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HYDROMAGNETIC OBSERVATIONS IN THE SOLAR WIND

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ABSTRACT

Observations by the Goddard-University of Maryland plasma experiment on Explorer 34 have been used to study the fluid properties of the solar wind. By combining the plasma data with magnetic field data from Explorer 34 a study of discontinuity surfaces has shown that (a) the magnetic field vectors are parallel to some discontinuity surfaces as required for a tangential discontinuity, (b) there are large bulk-speed discontinuities which probably indicate gliding motions at tangential discontinuities and are consistent with Sen's stability conditions, (c) there is indirect evidence for the Kelvin-Helmholtz instability at some discontinuities in the solar wind. Several propagating hydromagnetic shocks observed satisfy the Rankine-Hugoniot conditions for an isotropic, single-component fluid. A study of the causes of sudden commencements and sudden impulses showed that ssc's are nearly always caused by hydromagnetic shocks, but sudden impulses can be caused by shocks, hydromagnetic tangential discontinuities or small dense regions in the solar wind.

On a much larger scale, it was found that the bulk speed and temperature of the solar wind are related by the equation $\sqrt{T} = .036V - 5.54$. The Sturrock-Hartle model gives results which are consistent with this relation, but applies only at very quiet times. The V-T relation can be described by an extended 2-fluid model which postulates a heat source extending out to $\sim 20R$. There are some regions in which the temperature is anomalously high, and they usually occur at positive bulk speed gradients and are probably due to turbulent heating produced in isolated patches by colliding streams; however, such is not the dominant heating process of the solar wind. Heating seldom occurs at negative gradients, suggesting that the Kelvin-Helmholtz instability may not be a dominant large-scale process. A study of the helium in the solar wind showed that it moves with the same speed as the protons, its density relative to the proton density is variable and often correlated with solar activity, and its temperature may be 2 to 4 times greater than the proton temperature suggesting heating at some point by the dissipation of hydromagnetic waves. The flow behind the shock of 11 August 1967 was studied using simultaneous plasma data from Mariner 5 and Explorer 34. There was a high degree of correlation despite a separation of 1.6×10^7 km, indicating a quasi-stationary flow regime. The results suggest that the shock was driven by a broad, but not spherically symmetrical, high-speed plasma stream.

HYDROMAGNETIC OBSERVATIONS IN THE SOLAR WIND

I. INTRODUCTION

Experiments are conducted in the solar wind to determine the velocity distribution function of the plasma, which is a function of time, space, and the species of particles studied. As has been pointed out before by Vasyliunas (1969), the length scale of the instruments used is so much less than any of the characteristic lengths of the plasma, that these instruments are just devices for the analysis and measurement of charged particle beams, and do not exploit directly any of the cooperative properties of the plasma. What is done in practice is to determine the numbers of particles $\frac{dn}{dv}$ dv in various differential regions of velocity space by counting them, and then either to fit to an assumed function, or use these values of differential density to approximate the unknown function. There are thus two problems, which have been fully discussed by Vasyliunas;

1) The conversion of observed particle counts to values of $\frac{dn}{dv}$ dv, this is the unfolding problem, which requires a good knowledge of the characteristics of the instrument, and

2) The approximation to the distribution function

If we choose to restrict ourselves, or are restricted by lack of knowledge, to the fluid approximation, then we characterise the state of the plasma by a few parameters which describe the distribution function and are analogous to statistics. In this approximation, the fluid parameters, density, velocity, and temperature are the statistics which describe its distribution function. When these quantities are supplemented with magnetic field measurements, one has a complete hydromagnetic description of the plasma. These can be determined by fitting the differential densities to a known form of distribution function or by using the method of moments (Ogilvie, Burlaga and Richardson, 1967). The hydromagnetic approach is the appropriate one by which to study the situation in which there are scalar pressures for ions and electrons, large lengths, disturbances with rather low frequencies and very large electrical conductivity.

It has been shown by Hundhausen et al. (1968) that the mean coulomb collision time in the solar wind becomes of the order of the expansion scale time at .1 AU so that collisions between charged particles cannot maintain an isotropic, maxwellian distribution function beyond 0.1 AU, and similarly collisions of ions with neutral hydrogen which may be present are also unimportant. The result is that the temperature parallel to the magnetic field tends to become greater than the perpendicular temperature, $T_{\perp}$ as the plasma moves away from the sun. However, observations show that $T_{\parallel}/T_{\perp} \sim 2$ at 1 AU (Hundhausen et al., 1967) where the magnetic field usually makes a 45° angle with the earth sun line, so an experiment which measures the temperature, T, along the earth-sun line gives a temperature which is between $T_{\parallel}$ and $T_{\perp}$ and usually differs from these by $< 50\%$. Since temperatures vary from $< 10^4$°K to $\sim 10^6$°K, a factor of 2 is not important in many cases, and the fluid can be considered to be isotropic with temperature T to zeroth approximation. Presumably, this near isotropy is maintained in the absence of collisions by instabilities (Kennel and Scarf, 1968).

The Goddard-University of Maryland plasma experiment which formed part of the experiment complement of the satellite Explorer 34 had an acceptance angle of 2.5° in azimuth and +9° in elevation, which was parallel to the satellite spin axis and perpendicular to the ecliptic plane. The time resolution is 3 minutes. Each spin, corresponding to observation at one energy per unit charge, was divided up into 16 equal angular intervals of 22½ degrees width. This angular resolution is useful in the study of the flow of plasma around the magnetosphere, but does not allow us to detect the thermal anisotropy of the plasma. In this way, Burlaga and Ogilvie (1968) examined the change in bulk speed across the earth's bow shock and the flow direction behind the shock along the flanks of the magnetosheath, and found the results to support the fluid model.

The fluid parameters were obtained by taking moments of the distribution function as briefly described by Burlaga and Ogilvie (1968), and the temperature is measured along the earth-sun line.

The subjects to be discussed are as follows:

II. Hydromagnetic Discontinuities in the Solar Wind

III. Interaction of Discontinuities with the Earth

IV. Solar Wind Heating

V. Helium in the Solar Wind

VI. The Flow Behind Shocks

This choice of topics, and the discussion which follows, emphasizes our own work and interests but no attempt has been made to provide a comprehensive review of these subjects.

II. DISCONTINUITIES IN THE SOLAR WIND

Two types of hydromagnetic discontinuities have been identified in the solar wind - tangential discontinuities and shocks. Burlaga (1968) showed that there are simultaneous discontinuities in the plasma and magnetic field parameters in the solar wind. He found several signatures which are consistent with those for tangential discontinuities but not for shocks. To prove that such a discontinuity is indeed tangential, one must show that 3 necessary conditions are satisfied: (1) it does not propagate relative to the solar wind, (2) the total pressure does not change across the surface, and (3) the magnetic fields $\underset{\sim}{B}$ and $\underset{\sim}{B}'$ on either side of the discontinuity surface are perpendicular to the surface normal, $\hat{n}$. Condition 1) was discussed by Fairfield (1968) and Burlaga (1968) showed a cascade of discontinuities which satisfied condition 2. Explorer 34 plasma data were used together with magnetic field data from Explorers 33, 34, and 35 to show that some discontinuities satisfy condition 3 (Burlaga and Ness, 1969).

In an ordinary fluid, relative motions along the surface of a tangential discontinuity give rise to the Kelvin-Helmholtz (K-H) instability and thus cannot persist. In a hydromagnetic fluid, however, relatively large motions are allowed because of the stabilizing effect of the magnetic field. Several very large discontinuities in the bulk speed (>60 km/sec in < 3 min) were found in the Explorer 34 data and were attributed to relative motions along the surface of a tangential discontinuity (Burlaga, 1969a). Each of these discontinuities was associated with a directional discontinuity in the magnetic field, and the flow direction changed across at least 2 of the glide planes. The change in the magnetic field direction, w, tended to be near 90° and was never less than 46°; this is somewhat surprising, since Burlaga (1969b) showed that directional discontinuities tend to have small w. It was found that the large velocity discontinuities with w near 90° were consistent with the conditions for stability with respect to the Kelvin-Helmholtz mode (Sen, 1963, 1964), but that similar discontinuities with w near zero or 180° would be unstable. Thus, the unusual w distribution could indicate that large velocity discontinuities with small w disintegrated by the K-H instability.

Hydromagnetic shocks have been studied by several groups, but only the work of Sonett et al. (1966) and Ogilvie and Burlaga (1969) is based on simultaneous magnetic field and plasma data. Our work concerns the Rankine-Hugoniot conditions for 6 propagating shocks. It was found that density jump and in most cases the temperature jump is given within experimental errors by the R-H conditions for an isotropic, single fluid plasma. The values of shock velocities, density ratios and Mach numbers so obtained indicate that at 1 AU the typical interplanetary shock is not strong. This agrees with the predictions of numerical calculations carried out by Hundhausen and Gentry (1969), and with the average observed transit time for shocks which can be associated with flares.

Knowledge of the direction of the shock normal is necessary in order to apply the Rankine-Hugoniot conditions. Experience shows that this quantity is hard to determine from observations made by a single satellite, because the change in magnetic field direction is often small, or not accurately known. Our results include the description of shocks whose normal directions were found by the interpretation of magnetic field observations from more than one satellite.

III. INTERACTION OF DISCONTINUITIES WITH THE EARTH

A geomagnetic sudden commencement or sudden impulse can in principle be caused by a shock in the interplanetary medium whose front intersects the magnetosphere, or by a discontinuity convected past the magnetosphere with the bulk speed of the plasma. In a frame at rest in the plasma, pressure is balanced across such a discontinuity by definition, since it persists. The earth sees dynamic pressure changes at the passage of such a surface.

Gold (1955) suggested that ssc's were caused by shock waves propagating through the interplanetary medium from the sun. Subsequently, Sonett et al. (1966) reported direct interplanetary observations of a shock-like discontinuity which was moving from the sun and was associated with a ssc that was observed by 51 ground stations. Other observations of propagating events thought to be shocks, for which both plasma and magnetic field information was available, have been described by Ogilvie and Burlaga (1969). Nishida (1964) suggested that ssc's could also be produced by a non-shock mode, presumably a hydromagnetic wave or a tangential discontinuity.

Nishida (1964) also suggested that the non-shock mode discontinuity must be the cause of si, and Sonett and Colburn (1963) proposed that the si^- is generally due to a reverse shock. Gosling et al. (1967) presented interplanetary observations which showed a discontinuous decrease in density and a gradual increase in temperature at the time of a world-wide, discontinuous decrease in the earth's field, thus establishing that an si^- could be caused by a non-shock mode discontinuity. Ogilvie et al. (1968) examined simultaneous interplanetary plasma and magnetic field data associated with a similar si^- and observed a discontinuous decrease in density, and discontinuous increase in magnetic field intensity and no appreciable change in temperature, showing that the si^- was caused by a hydromagnetic discontinuity whose signature was that of a tangential discontinuity.

We have also shown that positive impusles si^+ are sometimes caused by hydromagnetic discontinuities. Gosling et al. (1967) reported an observation of a discontinuous decrease in temperature at the time of an ssc, showing that the event was not caused by a forward shock, but not ruling out a reverse shock.

It is clear from these observations that both si and ssc can be produced in a variety of ways.

Taylor (1968) examined the causes of 36 ssc events using interplanetary magnetic field data from Explorer 28. He concluded that 8 of these events were due to tangential discontinuities, and that 26 were possible shocks, which caused the "larger" ssc events. Nishida (1964) suggested that the rise time of the impulse is small ($\gtrsim$2 min.) for the events caused by shocks and large ($\gtrsim$2 min.) for events caused by thicker, non-shock mode disturbances which propagate slowly or not at all.

It seemed of interest to carry out a similar study using both interplanetary plasma and magnetic field data to see if it is possible to predict, using only ground observations, which type of interplanetary structure is responsible for a given si or ssc.

A theory of the interaction of the solar wind with the earth shows that the change ΔH in the horizontal component of the earth's magnetic field should be proportional to the change in momentum flux. Siscoe et al. (1968), from a study of 13 si^+ events, showed that from this theory one can calculate the change in momentum flux using ΔH and an empirical constant of proportionality which possibly varies with time. Ogilvie et al. (1968) showed a similar result for both si and ssc events. Clearly, ΔH alone is not sufficient to distinguish between a shock and a tangential discontinuity as the cause of a given event. We have combined magnetic observations by Ness and Fairfield and our plasma observations for 19 ssc's and si's during the period June to December 1967, in order to determine whether one particular type of hydromagnetic structure is associated with a particular type of event, and whether one can estimate the thickness of the causative discontinuity from the rise time of an event as suggested by Nishida.

As this work is described elsewhere (Burlaga and Ogilvie, 1969a), the procedure will be outlined. In order to classify the events as ssc or si, all events reported by 10 or more stations during this period were examined. A parameter A was defined using the number of stations calling a given event an ssc (#ssc) and the number calling it an si (#si)

$$A = \frac{\#(ssc) - \#(si)}{\#(ssc) + \#(si)}$$

Thus if all the stations are unanimous in calling an event an ssc, A = +1, while if they all classify it as an si, A = -1. Table I shows details of the events and values of A. One can see from the table that there are basically two classes of event, but in many cases there was no concensus among observatories as to which a given event belonged.

Examination of the data showed that all the events in Table I were associated with abrupt changes in the state of the solar wind near the earth. It has already been established by Ogilvie et al. (1968) and by Ogilvie and Burlaga (1969) that 8 of the events were caused by hydromagnetic shocks; these events are indicated by the asterisks in Table I. Of the remaining eleven, four resembled shocks (July 25, Oct. 28, Nov. 3, Dec. 29) but were weak or ambiguous, five were probably tangential discontinuities and two were caused by small dense regions in the solar wind, of spatial dimension $\sim$.005ÅU, which produced corresponding 'pulses' in the magnetogram.

These interpretations are shown in the last column of Table I, where we see that the eight most prominent events (those reported by $\geq$32 stations) were all caused by hydromagnetic shocks. It is significant that not all of these events were classified as sudden commencements - for Aug. 29, A = -.19 and for Nov. 29, A = 0.1. If we define a sudden commencement by the criterion A $\geq$ 0.75, then all sc's were caused by shocks, or conversely that A $\geq$ 0.75 indicates that the earth intersected a shock.

The sudden impulses, defined by A < -.75, were caused by interplanetary structures, but not of a single type. Among the rather small selection of events, there appear to be two in which a sudden increase in the H component is followed within minutes by a sudden decrease to the prepulse value.

Events in Table I with -.75 < A < .75 were not classified unambiguously as sudden impulses or sudden commencements. Five of these were caused by shocks, and three were caused by tangential discontinuities. Two of the three tangential discontinuities were associated with negative A and 3 of the 5 shocks were associated with positve A. There is thus a tendency for shocks to be identified as sudden commencements and tangential discontinuities as sudden impulses, but the relation is not good enough for predictions.

When we examine the rise-time t given in Table I for the magnetic disturbances associated with these events, we see that the rise times for the seven shock events with A > 0.75, are not systematically shorter than those of events caused by tangential discontinuities.

In general, although the thickness of a discontinuity in the interplanetary medium is not related to the rise time of the corresponding event, and one cannot associate the rise time of a sudden commencement with the velocity of the causative shock, the disturbances which are observed in the geomagnetic field have their origin in characteristic disturbances in the hydromagnetic fluid-shocks and tangential discontinuities.

IV. HEATING IN THE SOLAR WIND

We now consider the temperature of the solar wind, and the heating mechanism by which it is produced. Figure 1 shows a distribution of the square root of hourly average values of T plotted against bulk velocity V. Although a good deal of scatter is evident, a functional relation is suggested. When this data is replotted by computing T from three hour averages for bulk speed intervals 250 $km/sec^{-1} < V <$ 300 km/sec^{-1}, etc, in order to take out short period fluctuations in T and V, we see the result in Figure 2. Here the present observations are shown as open dots, and the variability is shown by the error bar on the uppermost point. Various theoretical predictions are shown on this diagram (Parker's original isothermal model, and the results of various single fluid models) as well as certain other experimental results. The point marked W is from Wolfe's observations (Wolfe and McKibben, 1968) on Dec. 15, 1965. The average values of $T^{1/2}$ and V for the flight of Mariner II in 1962 are given by the point N (Neugebauer and Snyder, 1966). The point H represents observations by Hundhausen referring to quiet times during 1962-1967. It is clear from the way these points lie on the line that it represents a valid relation between the average velocity and average temperature of the solar wind, in the sense that the solar wind properties are represented by a point on this line whose position varies with solar activity, but the slope of the line remains constant.

The functional form of the relationship,

$$T = (0.036 \pm .003)\ V - (5.54 \pm 1.5) \tag{1}$$

is empirical (Burlaga and Ogilvie, 1969b). The relation $V^2 = a + bT$, which is suggested by the Bernoulli equation, gives a somewhat worse fit.

It is widely believed that the predictions of the 2-fluid model, of Sturrock and Hartle (1966) are inconsistent with the observations, giving temperatures which are too low; this has led to the search for interplanetary heating mechanisms. However, Figure 2 shows that the predictions of Hartle and Sturrock (1968) are actually consistent with the extrapolated observations. Their 2-fluid model is simply a model for the very quiet solar wind, as the authors themselves have emphasized, and should not be applied to non-quiet conditions. Although the 2-fluid model does give lower than average temperatures, it also gives lower than average speeds. Since $k(T_e + T_i) \ll mV^2$, the low speed is a more serious problem than the low temperature.

Parker (1963) showed that, if heat were added to the plasma such that its temperature remained constant out to tens of solar radii with no heating beyond, high wind velocities could be obtained. Using Parker's model, Burlaga and Ogilvie calculated T and V at 1 AU, assuming $T = 10^6\,°K$ out to a radius R_1. The results are shown in Table II. Such a crude calculation gives velocity and temperature values which are not too different from those observed at non-quiet times. This leads us to the belief that an accurate calculation could account for the observed values of V and T by the use of a 2-fluid model with heating out to some characteristic distance R_1 and no heating in the interplanetary medium. Some preliminary calculations by Hartle and Barnes (1969) support this hypothesis.

Given the T-V relation, it is possible to identify regions having anomalously high temperatures. We have found that these regions usually occur during large positive gradients in bulk speed. This is consistent with heating due to the collision of a fast stream with slower plasma. Heating does not occur at most negative bulk speed gradients, which suggests that the Kelvin-Helmholtz instability is not an important heating process. Heating by the action of hydromagnetic shocks is not an important heating process due to the relative rarity of these events at 1 AU.

V. HELIUM OBSERVATIONS

The first long term observations of the solar wind, made by Neugebauer and Snyder (1966) on Mariner 2, showed that a second peak in the energy per unit charge spectrum was often present. This occurred at twice the energy per unit charge that characterized the H^+ peak, and was ascribed to H_e^{++}, an identification which has been confirmed by the present experiment. Thus, the solar wind should be considered a 3-component fluid - protons, electrons and H_e^{++}.

Explorer 34 observations (Ogilvie and Wilkerson, 1969) show that the bulk speeds of H^+ and H_e^{++} are equal on average. This is illustrated in Figure 3, which shows the independently determined hydrogen and helium velocities for a period of 50 minutes during which they increased by 8%. The accuracy of determination of the helium velocity, is of course, less than that of the hydrogen velocity, but the two are equal to within the combined errors.

The relative abundance of H_e^{++} is of basic importance in the study of the fluid properties of the solar wind and of basic astrophysical significance as well, and has been studied by several groups (Robbins et al., 1969, Neugebauer and Snyder, 1966). They can accurately determine H_e^{++}/H^+ only when the temperature is low, since they use only an energy per charge analysis. The Explorer 34 experiment separates H_e^{++} and H^+ by both a mass per charge and energy per charge analysis and can in principle obtain H_e^{++}/H^+ for any temperature. However, due to an instrumental background it was often not possible to determine a value for the abundance n_α/n_p, when this quantity was low simultaneously with the proton density, n_p, and temperature. Yet there were times of high density and temperature when H_e^{++} densities could be measured, so observations which confirm and extend earlier results have been obtained.

In Figure 4 we show the frequency distribution of all observations of n_α/n_p obtained during the life of the experiment. The number of measurements giving a relative abundance of zero (that is, no helium detected) is not shown and will be discussed below. This distribution is skewed and is not a normal distribution, as it would be if there were a unique constant relative abundance and the variability were the result of measurement errors. The presence of the background, although well determined and very constant, is one obvious cause for the skewing observed in Figure 4. We can conclude from this distribution that the average value of n_α/n_p is approximately 0.05 ± 0.015, and that there is considerable variability. The average value is, if anything, too high due to the exclusion of periods of time when the relative abundance of helium is especially low. The variability is a real physical effect, associated with solar conditions, and has time scale of order hours or tens of hours. There exist many continuous subsets of the data, lasting between a half day and two days and containing or order 500 consecutive readings, whose distributions are quite distinct from one another. The average value of n_α/n_p = (0.051) compares with the result of Neugebauer and Snyder, 0.046 ± .038, and of Strong, Asbridge, Bame and Hundhausen, 0.046.

In Figure 5 we see two distributions of n_α/n_p, the solid histogram being for measurements made on June 26-27, 1967, and the dotted histogram for measurements made earlier on June 8, 1967. Although the latter histogram contains relatively fewer events, the gross difference in characteristics between it and that for 26th-27th June is apparent. The most probable value of n_α/n_p is higher and the spread also probably greater.

The detection limit for the experiment is a complicated function of the plasma density, velocity and temperature. If the temperature is low, the bulk speed must coincide with a differential velocity channel or no counts will be recorded. If the temperature is high, enough counts must fall into each of the differential velocity channels covered by the distribution to exceed the background by twice the standard deviation of the background. For times when the proton density was high, (>10), the apparent absence of helium always coincided with low temperatures and bulk speeds falling appropriately between instrumental channels. Thus this biased sample does not provide evidence for an occasional complete absence of helium from the plasma.

Periods when the ratio n_α/n_p is greater than normal sometimes closely follow geomagnetic storms. Although it is tempting and almost certainly correct to assume that helium-rich plasma occurs as a result of flare acrivity on the sun, often as part of the driver of a shock, the data are consistent with a random association. In view of this and of known difficulties of associating storms and flares, we must regard this case as not entirely proven.

The ratio of the helium temperature, T_α, to that of the protons, T_p, is of particular interest from the point of view of understanding heating processes in the solar wind. If $T_\alpha = T_p$, the two species are in thermodynamic equilibrium, whereas if $T_\alpha = 4T_p$ they may be characterized by the same velocity distribution function. As pointed out by Jokipii and Davis (1968), a process which causes a change in the velocity distribution function depending only upon the particle velocity will give ions the same velocity distribution, and temperatures proportional to their masses. Thus, observations showing that $T_\alpha/T_p \simeq 4$ are consistent with heating by hydromagnetic waves, while equal temperatures would be consistent with collisional heating leading to thermal equilibrium. Such observations cannot tell us, however, where the heating took place, since adiabatic expansion conserves the ratio.

There have been many periods of time when more than 2 energy channels for the helium ions register counting rates above the background. It is then possible to determine independent values of the temperatures and other fluid parameters for each species during the same time period, by the curve fitting method normally used for the protons. Examples of the results of this procedure are shown in Table III. The periods of time indicated in the second column are those for which conditions remained constant; the fluid parameters set out are averages of those determined every three minutes during these periods. The proton density n_p, set out in the third column, is higher than average; this reflects the condition for good helium observations to be made by the present experiment. The two independent determinations of the bulk velocity of the plasma, in the last two columns, show remarkably good agreement. The ratio T_α/T_p is found to be always greater than one, and usually less than 4, suggesting that some form of hydromagnetic wave heating mechanism was operative. The helium observations thus agree well with the hypothesis of heating close to the sun, but cannot provide a decisive test of it.

VI. FLOW BEHIND SHOCKS

Shocks occurred on 11 August, 25 June and 26 June, 1967 when both Explorer 34 and Mariner 5 were measuring solar wind parameters at different locations. Examination of the fluid parameters behind the shocks showed a high degree of correlation between the measurements made at both separations; thus one may with confidence talk of the flow regime behind the shock fronts. In collaboration with Dr. A. Lazarus, we have examined the observed flows in terms of existing models:

1). An instantaneous coronal heat source leading to a spherical shock. This situation has been treated by Parker (1963), Rogers (1957), Dryer and Jones (1968) and Hundhausen and Gentry (1969).

2). An enhanced coronal heat source present for a finite time leading to a shock driven by a spherically symmetric plasma. This has also been treated by Hundhausen and Gentry (1969), and Parker (1963).

3). A shock associated with a narrow jet of plasma ejected from the site of a flare, as suggested by Gold (1955) and by Akasofu and Yoshida (1967).

4). A quasi-stationary shock aligned along the spiral direction, produced by a long lived, co-rotating, high speed stream.

Hourly averages of the solar wind parameters observed on Mariner 5 were used to predict the parameters seen at earth by making the following adjustments: 1) the number density was reduced by assuming an inverse square dependence on distance from the sun. 2) the convection speed, V, was assumed to remain constant, and the arrival time was obtained by dividing the difference in distance from the sun by that speed. These adjustments were applied to each of the hour averages. Note that we assumed an advancing "front" of plasma perpendicular to the sun-earth line. During the event of August 11, the spacecraft was essentially on the sun-earth line and 1.6×10^7 Km from the earth. During the events of 25 and 26 June, Figure 6, the distance separating the two spacecraft was less than 1.7×10^6 Km.

Consider the two shocks on 25 and 26 June. Figure 6 shows that the flow behind them is very complicated, possibly due to the short elapsed time between them. During the quiet periods immediately before the shock on 25 June, and around 1200 hours on 26 June agreement between the two plasma instruments was very good. The velocities and most probable thermal speeds agreed well at other times, and the disagreement between the density observations for the period 1800 on the 25 June to 0600 on 26 June is taken to indicate that the scale of density fluctuation was as small as 0.01 AU.

The bulk speed increases monotonically during the period of observation, and the mean thermal speed, equivalent to the temperature, shows three peaks, one immediately after each shock and one between them. The increasing velocity and temperature behind the shocks is inconsistent with their being blast waves, behind which the models predict monotonically decreasing density, velocity and temperature. This indicates that the shocks are probably driven, but the driving mechanism cannot be determined by the present experiment.

Having established the intercalibration of the two instruments, we now turn to considerations of the Aug. 11 event. Both spacecraft were situated on the earth–sun line, and separated by a distance of 1.6×10^7 Km. Figure 7 shows hour averages of the bulk speed, density and most probable thermal speed measured by the MIT instrument on Mariner 5, adjusted for the expected inverse square density-distance dependence and for distance. These are compared with the equivalent quantities observed at the earth by the Explorer 34 instrument. The agreement of all three quantities is striking, except for the period between 0600 and 1800 on August 11.

Let us now consider the bulk speed results at the top of Figure 7. The shock arrived at Explorer 34 at 0555 UT on 11 August, and the bulk speed increased monotonically until about 1600 UT. The drop at about 0800 is not real, being due to the deflection of the plasma out of the cone of acceptance of the instrument. The shock occurred at Mariner 5 during a data transmission gap between 0000 and 0600, and the bulk speed reached its maximum at about 1300. Since the time delay due to the 1.6×10^7 Km separating the two spacecraft has been corrected for, the remaining time difference, seen mostly clearly in the bulk speed curve of Figure 7, must be due to the velocity $(U-\dot{V})$ of the shock relative to the plasma. Using the times of observation at the two spacecraft we find $U > 749$ Km sec^{-1}. This is a reasonable value for such a shock speed (Ogilvie and Burlaga, 1969) although higher than usual. The very good agreement shown between the observations of all three quantities indicates that both spacecraft were studying the same material, which was moving with little distortion over the length scale of 1.6×10^7 Km, or ~ 0.1 AU.

The data are consistent with the material seen before the velocity maximum being ambient gas heated by the passage of the shock and piled up in front of the driving gas. This period of time has been identified as a region of local heating (Burlaga and Ogilvie, 1969b). The shock is then to be interpreted as "standing off" the advancing high speed stream. The observations qualitatively resemble the results Hundhausen and Gentry (1969) for driven shocks. If we identify the stand-off distance with the product of the bulk speed and the time between the shock and the velocity maximum, as shown in Figure 2, we see that this distance is of order 0.15 AU and that it increased by about 25% in going from the position of Mariner to 1 AU. This value is somewhat smaller than that predicted by Hundhausen and Gentry for a spherically symmetric shock. A small stand-off distance and a weak shock can be simultaneously achieved by postulating that the advancing driver gas is not spherically symmetrical. Using the earth's bow shock as an analogy, we find from the work of Spreiter and Jones (1963) that the radius of curvature of the front must be about 0.6 AU. This is consistent with observations of Akasofu and Yoshida (1967) and Hirschberg (1968) and also with shock observations by Taylor (1968), who noted departures from spherical symmetry in shock fronts.

We thus find that although the main features of the 11 August event can be described well in terms of a radially propagating driver shock as calculated by Hundhausen and Gentry, some quantitative details favor a tongue of plasma with a radius of curvature of about 0.6 AU similar to the Gold model. These observations are of interest because by the use of two satellites we can definitely rule out a co-rotating shock in this case.

CONCLUSION

We have interpreted approximately 3000 hours of satellite observations with reference to a hydromagnetic fluid model of the solar wind. We find that this model describes the main features of the observations and that many hydromagnetic phenomena are exhibited, including shocks, heating due to waves, and discontinuities, and also that the solar wind has a variable chemical constitution. These observations provide obvious pointers for the direction of future research into a rich variety of phenomena.

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REFERENCES

Akasofu, S. E., and S. Yoshida, Planet Space Sci., 15, 39, 1967.

Burlaga, L. F., Solar Physics, 4, 67, 1968.

Burlaga, L. F., Solar Physics, 7, 72, 1969a.

Burlaga, L. F., Solar Physics, 7, 54, 1969b.

Burlaga, L. F., and K. W. Ogilvie, J. Geophys. Res., 74, 2815, 1969a.

Burlaga, L. F., and K. W. Ogilvie, NASA-GSFC, X-616-69-142, 1969b.

Burlaga, L. F., and K. W. Ogilvie, J. Geophys Res., 73, 6167, 1968

Burlaga, L. F., and N. F. Ness, NASA-GSFC, X-616-69-143, 1969

Dryer, M., and D. L. Jones, J. Geophys. Res., 73, 4875, 1968.

Fairfield, D. H., J. Geophys Res., 73, 6179, 1968

Gold, T., in Gas Dynamics of Cosmic Clouds, North Holland, Amsterdam, 1955.

Gosling, J. T., J. R. Asbridge, S. J. Bame, A. H. Hundhausen, and I. B. Strong, J. Geophys. Res., 72, 3357, 1967.

Hartle, R. E. and P. A. Sturrock, Ap. J. L51, 1155, 1968.

Hartle, R. E. and A. Barnes, to be published, 1969.

Hirschberg, J., Planet Space Sci., 16, 309, 1968.

Hundhausen, A. J., H. E. Gilbert and S. J. Bame, Ap. J., 152, L3, 1968.

Hundhausen, A. J. and R. A. Gentry, J. Geophys. Res., 74, 2908, 1969.

Hundhausen, A. J., S. J. Bame, and N. F. Ness, J. Geophys. Res., 72, 5265, 1967.

Jokipii, J. R., and L. R. Davis, Enrico Fermi Institute Preprint No. 68-68, 1968.

Kennel, C. F., and F. L. Scarf, J. Geophys. Res., 73, 6149, 1968.

Neugebuaer, M., and C. W. Snyder, J. Geophys. Res., 71, 4469, 1966.

Nishida, A., Rep. Ion. Space Res. Japan, 18, 295, 1964.

Ogilvie, K. W., L. F. Burlaga and H. Richardson, NASA-GSFC, 612-67-503-1967.

Ogilvie, K. W., and L. F. Burlaga, Solar Physics, in press, 1969.

Ogilvie, K. W., L. F. Burlaga, and T. D. Wilkerson, J. Geophys. Res., 73, 6809, 1968.

Parker, E. N. Interplanetary Dynamical Processes, Interscience, 1963.

Robbins, D. L., A. J. Hundhausen and S. J. Bame, Trans. Am. Geophys. Union, 50, 302, 1969.

Rogers, M. H., Ap. J., 125, 478, 1957.

Sen, A. K., Phys. Fluids, 6, 1154, 1963; Phys. Fluids, 7, 1293, 1964.

Siscoe, G. L., V. Formisano and A. J. Lazarus, J. Geophys. Res., 73, 4869, 1968.

Sonett, C. P., D. S. Colburn, and B. R. Briggs, The Solar Wind, Pergamon 1966.

Sonett, C. P. and D. S. Colburn, Planet Space Science, 13, 675, 1963.

Spreiter, J. R., and W. D. Jones, J. Geophys. Res., 68, 3555, 1963.

Strong, I. B., J. R. Asbridge, S. J. Bame, and A. J. Hundhausen, NASA-SP150, 1967.

Sturrock, P.A., and R. E. Hartle, Phys. Rev. Letters, 16, 628, 1966.

Taylor, H. E., NASA-GSFC X616-68-239, 1968.

Vasyliunas, V. M., "Methods of Experimental Physics," IX Plasma Physics, 1969.

Wolfe, J. H. and D. C. McKibbin, Planet Space Sci., 16, 953, 1968.

Table I

si's and ssc's Reported by 10 or More Stations, June-December 1967

Ref.	Month	Day	Time	#(si)	#(ssc)	#(si)+ #(ssc)	A	t (min.)	Remarks
280	June	5	1912	2	44	46	.91	5	*shock
280		25	0222	1	54	55	.96	7	*shock
280		26	1459	8	35	43	.77	6	*shock
280		30	1817	12	3	15	-.60	2	T.D.
283	July	25	1739	15	9	24	-.25	2	shock
283	August	4	0702	7	15	22	.36	6	T.D.
283		11	0505	1	46	47	.96	5	*shock
283		11	1505	14	1	15	-.86	5	pulse
283		29	1738	13	19	32	-.19	3	*shock
283	Sept	13	0345	1	43	44	.95	2	*shock
283		19	1959	3	38	41	.85	2	*shock
283		20	1736	16	2	18	-.78	6	shock and T.D.'s (pulse)
285	Oct	8	1937	11	1	12	-.83	3	diffuse T.D.
285		28	1637	13	34	47	.45	3	shock
285	Nov	3	0914	0	18	18	1	6	shock
285		29	0512	18	22	40	.1	6	*shock
285	Dec	16	1025	14	4	18	-.56	6	T.D.
285		16	1133	19	1	20	-.9	5	T.D.
285		29	2227	4	11	15	.46	7	shock

*Identified as a hydromagnetic shock by Ogilvie and Burlaga (1969).

Table II

$R_1 (\times 10^6$ Km)	V (Km Sec^{-1})	T (°K)	T (observed, °K)
5.4	260	6×10^3	1.2×10^4
8	320	1.2×10^4	3.6×10^4
20	410	5×10^4	8.5×10^4
40	460	1.4×10^5	1.3×10^5

Table III

Day	Time U.T.	n_p cm^{-3}	n_α cm^{-3}	n_α/n_p	T_p °K	T_α °K	U_p Km Sec^{-1}	U_α Km Sec^{-1}	T_α/T_p
30 May	2258–2334	17.8	1.42	0.08	1.3×10^5	3.7×10^5	593	580	2.8
5 June	1922–1953	38.5	1.6	0.042	1.9×10^5	5.6×10^5	456	461	2.9
8 June	0638–0651	9.6	1.1	0.11	9×10^4	2.8×10^5	426	431	3.1
25 June	0306–0358	27.4	1.3	0.047	8.4×10^4	2×10^5	348	353	2.4
	0515–0626	18.6	1.3	0.07	1×10^5	2×10^5	351	347	2.0
	0653–0801	15.8	1.2	0.076	1×10^5	2.4×10^5	355	346	2.4
	0930–1007	20.5	1.1	0.054	9×10^4	2×10^5	357	351	2.2
11 Aug.	1136–1151	8.2	0.8	0.098	3.6×10^5	5.6×10^5	540	538	1.6
7 Sept.	1400–1538	17.7	1.1	0.064	8.4×10^4	2.4×10^5	386	388	2.9
20 Sept.	0342–0548	15.5	0.75	0.048	2×10^5	5.2×10^5	519	530	2.6
28 Oct.	2149–2216	11.0	1.05	0.095	8×10^4	4×10^5	479	478	5.0
29 Oct.	1730–1748	19	1.1	0.058	1.6×10^5	4×10^5	578	577	2.5

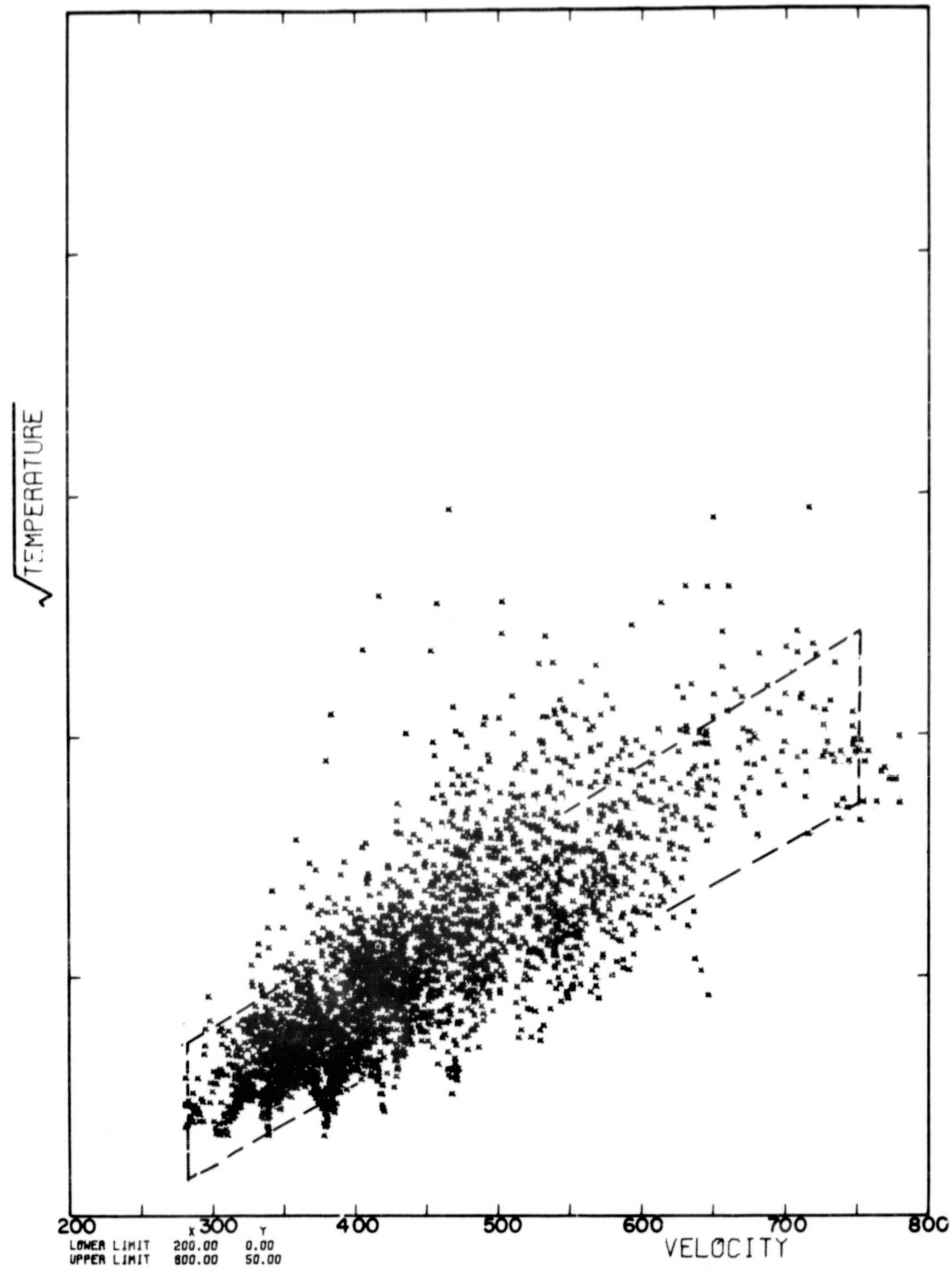

Figure 1. A plot of hourly average values of the square root of the temperature as a function of bulk speed.

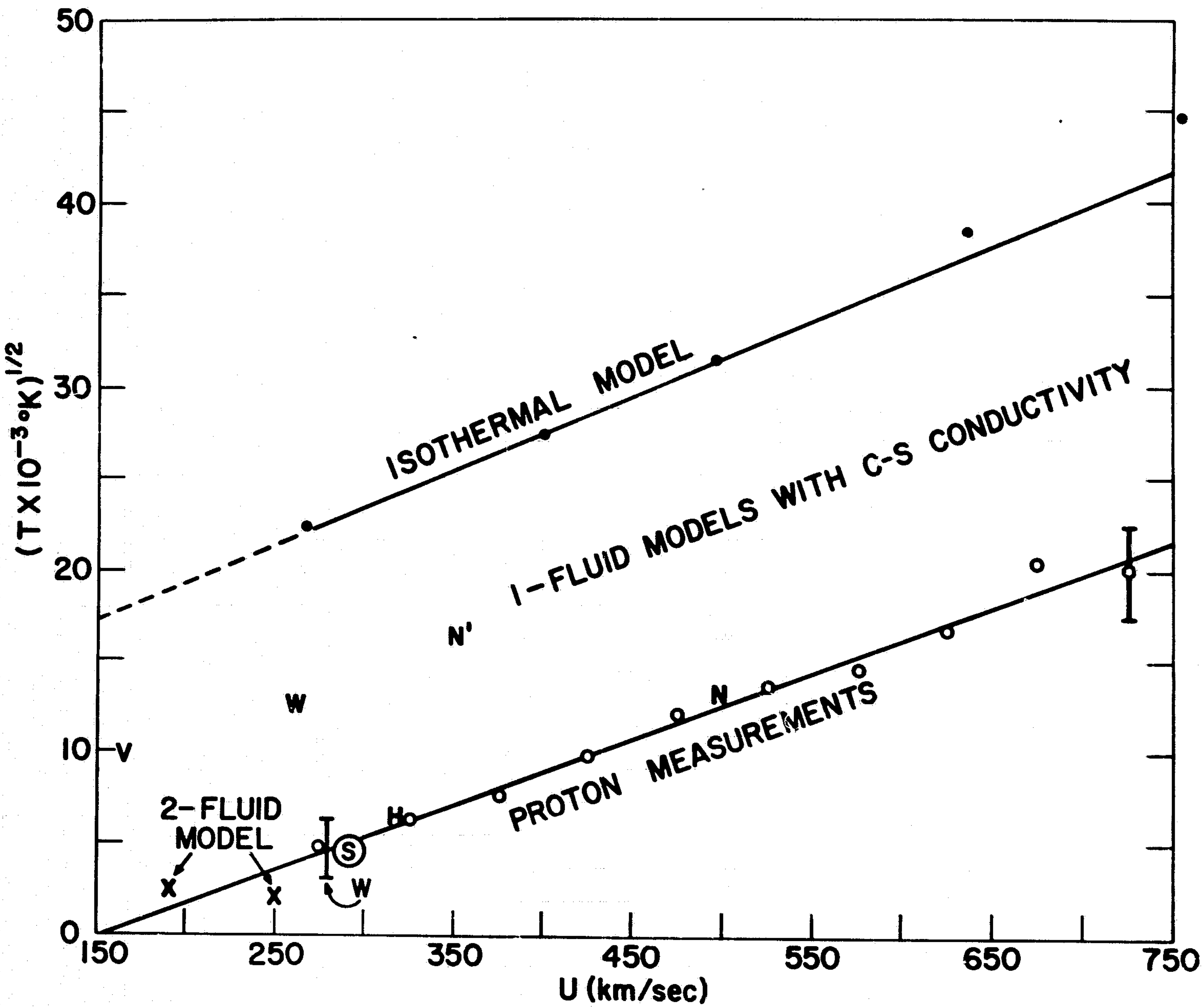

Figure 2. Values of $T^{1/2}$, computed from three hour averages, plotted as a function of bulk speed V for intervals of 50 km sec^{-1}. The open dots are Explorer 34 results, and the solid dots are Parker's solution to Bernoullis equation for an isothermal corona, $T \alpha V^2$

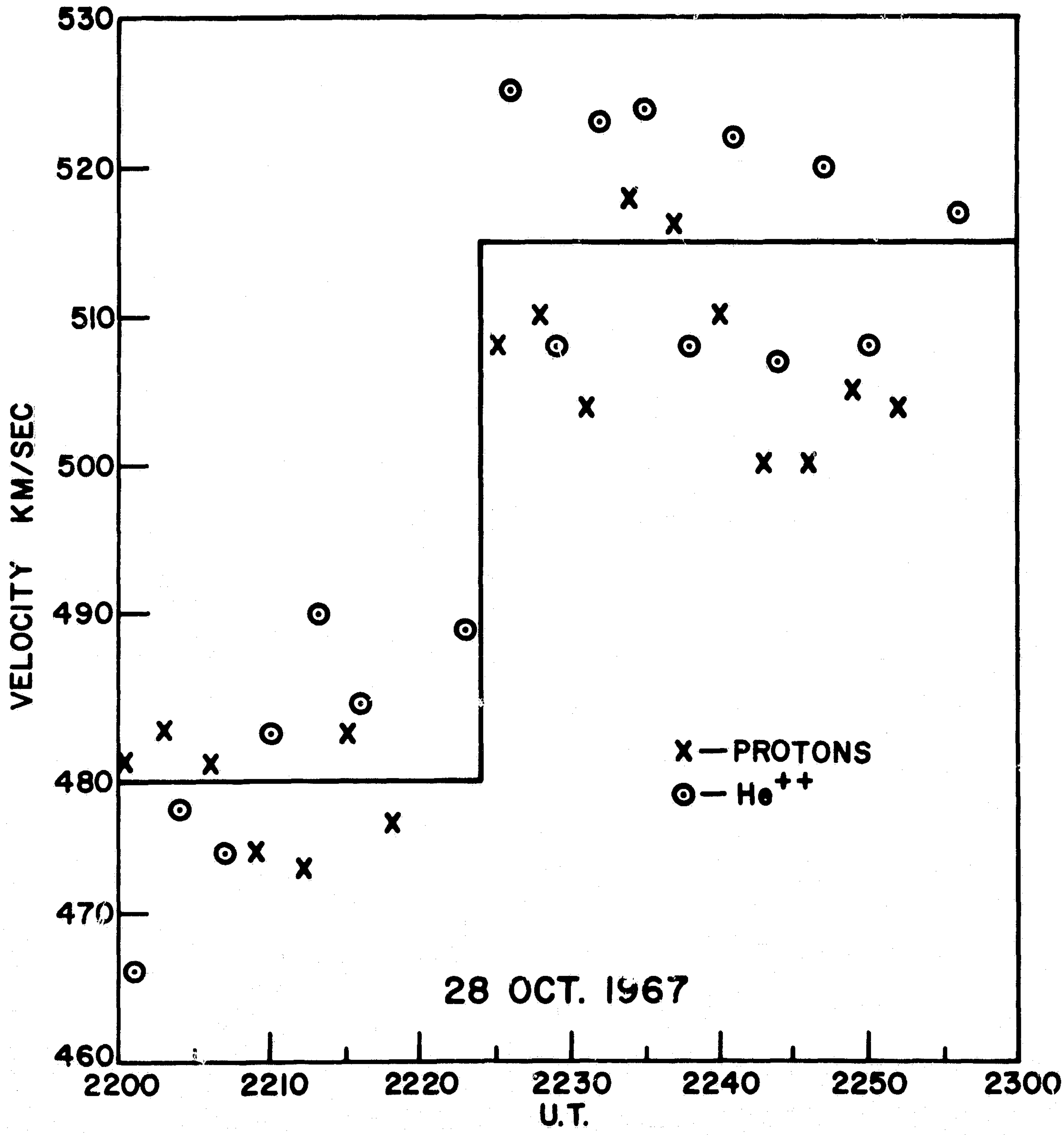

Figure 3. This diagram shows how the bulk speeds, calculated separately, for the Hydrogen and Helium ions undergo a coincident discontinuous increase.

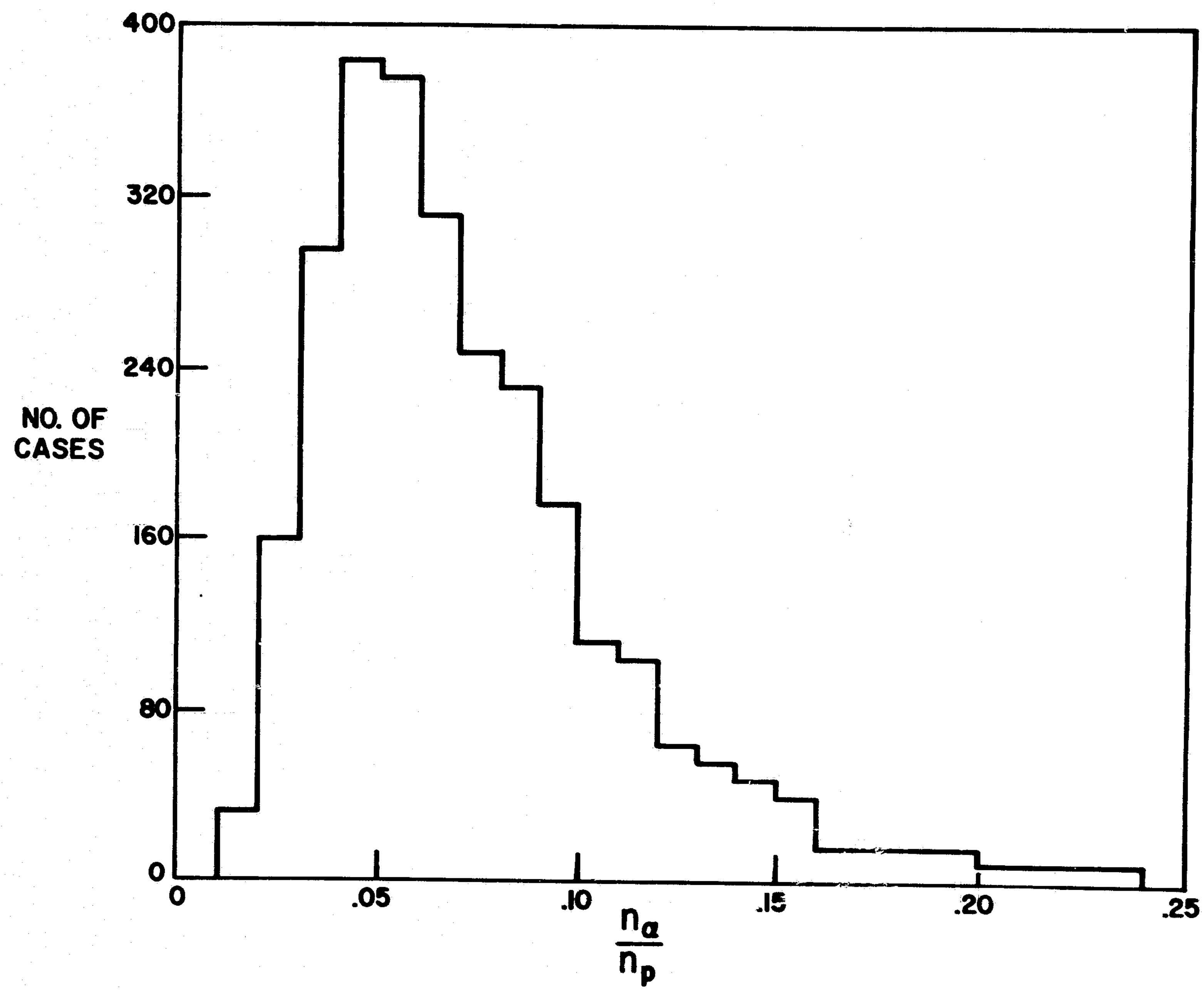

Figure 4. This histogram shows the results of the measurements of n_α/n_p for the period of operation of Explorer 34.

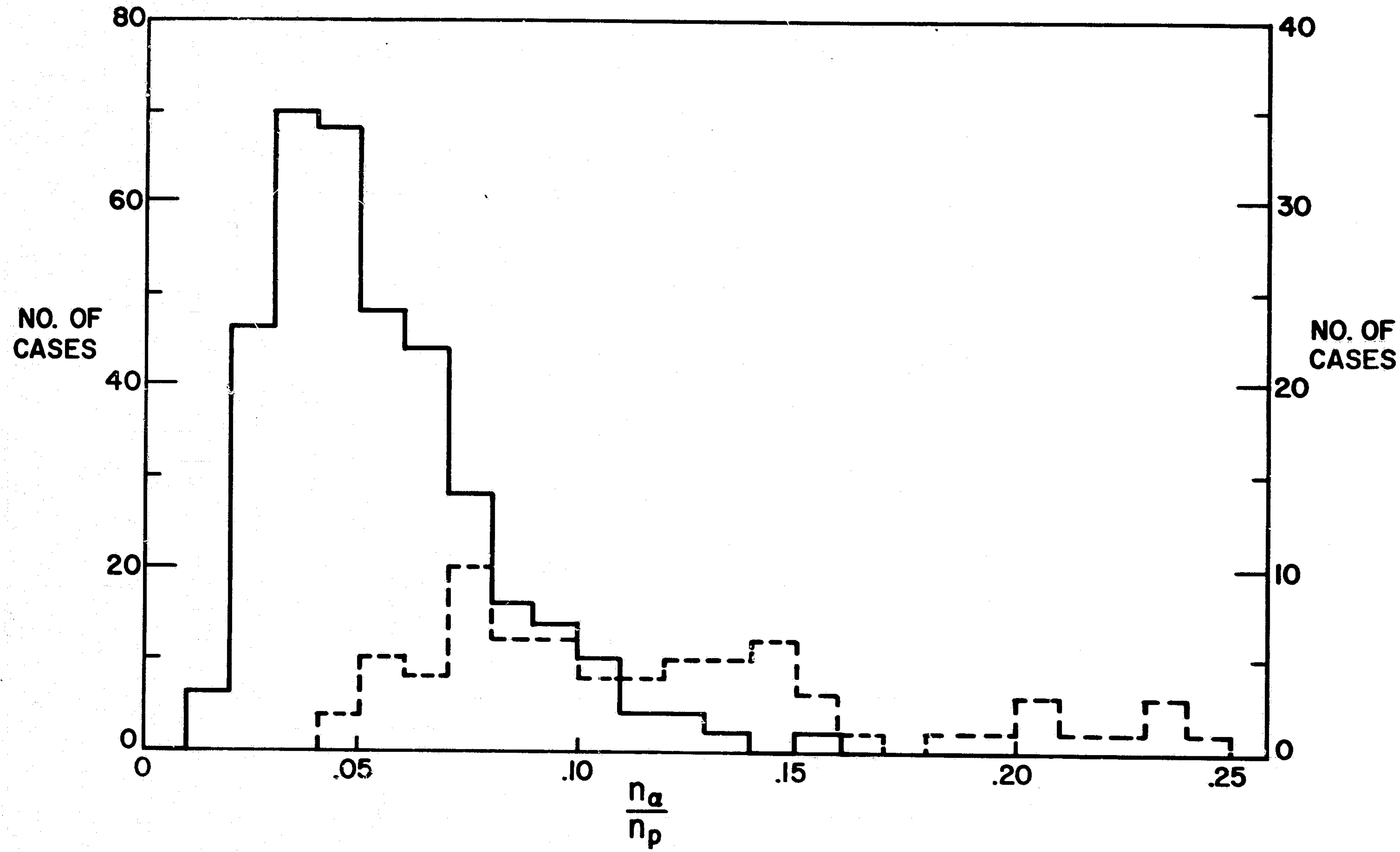

Figure 5. Two histograms showing observations of n_α/n_p at different times.

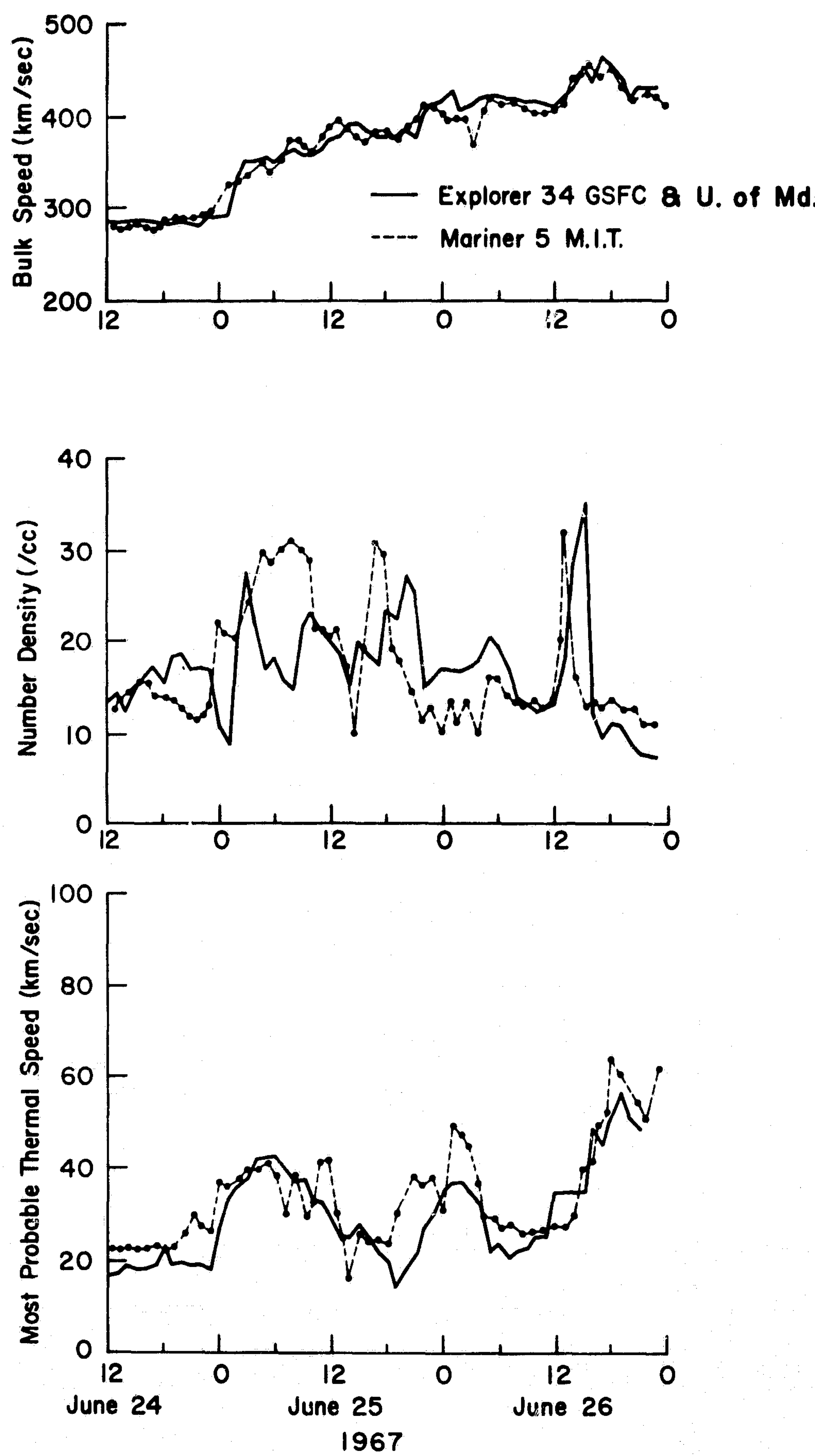

Figure 6. Comparison between Mariner 5 and Explorer 34 observations on June 15 and 26, 1967.

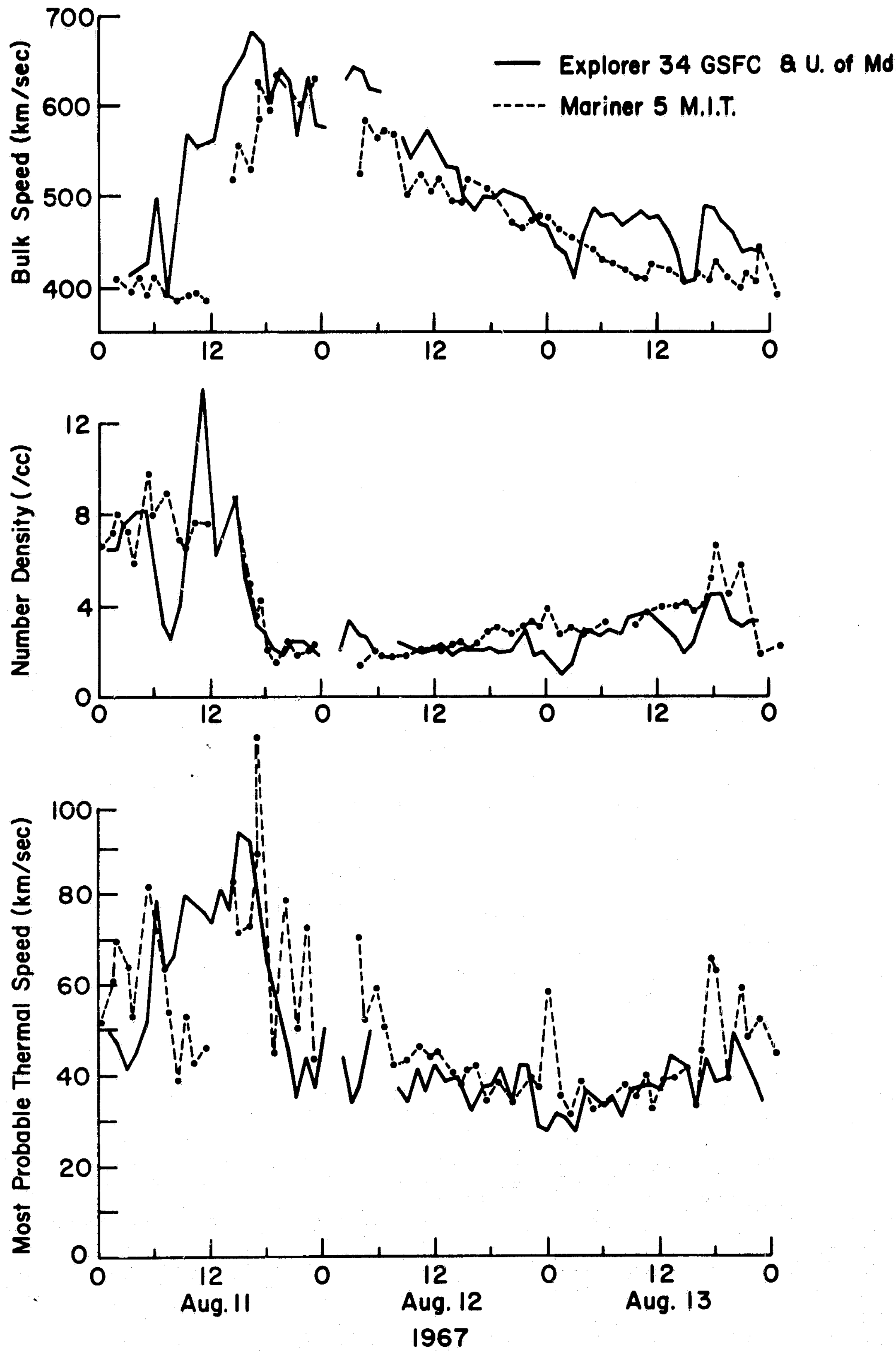

Figure 7. Comparison between Mariner 5 and Explorer 34 observations on August 11, 12 and 13, 1967. See text for method of treatment of Mariner results.