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J.D. Mihalov
J.H. Wolfe, Ames Research Center, Moffett Field, California

NASA
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Ames Research Center
Moffett Field California 94035

1. Introduction

The Pioneer 10 spacecraft was launched on March 3, 1972, on a trajectory that permitted encounter with Jupiter in late 1973, and after that, escape from the solar system. One of the principal objectives of the Pioneer 10 mission was the determination of the properties of the interplanetary medium beyond the orbit of Mars (Wolfe, 1976). An ecliptic plane projection of the Pioneer 10 trajectory from launch through February 1977, encompassing the period of the data discussed here, is given on Figure 1, and demonstrates the temporal and spatial coverage that has been obtained. The extreme values of solar latitude along this trajectory are -8 deg, reached in March 1972 not long after launch, and +8.6 deg, reached at the end of December, 1974.

2. Experiment Characteristics

The complement of scientific experiments aboard Pioneer 10 (see Wolfe, 1976, and Table 1 of Hall, 1974) included the Ames Research Center solar wind plasma analyzer, described by Wolfe et al. (1974) and McKibbin et al. (1977). This experiment contains two separate sets of quadrispherical electrostatic deflection plates, with the solar wind fluxes within a stepped energy/charge response range measured by current collectors in one case, and by closed channel multipliers in the other. In this report, solar wind proton temperature measurements, obtained from normalized least-squares fitting of an isotropic temperature, convecting Maxwellian proton velocity distribution model, to the flight data (currents and channel multiplier counts), are used. The velocity distribution model fits the logarithms of the flight data. Experiment calibration information for the five current collectors was obtained in the laboratory before launch as described by McKibbin et al. (1977), and refinements of this current calibration were made using later results from laboratory calibration of the Pioneer 11 flight and spare plasma analyzers. To date, however, the only calibration information used for the instrument's channel multipliers is that obtained by intercomparison of flight data from the two deflection plate sets, when the solar wind proton temperature is in the higher portion of its range, the proton flux is adequately large, the spacecraft telemetry rate is not low, and the solar wind temporal variations appear to be small. This procedure permits an independent assessment of, and a calculated correction of channel multiplier count rates for possible variations with time of the multiplication factors of the channel multipliers.

3. Results and Analysis

The set of calculated solar wind proton isotropic temperatures was organized in time using Carrington rotations 1587 through 1649 as viewed at Earth, and also was restricted to one sample or less per hour. The 22,281 hourly samples which appear to correspond with these Carrington rotations were manually edited for least-squares fitting errors that appeared excessively large. Transit time delay and differences in solar longitude were considered, and radial flow was assumed. Then average temperatures for 21 time periods, each corresponding to three consecutive Carrington rotations, were obtained. During this time the Pioneer 10 spacecraft moved out from 1.26 to 12.19 AU in heliocentric distance. It has been reported that at least out to 6.5 AU, the solar wind proton fluxes measured by Pioneer 10 are consistent with a $1/P^2$ decrease (Wolfe and Mihalov, 1977).

The plot of average temperatures against heliocentric distance is given in Figure 2 on a log-log scale. On this Figure the average Pioneer 10 proton isotropic temperature corresponding with each time period of three Carrington rotations is expected to lie within the ranges shown. These indicated ranges are defined to lie between the average temperature calculated when least-squares values that appear misfit are deleted, and 2/3 of the distance along the ordinate of the plot (the logarithm of the temperature) to the average temperature calculated without deleting these values. For the three time periods centered at 4.5, 5.06, and 5.5 AU heliocentirc distance, calculated temperatures that appeared misfit were replaced with correctly recalculated, or estimated values, and the resulting corrected average proton temperature is indicated with arrows.

Unresolved multiple velocity and temperature characteristics of the solar wind proton velocity distribution (Asbridge et al., 1974; Feldman et al., 1974; 1976) could cause erroneous enhancement of proton temperatures included in the averages of Figure 2. Evidence of multiple velocity streams appears at times in the Pioneer 10 data, but these occurrences have not yet been analyzed, or searched for exhaustively. Because the least-squares analyses employed to obtain the solar wind proton temperature values discussed in this paper tend to weight the largest instrumental responses most heavily, many of these isotropic proton temperature values should be characteristic of the principal component of the velocity distribution, for cases with multiple components. The appropriate principal component just referred to would be the one yielding the several highest current or channel multiplier count values.

Least-squares fitting uncertainties are available for each individual isotropic proton temperature used in the calculation of the averages plotted on Figure 2. These relative uncertainties are given by (scale factor) X $\sqrt{\chi^2 \Sigma_i p\varepsilon_i}$ where $\varepsilon_i = (H^{-1})_{ii}$, $H_{ij} = \frac{\partial^2(\chi^2)}{\partial p_i \partial p_j}$, and p_k refers to the kth solar wind plasma parameter determined from one measured velocity distribution. $\chi^2 = \sum_i \left(\frac{F_i - S_i}{u_i}\right)^2$, where F_i and S_i are the flight and simulated data points (both current values and channel multiplier counts), the sum is over the data points of each measured proton velocity distribution, and u_i is an estimated uncertainty for F_i, including the effects of the ~2.3% digitization window width, and of the noise levels of the electrometer amplifiers. For the 21 average temperatures of Figure 2, this most probable fractional temperature uncertainty due to fitting is typically .13 to .18. These temperature uncertainties are expected to be correlated with the value of the temperature, but this has not yet been studied completely.

At the bottom of Figure 2 are given the Zurich Relative Sunspot Numbers R_z as an indication of solar activity, and the geomagnetic index A_p which should be related to the number of solar wind high-speed streams encountered by Earth at 1 AU. Both of these quantities are averaged over time periods that correspond with the same Carrington solar rotations associated with the time periods for the Pioneer 10 proton temperatures, and are plotted linearly. When there are long gaps in the Pioneer 10 data, the corresponding sunspot and geomagnetic activity data are deleted from the averages.

Some correlative features are suggested by the data of Figure 2, and this in turn is an indication of temporal variations in the average proton temperatures. For example, enhanced proton temperatures for the Pioneer 10 distance range centered at 4.1 AU, and perhaps that centered at 9.9 AU when Solar Cycle 21 began, appear to correlate with the largest two average A_p values. Similarly, the proton temperature appears to be enhanced at 8.0 AU, in association with a relatively large value for the average R_z.

A least-squares fit to a power-law dependence on heliocentric distance, R, of the proton temperature data of Figure 2, weighted by the numbers of valid values in each of the 21 time intervals, has been calculated (Bevington, 1969). The average temperatures used for the calculation were for the middle of the ranges plotted on Figure 2 for the 18 time periods for which a corrected average is not available. The power law $R^{-.52}$ was obtained, with a correlation coefficient of -.85.

Solar activity, at least as measured by the sunspot number R_z, underwent a pronounced decline as Solar Cycle 20 ended during the time of these Pioneer 10 observations, as is evident from Figure 2. If any aspect of increased solar activity results in enhanced solar wind proton heating and is also associated with R_z, the result obtained above for a heliocentric gradient of solar wind proton temperature would not be characteristic of specific solar conditions, as no account was made for the decrease in solar activity. In order to explore this possibility, a multiple correlation calculation was done, with the 21 average proton temperature values fit, in the least-squares sense, to an expression proportional to $R^{-n}\alpha_1^{\bar{R}_z}\alpha_2^{\bar{A}_p}$, again weighted by the number of valid samples in each time interval. Here $\bar{R}_z$ and $\bar{A}_p$ are the average sunspot number and geomagnetic activity index A_p, as plotted on Figure 2. The resulting multiple correlation coefficient is .88, with estimates of partial correlation coefficients (Hald, 1952; Croxton, 1959) of -.29, .21 and .27 for R, $\bar{R}_z$, and $\bar{A}_p$, respectively. The average temperatures are not fit much better using $\bar{R}_z$ and $\bar{A}_p$ as two variables added to R. Furthermore, any two of the three variables, R, $\bar{R}_z$, and $\bar{A}_p$ can be used to fit the average temperatures equally well, as indicated by the partial correlation coefficients. It seems, in particular, that inclusion of <u>either</u> R or $\bar{R}_z$ will produce as good a least-squares fit as available here, since ℓn R and $\bar{R}_z$ are correlated together much better (-.95) than either ℓn R or $\bar{R}_z$ alone with the logarithms of the average temperatures. It is not likely, then, that improved knowledge of the temperature gradient will be obtained by including $\bar{R}_z$ as an independent parameter of the least-squares fit, and this expectation is verified by the physically unrealistic value for the exponent n that is obtained from the calculation described above, with three independent parameters.

4. Summary and Discussion

In summary, the profile of proton isotropic temperature with heliocentric distance as measured by Pioneer 10 and presented in Figure 2 does not appear to drop as steeply as the -4/3 power behavior expected (cf. review by Barnes, 1974) for the case of an adiabatic, radial, and spherically symmetric expansion. There are structural reasons that could contribute to this difference, in addition to temporal effects such as were just discussed.

One such structural effect would be heating of the proton component of the distant solar wind that may be produced by the co-rotating shock waves generated in this medium (Smith and Wolfe, 1976; 1977). An increase of the numbers of these shocks with increasing heliocentric distance, between 1.5 and 5 AU, was reported, which would imply an increased heating with distance, in this distance range, due to these shocks. One could study the partial correlation of the proton temperature in the distant solar wind with the numbers of these shocks, but these numbers will not be available accurately for some of the larger heliocentric distances of Figure 2 when there are substantial gaps in the tracking of Pioneer 10 by the ground receiving stations.

Calculation of the heating of solar wind protons and electrons by interaction with incident interstellar gas has indicated a proton temperature minimum at about 3.5 AU (Holzer and Leer, 1973; Holzer, 1977). This calculated effect seems similar to the behavior of the average proton temperatures for the first five time periods of Figure 2. Because, from Figure 1, the trajectory of Pioneer 10 prior to encounter with Jupiter is generally toward the direction of relative incoming flow of the interstellar medium, it is tempting to consider both identification of the minimum near 3.5 AU on Figure 2 with heating associated with interstellar hydrogen, and the subsequent decline of proton temperature beyond ∿5 AU heliocentric distance with the movement of Pioneer 10 into the region downstream from the Sun with respect to the interstellar gas flow. However, a contribution to the solar wind proton temperature in the ∿1.5 to 5 AU range is also expected due to co-rotating shocks, as discussed above, as well as a certain amount of variation due to temporal changes of the solar wind. Consequently, it is not clear that the apparent minimum in the Pioneer 10 proton temperatures near 3 AU can be associated solely with the effect of the interstellar medium. Both a detailed assessment of heating due to the co-rotating shock waves observed by Pioneer 10, and also study of the Pioneer 11 solar wind proton temperature measurements at somewhat different times and celestial longitudes, may serve to clarify this matter.

With regard to the temporal variation of the solar wind, the situation as observed near Earth during the time period of this paper has been presented and discussed by Feldman et al. (1978), who report enhanced solar wind stream structures during 1973 to mid-1976, during the central portion of the time period of this paper, and discuss associations of these enhanced speeds with changes in the area and location of the Sun's polar coronal holes. It should be noted that the data of Feldman et al. (1978) exhibit particularly high solar wind proton temperatures during the first half of 1974, which may be reflected in the data of Figure 2. Temporal variations are eliminated from results for heliocentric gradients that use observations at two widely separated but radially aligned spacecraft, as has been done for Pioneers 10 and 11 (Wolfe and Mihalov, 1977).

Searches, reviewed by Feldman et al. (1977) (see also Bame et al., 1977), have been conducted for a "structure-free" solar wind state in the experimental results, in order to represent more realistically conditions of theoretical models, such as steady state, symmetric expansion cases. These studies sometimes use solar wind parameters at only restricted ranges of proton bulk speed, such as only the high or low speed portions of the speed record. Such partitioning has also been used for heliocentric radial gradient studies (Intriligator, 1977; Eyni and Steinitz, 1978), but was not done for the present study; additional analysis would be required for the following reason. While stream structure persists in the distant interplanetary medium (Collard and Wolfe, 1974), both the high and low ends of the range of speeds is diminished as heliocentric distance increases. Consequently the high and low speed ranges characteristic of conditions at 1 AU distance from the Sun would have to be re-identified in the distant solar wind with other different speed ranges closer to the mean value.

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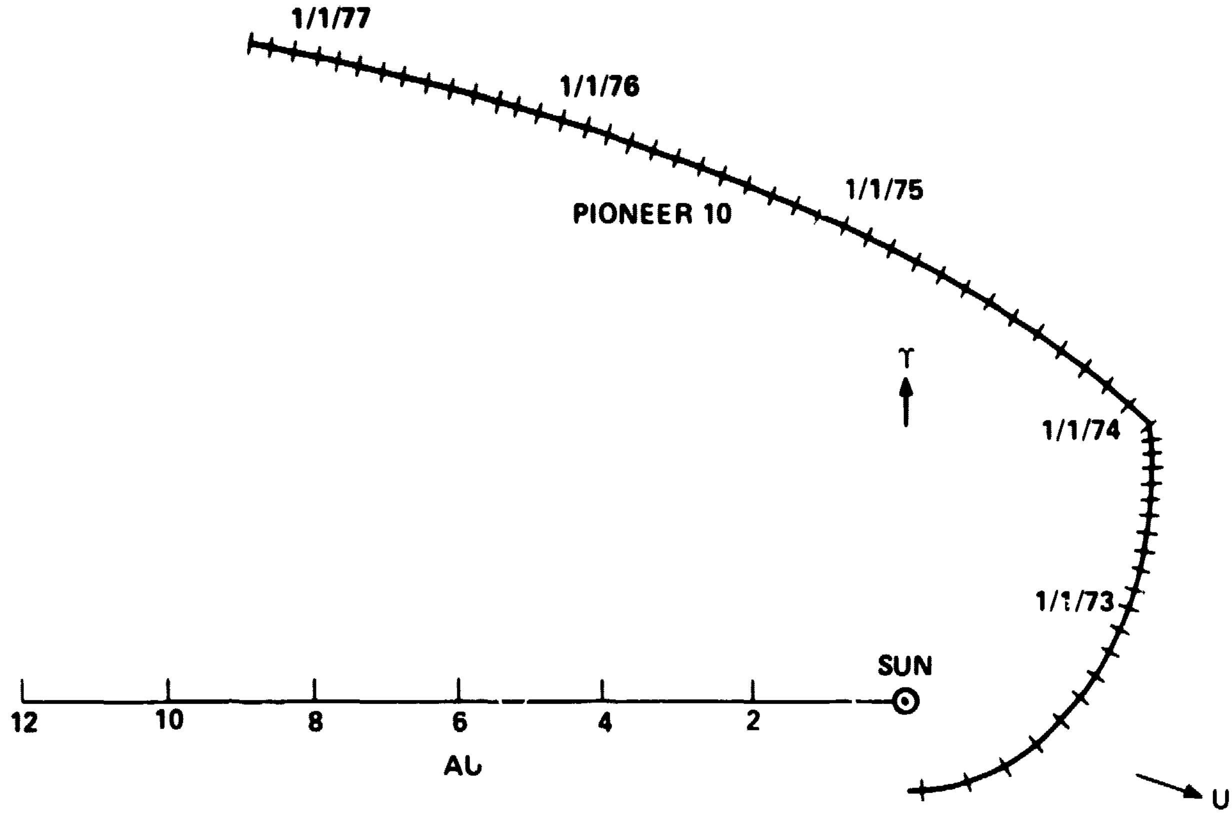

Figure 1.- Projection onto the ecliptic plane of the Pioneer 10 trajectory from launch until March 1977. Tic marks along the projected trajectory indicate the beginning of each month. The apparent discontinuity in the path occurs at the encounter with Jupiter. The projection of the upstream direction in the interstellar wind, relative to the solar system, as given by Weller and Meier (1974) and Thomas (1978) is indicated by "U". The direction of the vernal equinox is also shown.

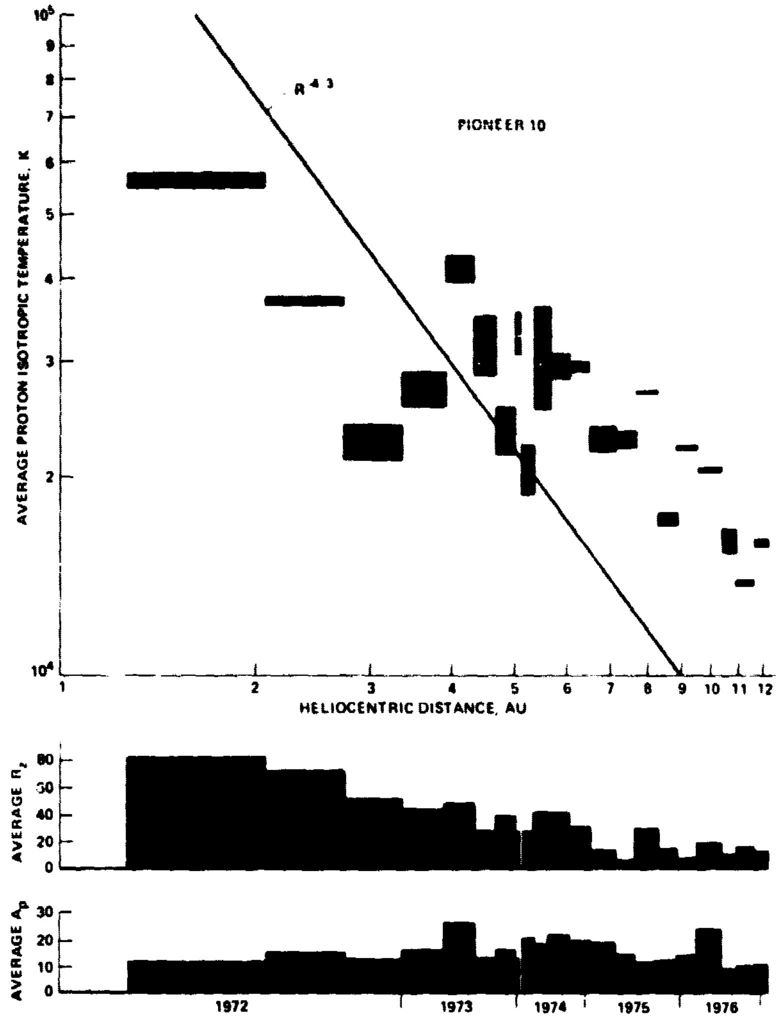

Figure 2.- Proton isotropic temperatures measured by Pioneer 10 and averaged over 21 time intervals, each corresponding with three successive Carrington solar rotations, plotted with log-log scales against the heliocentric distance in AU of the measurements. The derivation of the temperature intervals that are indicated for the various time intervals is discussed in the text. The three horizontal arrows at 4.5, 5.06, and 5.5 AU heliocentric distance are corrected average temperatures as described in the text. At the bottom of the temperature plot are also corresponding linear plots of average Zurich relative sunspot numbers, R_z, and the average geomagnetic activity index A_p, as explained in the text. Also, a scale gives the years when the proton temperatures were measured. There is a gap in the Pioneer 10 data series during nearly all of February 1974, because of a superior conjunction. An $R^{-4/3}$ line, the case for adiabatic, radial, spherically symmetric expansion is given through the center of the plot, for comparison with the data.

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16. Abstract

Solar wind isotropic proton temperatures as measured out to 12.2 AU heliocentric distance by the Ames plasma analyzer aboard Pioneer 10 are presented as consecutive averages over three Carrington solar rotations and discussed. The weighted least-squares fit of average temperature to heliocentric radial distance, R, yields the power law $R^{-.52}$. These average proton temperatures are not correlated as well with Pioneer 10's heliocentric radial distance (-.85) as are the corresponding average Zurich sunspot numbers $\bar{R}_z$ (-.95). Consequently, it is difficult to isolate the spatial gradient in the Pioneer 10 solar wind proton temperatures using that data alone.

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