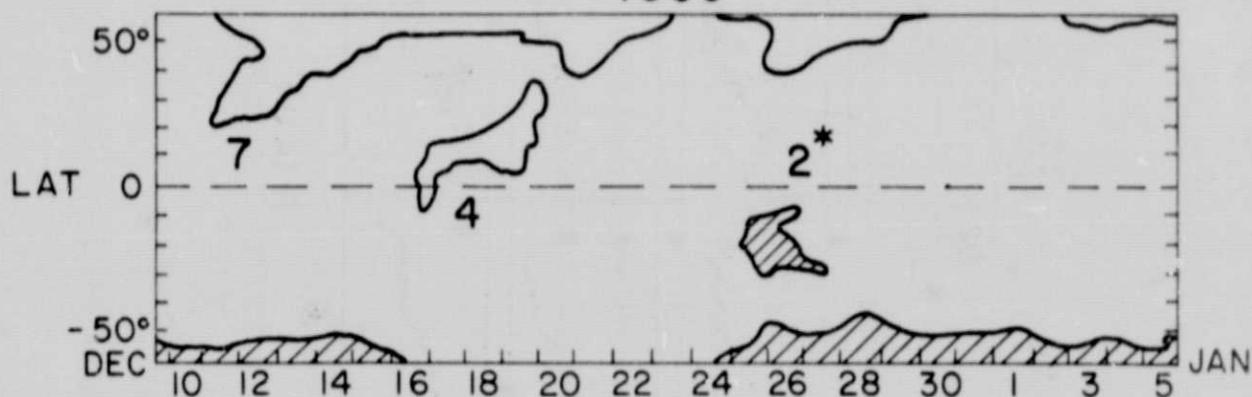
- Figure 1 Mariner-10 electron plasma observations plotted as a function of heliocentric radius, (R). The quantities are hourly averages of 6-second measurements: In order from the top, spacecraft potential; core temperature; halo temperature; times of sector boundary crossings are indicated by vertical broken lines, and solid vertical lines indicate times when T_H/T_C becomes small.
- Figure 2 Coronal hole structures, after Burlaga, 1977, covering the period November 14, 1973 to February 1, 1974.
- Figure 3 Hourly averages of core temperature, halo temperature and the ratio T_H/T_C , plotted against solar longitude.
- Figure 4 Plots of observations of density, T_H/T_C and T_S for three successive rotations of an individual high speed stream, made at $R = 0.755$ AU (A), 0.63 AU (B), and 0.485 AU (C).
- Figure 5 Electron distribution functions measured at $R = 0.6338$ AU (B2 in Figure 1) and at 0.4580 AU (C2 in Figure 1) compared to a "normal" distribution function.
- Figure 6 Values of T_H/T_C , ξ_{CORE} and ξ_{CH} plotted as a function of solar longitude.



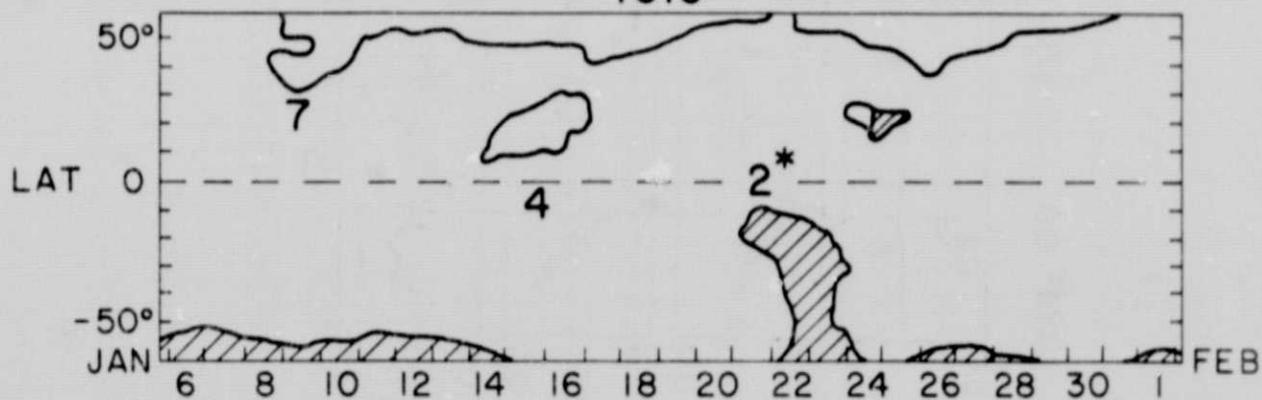
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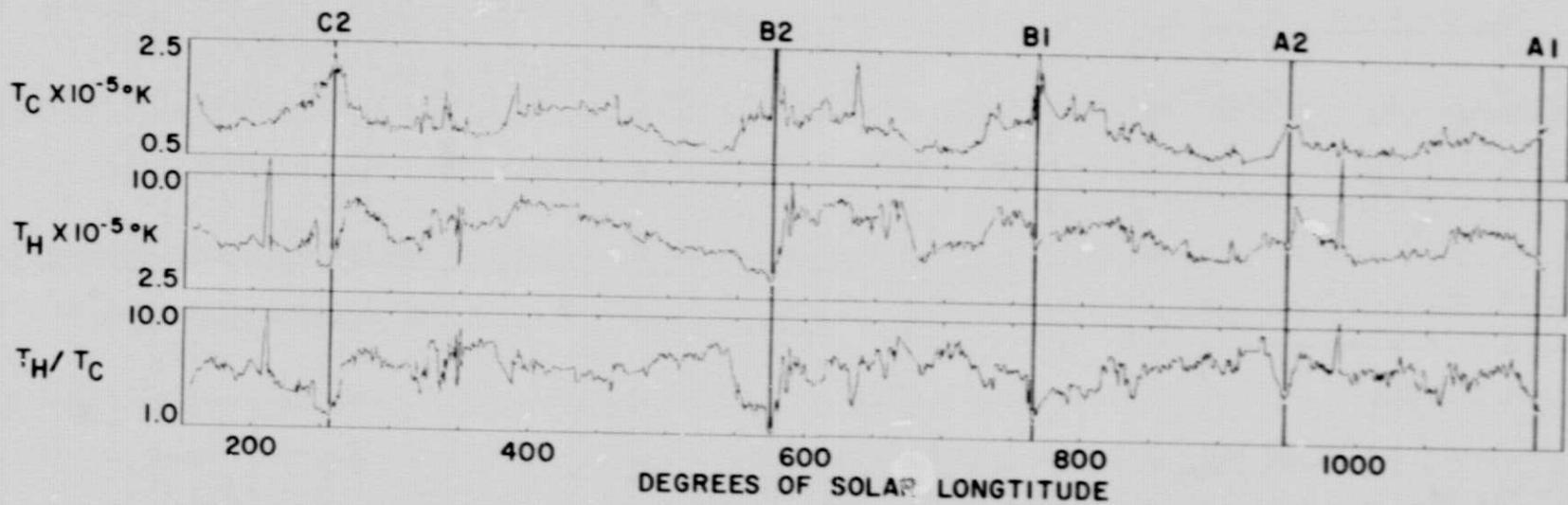


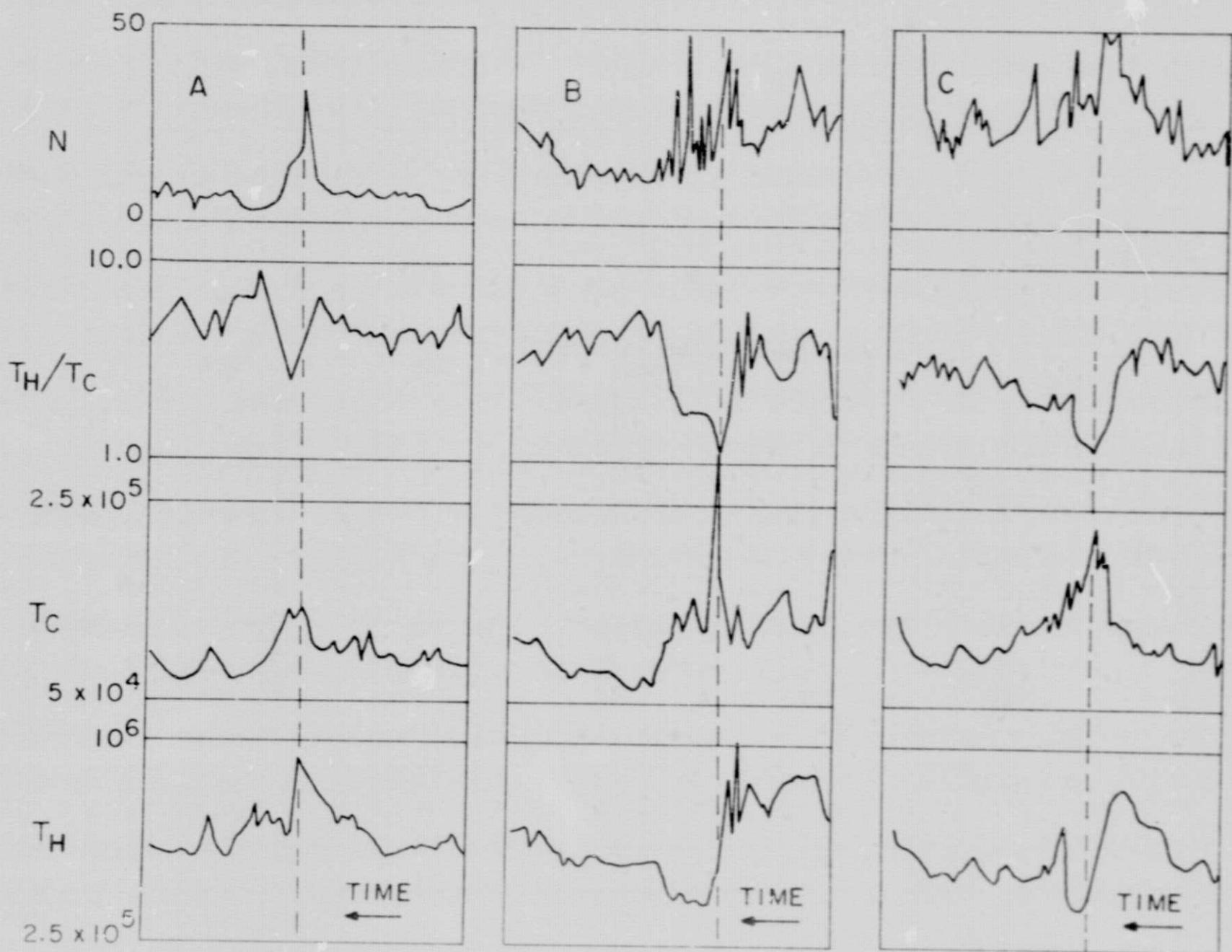
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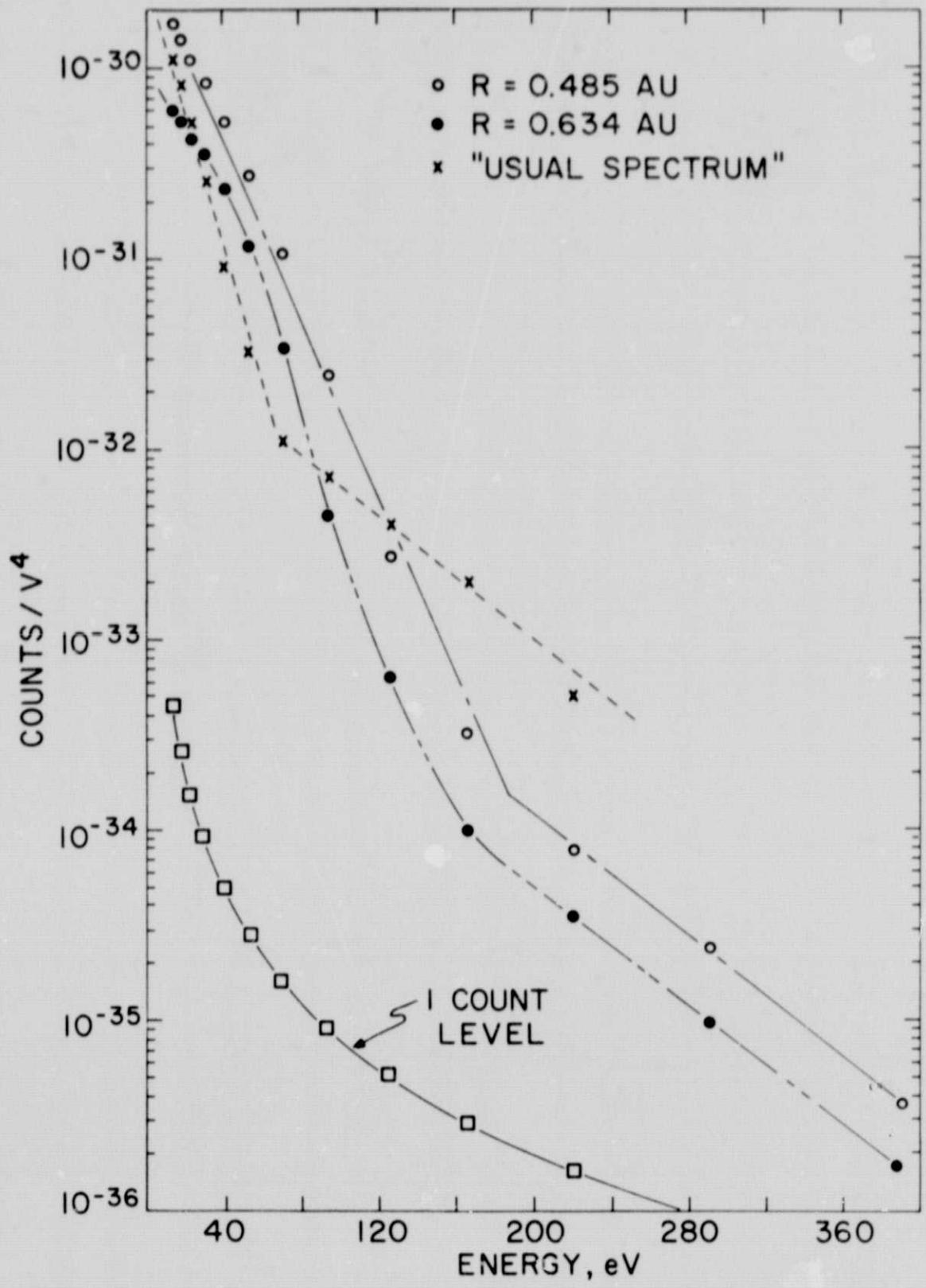


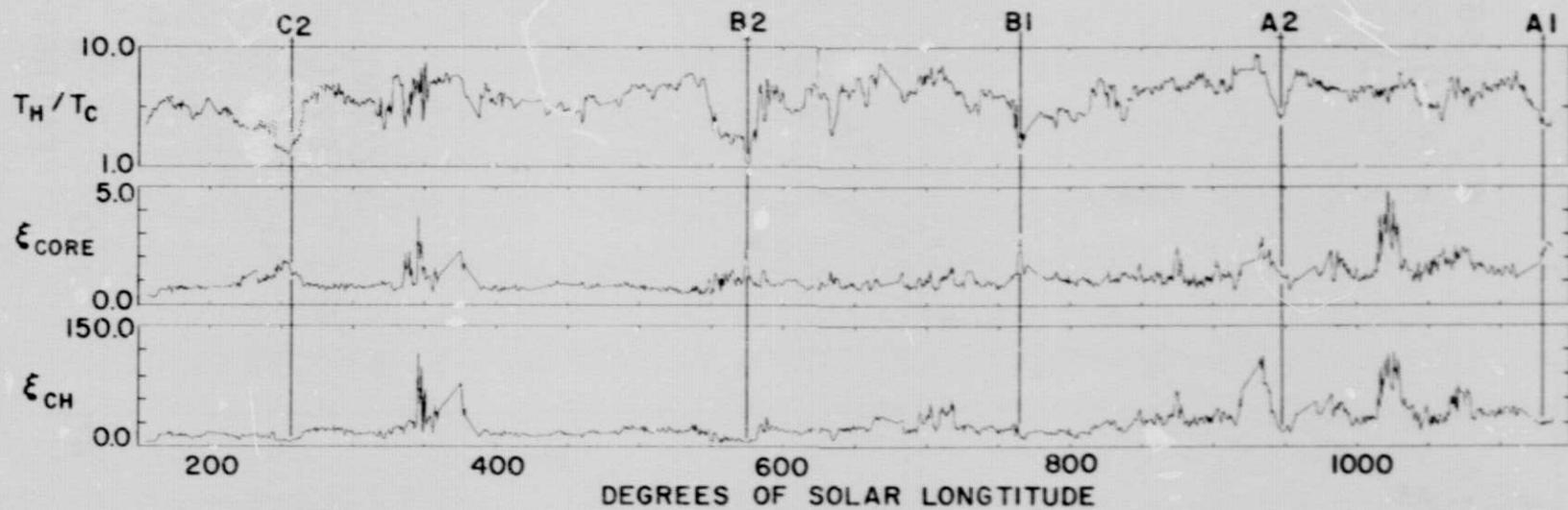
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| 16. Abstract The plasma instrument on Mariner 10 carried out measurements of electron density and temperature in the interplanetary medium between heliocentric distances of 0.85 and 0.45 AU. Due to the stable coronal configuration and low solar activity during the period of observation [January 9 to March 30, 1974], the radial variations of these quantities could be obtained. The power-law exponent of the core temperature was measured to be -0.3 ± 0.04 , and the halo temperature was found to be almost independent of heliocentric distance. The exponent of the power law for the density variation was 2.5 ± 0.2 and the extrapolated value at 1 AU was consistent with measured values during the same period. Calculations of the core electron self-collision time, and the core-halo equipartition time were made as a function of radial distance. These measurements indicate a macroscale picture of a Coulomb-collisional core and a collisionless isothermal halo. Extrapolating back to the sun, core and halo temperatures become equal at a radial distance of $\sim 2-15$ solar radii. Temperature variations were observed at the time of passage of high speed streams, and at the time of observation of stream interfaces, where the density falls before the temperature, Coulomb colli- | | | |
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16. ABSTRACT Continued

sions in the core become much less important and the halo density is observed to decrease by more than an order of magnitude.