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Dynamics of the Solar Wind and its Interaction with Bodies in the Solar System

This quarter saw the completion of two major papers, copies of which are attached to each copy of this progress report. The one entitled "Shock Waves in the Solar System" by John R. Spreiter provides overall unified account of the role of shock waves in the heating of the solar corona, the transmission of solar disturbances to the Earth and elsewhere throughout the solar system, the flow fields of the Earth, Moon and planets, and of possible biological effects that may be associated therewith. It has been accepted for publication in Astronautica Acta. It forms the written record of an invited review lecture presented at the Symposium on Cosmic Explosions at the Third International Colloquium on Gasdynamics of Explosions and Reactive Systems in Marseilles, France on September 13.

The second paper, copies of which are also attached hereto, entitled "Observation of a Solar Flare Induced Interplanetary Shock and Helium Enriched Driver Gas" has been written by Dr. Joan Hirshberg in collaboration with Mrs. Alberta Alksne and Dr. David S. Colburn of NASA Ames Research Center and Drs. S. J. Bame and A. J. Hundhausen of the Los Alamos Scientific Laboratory of the University of California. In this paper, a study is made of the data from the Ames magnetometer on Explorer 33 and the Los Alamos plasma probe on Vela 3A associated with the disturbance in space on February 15 and 16, 1967 that followed the class 3B solar flare that appeared at $20^{\circ}\text{N } 10^{\circ}\text{W}$ on February 13. The initial discontinuity in the solar wind was identified as a shock wave, obviously not propagating spherically from the Sun as described by simple theory as evidenced by the 60° angle between the shock normal and the plane of the ecliptic. The data indicated that nine hours after the shock passed, plasma containing 22 percent helium was observed, as contrasted with the more normal value of about 4 percent; and that the velocity of the solar wind continued to increase for a few hours after the helium plasma passed. In a

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discussion of the results, it is argued that the high helium content of the interplanetary medium brands the plasma as having been produced by a flare. A number of suggestions are put forward regarding the detailed structure of the interfaces between the flare plasma and the ambient solar wind plasma.

During this reporting period, a paper entitled "Effect of Dissipation due to Firehose Instability on Half-jet Flow of a Collisionless Plasma" by Shigeki Morioka, of Osaka University, Japan, and John R. Spreiter was presented by Dr. Morioka at the IUTAM International Symposium on Dynamics of Ionized Gases in Tokyo, Japan. The Abstract of this paper was included in the preceding quarterly progress report for this Grant.

The Principal Investigator also participated in the Ninth ESRO Summer Advanced Institute on the Earth's Particles and Fields in Cortina, Italy, August 30 to September 10 in Cortina, Italy. As with the previous Institutes, this was a very well organized and successful meeting. The program consisted of a well-balanced mixture of excellent critical reviews and reports of latest observations and interpretations in a wide range of topics of prime concern to magnetosphere physics.

SOLAR FLARES AND SOLAR WIND HELIUM ENRICHMENTS:

July 1965 - July 1967

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Abstract

It has previously been suggested that the very high relative abundances of helium occasionally observed in the solar wind mark the plasma accelerated by major solar flares. To confirm this hypothesis, we have studied the 43 spectra with $\text{He}/\text{H} \geq 15\%$ that were observed among 10,300 spectra collected by Vela 3 between July 1965 - July 1967. The 43 spectra were distributed among 16 distinct periods of helium enhancement, 12 of which (containing 75% of the spectra) were associated with solar flares. Six new flare-enhancement events are discussed in this paper. It is concluded that the association of helium enhancements with major flares is real, non-random and very strong.

With this study, there are 12 cases of reliable associations between helium enhancements ($\text{He}/\text{H} \geq 15\%$) and flares reported in the literature. The general characteristics of these events are discussed. It is found that the flares are typically large and bright (2B or 3B), often they produce cosmic ray protons, and they are widely distributed in solar longitude. The average transit velocity of the pistons (i.e., flare accelerated driver gas) is in excellent agreement with earlier observations of flare shock velocities. The degree to which the pistons have been slowed in transit is in good agreement with theory. The average percentage of helium in the enhanced regions is 15%, but this number should not be considered more than an extremely rough estimate because of very arbitrary decisions that had to be made as to when we would consider an "enhancement" had ended. The number of positively charged particles in the enhanced region is estimated to be of the order of 4×10^{39} .

A qualitative discussion of some of the possibilities for the source of helium enhanced plasma is presented. It is suggested that the helium enriched plasma may be the piston producing the shock causing the Type II radio emission. The size of the Type II emission region and the number of particles in the helium enhancement permit an estimate to be made of the density of the corona at the origin of the piston. From this it is estimated further that the piston must come from below about $0.5 R_{\odot}$, in agreement with the $0.2 - 0.3 R_{\odot}$ often given for the initial height of the Type II emission source. Recent theoretical discussions have indicated that the corona as a whole can be expected to show helium enrichments at these levels.

It is pointed out that observations of solar wind helium enhancement can be expected to be a useful tool in studying the distribution and relative abundance of helium in different layers of the solar corona, as well as mechanisms for the acceleration of plasma by solar flares.

1. Introduction:

The relative abundance of helium in the solar wind at 1 A.U. is, of necessity, closely related to He/H in the solar corona from which the wind arose. Although the relationship is not yet understood and may be complex, none-the-less, studies of He/H in the interplanetary medium can be useful tools in gaining an understanding of the abundance and distribution of helium in the solar corona.

The problem of extrapolating the observed solar wind helium abundance back to the sun is considerably complicated by the observed extreme variability

of He/H. Although the average relative abundance of doubly ionized helium is of the order of 4-5% by number (Neugebauer and Snyder, 1966, Wolfe et al., 1966, Robbins et al., 1970, Ogilvie and Wilkerson, 1969, Formisano et al., 1970) individual spectra exhibit abundances ranging from less than 1% to over 25%. The causes of the variability must be understood before we attempt to extrapolate from the interplanetary measurements to a value for the solar helium abundance.

It has previously been suggested (Hirshberg, et al., 1970) that very high helium abundances mark the plasma accelerated into the interplanetary medium by major solar flares. This would constitute a mechanism of producing interplanetary plasma very different from the normal expansion of the corona into the solar wind. The helium enhanced flare plasma would provide information on the relative helium abundances of a different portion of the corona than that sampled in the normal solar wind. The suggestion, that helium enhancements mark flare plasma, is supported by the observations of plasma containing more than 10% helium following several major solar flares. Lazarus and Binsack (1969) have described the helium enrichment (12%) following the proton flare of July 7, 1966. Bame et al., (1968) discussed the enrichment (29%) associated with the 3B flare of Jan. 11, 1967, while Ogilvie et al., (1968) discusses the enrichment (17% helium) following the 3B flare of May 28, 1967. The solar wind also showed helium enrichments following the 3B flare of Feb. 13, 1967 (Hirshberg et al., 1970) and 4 separate enrichments associated with the series of flares of August - September, 1966 (Hirshberg et al., 1971).

In order to fully establish that the helium enrichments mark the plasma accelerated by flares, we must deal with the problem of whether or not these apparent associations between helium enrichments and flares could be explained as the random coincidences of high helium periods with post flare periods (Ogilvie and Wilkerson, 1969). In section 2 of this paper we report on a study of all of the helium enhanced spectra ($\text{He}/\text{H} \geq 15\%$) observed by Vela 3A and 3B during the two years from July 1965 to July 1967. It is found that by far the majority of these helium rich spectra were associated with major flares observed in H_α . It is concluded that the association is real, not random. Having established the reality of the effect, in section 3 we describe the characteristics of typical helium enhancements and the causative flares. This permits us to put constraints on possible models of production of enhancements. Qualitative models are discussed in the 4th section.

2. Helium Enhancements

The data discussed in the present study were collected by the plasma probes aboard the earth orbiting satellites Vela 3A and 3B, during the period from July 1965 to July 1967. For a discussion of the plasma probe, see Hundhausen et al., 1967. Robbins et al. (1970) have studied the relative helium abundance and plasma properties of the 10,314 spectra that showed no evidence of disturbance during the 256 seconds required for the observation of a complete spectrum. For a discussion of the data analysis see Robbins et al., 1970, and Hundhausen et al., 1970b. An example of the variability of He/H observed by

Vela 3 is shown in Figure 1. The top spectrum indicates less than 1% helium, while the lower spectrum shows 22% He. Note that the helium peak occurs at an E/q twice that of the hydrogen peak, showing that the hydrogen and helium components had equal speeds. Robbins et al. (1970) found that a correlation coefficient between the speeds of He and H was 0.99 and concluded that the speeds of the two components were equal to within the accuracy of their determination. The average helium abundance was 3.7%, while 2% of the spectra showed more than 10% helium. There were 14 periods during which the daily average He/H exceeded 8%. In all cases but one, Robbins, et al. (1970) reported that there was an associated Forbush decrease and/or geomagnetic storm. The correlation coefficient between the 28-day-average helium abundance and the 10.7 cm solar radio flux was 0.4.

Before proceeding with a discussion of the individual helium enriched spectra, we discuss briefly the observation that there was a general tendency for the average relative helium abundance to increase as the solar cycle progressed (Robbins et al., 1970). He/H was about 3.4% from July 1965 to July 1966 and about 4.3% from July 1966 to July 1967. Formisano et al. (1970) found that the increase continued as the solar cycle progressed; the average found by their HEOS-1 plasma probe being 5.5% from Dec. 1968 to March 1969. In Figure 2 we show a comparison of the distribution of relative abundances found in the Vela data (1965-67) and the HEOS data (1968-69). Note that the increased average was not due to a general shift of the distribution curve to the right. The most common value for the two periods was the same, suggesting that the percentage

of helium emitted by undisturbed regions of the sun remained unchanged. The increase in the mean was due entirely to more frequent observations of large values of He/H in the data for the more active sun, as would be expected if the plasma produced by flares contained a higher percentage of helium than the solar wind.

Returning to the Vela data, during the period 1965-67 values of $\text{He}/\text{H} \geq 15\%$ were sufficiently rare so that it is feasible to study each of these events in detail. For this reason, 15% was arbitrarily chosen as the lower cutoff to define "helium enhancements" in the present study. The frequency distribution of He/H is shown in Figure 2. Only 48 out of the more than 10,300 spectra had more than 15% helium. These spectra almost always are part of distinct events in which several consecutive spectra are observed to have over 10% helium. There were only 5 spectra that were isolated in the sense that, although data for proximate time intervals were available, no other proximate spectra showed $\text{He}/\text{H} \geq 10\%$. These 5 spectra probably were inaccurate determinations of He/H, and they were omitted from this study. Of the remaining 43 spectra, 22 have already been discussed in the literature. They were attributed to the flares of Jan. 11, 1967 (Bame et al., 1968), and Feb. 13, 1967 (Hirshberg et al., 1970) and to the series of flares of August/September 1966 (Hirshberg et al., 1971). The periods during which the remaining 21 helium enhanced spectra were observed are discussed below.

A. ENRICHMENTS IDENTIFIED WITH SPECIFIC FLARES

March 1966

The Vela plasma probes collected 3,235 spectra between Sept. 28, 1965 and March 23, 1966 without collecting a single spectrum in which the relative abundance of helium was as great as 15%. During this same 6 month period, the sun was quiet, producing only one flare (66-01-17, N19,E27) that was listed as 3B by any observatories, and that flare was listed by only one observatory. Then, at the end of March, three distinct periods of helium enhancement were observed. During the same period, plage 8207 became extremely active (Hundhausen, 1970). The region produced 10 particle events including the large proton flare of March 24 (Švestka and Simon, 1969).

The first helium enhancement appeared on March 23, at 10 hr. 14 min., when a spectrum indicating 31% helium was observed. The next 3 spectra, taken over a span of 13 minutes, all show 20% or more helium. The velocities of the four enhanced helium spectra were 436^{+0}_{-4} km/sec. Normal percentages of helium were observed 80 minutes after the onset of the enhancement. The width of the helium region was at least 1×10^6 km. If this enhancement were due to the 3B flare of March 19th (N22, E35) the apparent mean velocity of the plasma from the sun to the Earth would be 405 km/sec. We have elsewhere (Hirshberg, et al., 1971) defined a "slowing-ratio" as being the ratio of the observed velocity of the first appearance of the helium enhanced plasma to its apparent mean velocity.

That is

$$S = \frac{v_0}{\langle v \rangle}$$

where v_0 is the observed velocity of the plasma and $\langle v \rangle$ is the mean velocity calculated from the distance to the sun divided by the time of flight of the plasma. A slowing-ratio greater than one indicates the plasma has speeded up on its way to earth. If the above enhancement were due to the March 19th flare the slowing ratio would be 1.08. However, if we attribute the enhancement to the 3B flare of March 20 (N21, E18) the apparent mean velocity would be 576 km/sec, and the slowing ratio 0.76. Although either of these identifications is possible, the latter seems more likely.

The next spectrum showing a relative helium abundance greater than 15% was observed on March 26 at 9 hr. 12 min. when 26% helium was observed. The spectrum was part of a series of relatively high helium abundances that began with a spectrum showing 10% helium at 8 hr. 4 min. of the same day. The velocity of the helium enhanced (26%) spectrum was 535 km/sec. The width of the helium enhanced region is uncertain because of fluctuations in the helium abundance to values below 10%. The width is estimated to be between 2.0×10^6 km and 2.7×10^6 km. This helium enhancement is identified with the major 3B proton flare of March 24 (N18, W37), giving a slowing ratio for the plasma of 0.70.

The enhancement of March 26th died away and early on March 28th Vela was again observing normal helium abundances of between 2 and 6%. Then, at 1319 U.T., after a data gap of 11 hours, plasma was observed with 18% helium. The enhancement lasted approximately 3-1/2 hours. The velocity of the helium enriched plasma was 525 km/sec. The enhancement is attributed to the 3B flare

of March 25 (N14, W54). Then the apparent mean velocity of the plasma was 520 km/sec, i.e., essentially the same as the observed velocity. The slowing ratio was 1.01. The width of the helium enhanced region was 7×10^6 km.

In Table I we have listed all the flares from plage region 8207 that were given as 3B or 4N by at least one observatory. There are 6 flares, to be compared with 3 distinct helium enhancements. The first flare, on March 16th, did not produce solar protons (Valdez and Altschuler, 1970). There is no evidence for enhanced helium from that flare, but a data gap of more than one day spanning March 20th makes it impossible to come to a definite conclusion on this point. The first observed helium enhancement is attributed to either the flare of 3-19 or of 3-20. No helium enhancement was observed to be associated with the next flare, but again a data gap makes definite conclusions impossible. The next two flares both produced helium enhanced plasma. The slowing ratios are shown in the last column of Table I. Note that the necessity of having reasonable values of the slowing ratio puts a severe restriction on the possible flare-helium associations.

September 19, 1966

Normal values of relative helium abundance were observed on Sept. 19th, 1966 until 17 hr. 53 min., when a helium abundance of 13% was observed. The next spectrum (17 hr. 57 min.) showed 17% helium. An extremely long period of high helium followed. During the period between the first appearance of high helium and Sept. 20 at 11 hr. 6 min., 16 spectra were collected. Fourteen of them showed helium abundances of 10% or more. If this is considered to be a

single period of enhancement, it lasted 18 hours. The velocity of the plasma in the first spectrum to exhibit high helium abundance was 520 km/sec. This gives a width of 32×10^6 km to the region.

A class 2B flare had occurred in McMath plage 8496 on Sept. 17 (N25, W65). The last previous flare listed as class 3 by any observatory had been a limb flare (W90), 13 days earlier. The next class 3 flare occurred after the helium enhancement had already arrived at Earth. The flare of Sept. 17, then, is the only flare that can reasonably be associated with the Sept. 19 enhancement. It produced solar cosmic ray protons (Lin 1970). This flare identification yields an apparent mean velocity for the plasma of 745 km/sec, giving a slowing ratio of 0.7.

October 17, 1966

No $\text{He}/\text{H} > 15\%$ were seen during the first 16 days of Oct, 1966. On Oct. 13 helium abundances of the order of 1% or lower were observed. Then no more data was taken until 13 hr. 55 min., Oct. 17, when data collection started with an observation of 13% helium. During the next 38 minutes, 10 spectra were collected, all of which showed helium abundances greater than 10% while 2 spectral abundances exceeded 15%. The percentage of helium then dropped to normal in the 13 spectra collected during the rest of the day. The velocity of the first helium enriched plasma was 358 km/sec. The width of the region was 0.8×10^6 km.

The enhancement is attributed to the major solar flare (2B) that was observed to occur at N20 E42 on Oct. 14. The mean transit velocity of the plasmas was 577 km/sec, giving a slowing ratio of 0.62.

Events of May 1967

A series of intense flares took place during the last 10 days of May, 1967. Flares listed as 3B by at least one observatory were reported on May 21, 23 and 28.

A helium enrichment (17% helium) was observed on Explorer 34 (Ogilvie et al., 1968) on May 30th. The Vela data during this period is very sparse and Vela was not in the solar wind during the period when Explorer 34 observed the enhancement. The enhancement was attributed to the 3B proton flare of May 28th at N27 W36. This identification yields a slowing ratio for the plasma of 0.97.

A helium enrichment was observed by Vela on May 26th. Only two spectra were collected that day, both of which indicated 16% helium. The velocity of the helium enriched plasma was 655 km/sec. The enhancement is attributed to the 2B proton flare of May 23 (N28, W24). The cosmic ray alpha particles due to this flare have been discussed by Lanzerotti and Robbins (1969). The slowing ratio of the plasma is found to be 0.84.

B. ENRICHMENTS NOT IDENTIFIED WITH SPECIFIC FLARES

Major enhancement - Aug. 17, 1965

Vela 3 started to collect data on July 24, 1965. The first spectra exhibiting a relative abundance of helium greater than 15% occurred on August 17. On that day 25 spectra were collected, 6 of them showed helium abundances greater than 15% while 12 had more than 10% helium. The maximum relative abundance was 26%. The velocity (360 km/sec) of the plasma was slower than in most other helium enhancements. The width of the region was 13×10^6 km.

This period of enhancement was well isolated. During the 7 months between this event and the March enhancement discussed above approximately 4,300 spectra were collected, only two isolated spectra of which showed relative helium abundances exceeding 15%.

An unsuccessful search has been made to find a flare that could have been responsible for this event. There is however, other evidence of an interplanetary disturbance associated with this helium enhancement (Robbins et al., 1970).

Bartel's musical diagrams of geomagnetic activity shows a sudden commencement late on August 16th and the Deep River Neutron Monitor cosmic ray indices (see Figure 3) show a very small Forbush decrease early on the 16th. These observations suggest the possibility that these events were due either to a relatively weak solar event or, perhaps to an event taking place on the far side of the sun.

Minor enhancements —

Three other minor periods of helium enhancement not associated with major flares in H_{α} are described below. They all seem to be weak enhancements, although this impression may be due to spotty data coverage. One of the events is probably associated with solar protons from an unidentified flare, while the two others are not known to be associated with major solar events.

September 27, 1966

A very short lived enhancement occurred on September 27, 1966. At 6 hr. 39 min. normal helium abundances were observed. Then 19% helium was observed at 6 hr. 44 min. and 14% in the next spectrum 42 minutes later. The

next spectrum, taken 1-1/4 hours later, showed a normal 5% helium. Kane et al. (1968) report a small proton event on September 25, 1966, but they were not able to identify the flare. The helium enhancement may have been associated with the event producing the protons. However, in the absence of enough information to compute a slowing ratio, this identification is very speculative.

January 11, 1967

A spectrum showing 19% helium was observed at 16 hr. 55 min. The preceding spectrum (13 hr. 39 min.) had shown a normal 5% helium. The two following spectra showed less than 10% helium (8% and 6%) but the next spectrum following after that, (17 hr. 37 min.) showed 14% helium. Data collection was then interrupted until 2 days later, when normal helium abundances were observed early in the day and the great helium enhancement due to the flare of January 11, 1967 (Bame et al., 1968) was observed to begin later in the day. We do not know of any major solar events to be associated with this sporadic enhancement of January 11.

January 7, 1967

Only two spectra were observed on January 7, 1967. The first showed 12% helium while the second showed 20% helium. Spectra observed the day before and the day after showed less than 10% helium. There are no major solar events known to us that were associated with this enhancement.

C. DISCUSSION

One of the purposes of this study was to establish that the apparent association between major solar flares and interplanetary helium enhancements was not

due to chance. We have shown that the 43 spectra with $\text{He}/\text{H} \geq 15\%$ are distributed among 16 periods, 12 of which are associated with known flares. Of the remaining 4 periods, one was accompanied by a small Forbush decrease, one may have been associated with solar protons, and two are not associated with any known disturbance. Thirty-four of the 43 spectra were observed during the 12 periods of enhancement associated with flares. The necessity to have reasonable values for the slowing ratios severely limited the freedom of choice among major flare candidates that usually plagues attempts at flare identifications.

As a further test of the statistical significance of the results we note that there were 4 periods of truly major activity between July 1965 - July 1967. All of these periods (March 1966, July 1966, Aug.-Sept. 1966, May 1967) have been associated with high helium abundances observed either by Vela or by other probes (Lazarus and Binsack, 1969, Ogilvie et al., 1968).

The data show that there is a real, non-random, and very strong association between major solar flares and interplanetary helium enhancements. The major obstacle to the conclusion that all helium enhancements are produced by solar flares is the well marked event of August 1965. Although there was evidence of a weak Forbush decrease at the expected time, there was no other evidence of major solar activity on this side of the sun.

3. Characteristics of Helium Enhancements and Flares

There are now enough flares associated with helium enhancements so that some of the general properties of the events can be determined. Before discussing

these general properties however, we briefly describe a model for flare disturbances with which we will compare our results. This model has been gradually emerging from studies of solar flare material, however, it is not yet fully confirmed experimentally or theoretically. As will be seen, the present study provides strong experimental evidence in favor of the model.

In the model, shown schematically in Figure 4, major solar flares cause the actual ejection of solar material (piston plasma) into the interplanetary medium. This is in contrast to the blast wave model, in which only the disturbance is propagated into space. The difference between the two types of events is analogous to a bullet vs. a clap of thunder. The flare accelerated material from the largest major flares propagates all the way to the Earth, and is identified as the plasma showing high He/H. The region of helium enhancement is shown shaded in Figure 4. In order to propel the solar material to Earth, the flare must deliver energy to the accelerated plasma over a finite period of time. Observations of the disturbances indicate that the time period over which the acceleration takes place is of the order of 4×10^3 sec. (Hirshberg et al., 1970, Hundhausen et al., 1970a), i.e., an order of magnitude longer than has often been assumed in critiques of postulated flare theories (Sweet, 1969). As the high velocity flare plasma travels in space, a shock forms before it in the ambient plasma. Observations (Hirshberg, 1968, Taylor, 1969) indicate that the shock has a very broad front as shown in Figure 4. Considerable progress has been made in theoretical calculations of the propagation of the shock and piston plasma (see for example Hundhausen and Gentry, 1969, De Young and Hundhausen, 1971, and Dryer, 1971). After the flare, the sun continues to emit a low density high velocity solar wind for a day or so.

In this section the observations will be compared to this model with particular attention to the question of the nature of the causative flares, the spatial extent of the plasma piston, a comparison of these observations with theories of disturbance propagation, and the width of and number of particles in the helium enhanced region.

In Table II we summarize the observations of 12 solar flare helium enrichments of over 15%. We have omitted the enrichment due to the 3B proton flare of July 7, 1966 (Lazarus and Binsack, 1969) because only 12% helium was observed. In the second column of Table II we give the importance of the flare. Note that 11 of the 12 flares were classified as "bright" in $H\alpha$ while 8 of the 12 were class 3 as far as area of the flare was concerned. A star indicates that prompt energetic solar protons were observed on satellites following the flare, as listed by Lin (1970).

The flare positions are shown in column 3. Eleven of the 12 flares occurred in the northern hemisphere, which was much more active than the southern hemisphere during this period. Four helium events were due to eastern flares, while eight were due to western flares. This cannot be considered a statistically significant east-west effect because of the small sample size. Although no east-west effect is expected in the propagation of flare plasma, more data should be accumulated on this point. There is, of course, an east-west effect for solar proton events and we note that two of the helium enhancements that were not accompanied by observations of cosmic ray protons were eastern flares. Thus, the association of proton flares and solar wind helium flares may be even closer than indicated in the table.

An estimate of the spatial extent of the helium enriched region may be made by noting that the flares occurred as far west as 65° and as far east as 42° . The plasma body evidently subtends a wide angle, of the order of 130° or more. This wide angle is in agreement with the shape derived from a study of sudden commencements of geomagnetic storms (Hirshberg, 1968) and from interplanetary shocks (Taylor, 1969). In the estimates that follow we shall approximate the shape of the plasma front as $1/4$ the area of a sphere.

The fourth column of Table II indicates the maximum percentage of helium seen in each enhancement. The values range from 16% to 31%. The lower cut-off is, of course, arbitrarily set in this study. In five of the events, more than 20% helium was observed. The average maximum percentage for the events listed was 20%.

Column 5 shows the observed velocity of the plasma in the spectrum containing the maximum percentage of helium. The velocities range from a high of 655 km/sec to a low of 358 km/sec, with an average of 546 km/sec. This is considerably higher than the 400 km/sec average velocity for all of the data collected by Vela 3 (Robbins et al., 1970). Since this helium enhanced plasma is attributed to flare piston plasma, the velocity of the plasma should be related to the velocity of the interplanetary shocks that form in the ambient solar wind in front of the piston. At 1 A.U. the shock and piston plasma velocities are expected to be almost, but not exactly, equal; the velocity of the shock being somewhat greater. Hundhausen (1970) found an average velocity of 500 km/sec for 27 interplanetary shocks, in excellent agreement with the 546 km/sec plasma

piston velocity found in the present study. There are three disturbances that appear in both studies (3-20-66, 1-11-67, 2-13-67).

The mean transit velocity, $\langle v \rangle$ of the helium enriched plasma from Sun to Earth, is given in column 6. Values range from 488 km/sec to 780 km/sec with an average of 629 km/sec. The transit velocity for the piston should be less than that for the shock, since the shock stands out in front of the piston. Hundhausen (1970) found an average transit velocity for shocks of 730 km/sec. From these numbers, the distance between the shock and the piston is estimated to be of the order of 20×10^6 km or about 0.14 A.U. This is in excellent agreement with the 0.13 A.U. expected from the calculations of Hundhausen and Gentry (1969) for the case in which the flare deposits energy into the solar wind over a period of about 20 hours. The width of the standoff region is calculated to be somewhat less (0.11) for the case for which the solar flare continues to deposit energy indefinitely. The present results cannot be used to make an accurate estimate the length of the period during which energy is deposited into the solar wind since neither the numerical model nor the determination of the standoff distance is good enough. However, it is encouraging that the numerical calculations and the experimental values agree so well.

Further agreement between observation and the model is found in the slowing ratio given in the seventh column. The values range from 0.62 to 1.1. The value 1.1 indicates that the plasma was speeded up on the way to the earth. There is some evidence that the plasma involved in this case was accelerated by piston plasma from a later flare (Hirshberg, et al., 1971). The average of the slowing

ratios for the piston was 0.8. Hundhausen and Gentry (1969) found that the slowing ratio for shocks was expected to be 0.8 and remarkable insensitive to details of the shock deceleration. This is because the major deceleration takes place close to the sun so that the shock is traveling at the slower velocities during most of its journey from the sun to the earth. The average value of the piston slowing ratio is in general agreement with the model of Hundhausen and Gentry. However, the individual values vary quite markedly. This variation in piston slowing ratios is not as great as the variation in shock slowing ratios reported by Vernov et al., (1970) who use flare shock identifications that apparently lead to some shock slowing ratios of the order of 0.4 ± 0.2 . The piston slowing ratios shown in Table II suggest that the amount of deceleration of the piston may be increased or decreased in the region far from the sun, as it meets the inhomogeneities of the solar sector structure and the fast interplanetary streams. The velocity and density variations that occur in the streams (Neugebauer and Snyder, 1966, Wilcox and Ness, 1965) can be expected to be the major cause of the effect. In addition, if there are a series of flares, the slowing ratio may be affected in the region far from the sun because the flare plasma may be pushed from behind by another piston from a later flare.

The agreements between theory and observation of piston velocities, slowing ratios, and the distance between the shock and the piston are all remarkably good. This can be considered confirmation of the hypothesis that the enriched plasma bodies mark the pistons produced by the flares. We may also conclude that the model used by Hundhausen and Gentry is valid, at least in broad outline,

and probably in some degree of detail. Since the model describes the propagation of plasma having a velocity of the order of 1,000 - 2,000 km/sec at 0.1 A.U., it can be argued that our results indicate that the velocity of the disturbance was of that order of magnitude at that distance.

The last two columns of Table II give information on the width of the helium enhanced band and on the number of particles involved. The widths are only approximate since they are estimated from

$$w = v \Delta T$$

where v is the velocity of the plasma and ΔT is the time that it took for the enhanced region to pass. The velocities remain fairly constant during the passage of any given enhancement. The major uncertainty in the width arises from two independent uncertainties in the determination of ΔT . First, an arbitrary decision must be made as to the level of $\frac{\text{He}}{\text{H}}$ that should be considered to signal the end of the enhancement. Figure 2 shows that the most common value of $\frac{\text{He}}{\text{H}}$ is between 2 and 4%. However, the helium ratios are not randomly distributed in time even when there are no flares, so that we cannot estimate ΔT by waiting until the helium ratio reaches 4%. Furthermore, we cannot estimate the time by finding when the plasma returns to its preflare value because changes in the level of $\frac{\text{He}}{\text{H}}$ are too frequent even in the absence of flares. We have arbitrarily chosen to say that the enhancement has passed when the relative abundance falls below 10% helium for a few consecutive spectra. Since only 2% of the spectra collected by Vela showed more than 10% helium, this criterion leads to a very conservative estimate of the width of the enhancement. The second problem in determining ΔT is due to data

gaps. Sometimes the helium appears in the first spectrum after a data gap. In other events an enhancement is present in the last spectrum before a gap, but has faded away by the time data acquisition is resumed. We have again chosen the conservative route, omitting the data gaps and counting ΔT from the time when the enhancement is first observed to the time of the last observation. Since both these decisions minimize ΔT , the true widths will tend to be larger than those shown in the table.

The widths range from 0.8×10^6 km to 32×10^6 km (5×10^{-3} A.U. to 0.2 A.U.). Since the range is so large and the number of events so small, the average value (9×10^6 km or .06 A.U.) is not expected to have much physical meaning. The largest width was found for the case of the flare of Sept. 17, 1966 when the data coverage was good. There were no long data gaps during the enhancement, or at its beginning, or end. After the enhancement, the $\frac{\text{He}}{\text{H}}$ ratio returned to the levels that were present before. There were no other flares or enhancements near this time. For these reasons, this width, although large, seems to be determined quite accurately. On the other hand, the width from the flare of Feb. 13, 1967 was also accurately determined and was only 1×10^6 km.

The average $\frac{\text{He}}{\text{H}}$ in the enhanced band was 15%, but this number has little meaning because of the criteria used in determining the width.

The number of particles in the helium enhanced region is estimated from

$$N = \rho w A ,$$

where w is the width, ρ the density and A the cross-sectional area. For A , we use $1/4$ the area of a sphere of radius 1 A.U. (7.1×10^{26} cm²). This will permit

direct comparison with previous studies of the large scale characteristics of disturbances associated with flares (Hundhausen et al., 1970a). This area is also quite close to half the area of a sphere of radius 0.6 A.U. (area 5.2×10^{26}) which approximates the shock front derived from the sizes of sudden commencements of geomagnetic storms (Hirshberg, 1968) and shown in Figure 4. Using this value for A, the estimated number of particles ranges from 0.3×10^{39} particles to 15×10^{39} particles. The largest value is found for the southern hemisphere flare of Jan. 11, 1967. The average is about 4×10^{39} particles. Hundhausen et al., (1970a) estimated the total number of particles in the stronger interplanetary blasts to be about 6 times this figure. The average mass in the helium enhanced band is the order of 1×10^{16} grams, or about 1/4 the mass in the entire interplanetary blast. Because of the many uncertainties involved in the estimates of number of particles, they should be considered as approximations.

4. Discussion

The observations of enhanced helium abundances in plasma pistons has been interpreted as indicating that the corona is not mixed well enough to prevent the appearance of regions relatively rich in helium (Hirshberg et al., 1970), however the relationship between the helium observed at 1 A.U. and the relative helium abundance in the source region from which the plasma arose is not yet well understood. As far as the corona is concerned, recent theoretical work indicates that helium is probably not distributed uniformly in the solar corona. Even in the earliest treatments of the problem (Brandt, 1966), it was recognized that the

percentage of helium in the solar wind would not be the same as in the corona, since helium is more difficult to raise into the wind than hydrogen due to the larger mass and smaller charge-to-mass ratio of the helium. The distribution of helium in solar corona and the relation to solar wind abundance have been discussed in several recent theoretical papers. The physical models vary from study to study, but the basic approach is to consider the consequences of diffusion in an atmosphere flowing away from the sun as a solar wind. The diffusion can be due to thermal or pressure gradients, electric fields and/or gravitation. In order to make the equations tractable, the sun is considered to be spherically symmetric and the effects of solar magnetic fields are omitted. Diffusion due to concentration gradients is neglected. Different types of diffusion would dominate in the various regions of the solar atmosphere. Thermal gradients will be most important in the transition region just above the chromosphere, while gravitation and electrical effects will dominate in the outer corona. The photospheric abundance of helium may be considered a boundary condition of the problem, but unfortunately that abundance is unknown. The chromospheric abundance is also uncertain, but is probably of the order of 10% or so. A large amount of mixing probably takes place between the photosphere and the chromosphere. Higher in the chromosphere and in the lower corona, diffusion in the huge thermal gradients in the transition region will tend to cause a relative helium enhancement (Jokipii, 1966, Delache, 1967, Nakada, 1969) since heavier elements migrate toward high temperatures. If there were no mixing between the corona and chromosphere, Nakada's study indicates that the lower corona might even become a predominantly helium atmosphere.

Above the transition region, thermal gradients become less important than the gravitation, electric and pressure terms in the diffusion equation. In this region of the corona itself we must distinguish two subregions; a lower region where the corona tends to be somewhat like an isothermal corona (the polytropic index $\alpha < 4/3$), and an upper region in which the solar wind is more nearly adiabatic ($\alpha > 4/3$) (Geiss et al., 1970). In the lower region (below a few solar radii perhaps), the velocities of the helium and hydrogen components need not be equal. The larger mass and smaller charge-to-mass ratio of the helium results in lower velocities for the alphas than for the protons. This results in an altitude dependent relative abundance (Nakada, 1970, Yeh, 1970, Alloucherie, 1970, Geiss et al., 1970). In contrast with other workers, Alloucherie finds an increase in relative abundance with height. However, since the bottom of this region is probably already enhanced in helium relative to the photosphere, these results lead to an uncomfortably large percentage of helium in the lower corona. This is especially true since Nakada's work shows that the drag of too much helium tends to inhibit the solar wind itself. It is more likely that the relative abundance of helium decreases with altitude as found in the models of Nakada (1970), Yeh (1970), and Geiss et al., (1970). In the upper region (Geiss et al., 1970) where $\alpha > 4/3$ (compared to the fully adiabatic case $\alpha = 5/3$), the velocities of the helium and hydrogen are constrained by dynamical friction to become equal, and no further change in relative abundance is expected during the expansion of the solar wind.

It should be emphasized that these results apply only to a stationary spherically expanding corona and care must be exercised in applying the results to non-stationary problems.

Two salient facts emerge from the theoretical discussions reviewed above. The first is that normal solar wind processes, which produce the observed equality of velocity between helium and hydrogen, also produce a solar wind with a lower percentage of helium than present in the regions from which the wind arose; and second, that diffusion in the solar atmosphere is easily capable of producing helium enhancements to relative abundances much greater than those observed in interplanetary space.

In this discussion we have neglected the effect of diffusion in the temperature, magnetic field and density gradients that exist in the neighborhood of solar active regions. However, the same processes that produce a tendency toward elemental separation in the corona as a whole, will act to produce separation in the neighborhood of active regions.

Summarizing then, in the absence of sufficiently strong mixing mechanisms, diffusion in the solar atmosphere will produce a separation of elements, both on the scale of the atmosphere as a whole and in the neighborhood of active regions. The interplanetary medium, produced from various regions of the atmosphere, samples diverse parts of it. The relationship between the relative abundance of the sample and its source depends on the method used to accelerate the sample.

In order to determine what region of the solar atmosphere is sampled by the piston plasmas, we wish to discuss, in a qualitative way, a model that may produce the observed piston plasma.

We start by rejecting as unlikely the notion that the plasma piston is simply enhanced solar wind emitted from a large region of hot corona. There are many difficulties with this concept. First, the corona is so tenuous that in order to find enough particles (4×10^{39}) at several $R_{\odot}$, the area of the emitting region must be of the order of the area of the visible side of the sun. For example, above $2 R_{\odot}$ in the corona, there are only of the order of 10^{40} particles all together. Such a broad solar source is very difficult to reconcile with the observed shape of shocks that form in front of the piston (De Young and Hundhausen, 1971). A second difficulty with the concept of the plasma piston as an enhanced solar wind is that our observations imply a velocity of about 1,000 km/sec or more at 0.1 A.U. This is considerably faster than the maximum velocity possible (800 km/sec) according to the one fluid model of solar wind production (Parker, 1963). Even if more sophisticated models could produce such velocities, which is doubtful, it would still be required that the corona be heated up to 4×10^6 °K over the entire emitting region. A third difficulty and perhaps the most important objection to this model is that since normal solar wind processes tend to leave helium behind, a piston $\text{He}/\text{H} \approx 15\%$ implies unreasonably high values for the relative helium abundance in the emitting region.

The concept of a localized source of the flare plasma, leads to fewer conceptual difficulties. In these models, the piston plasma would arise from a region of a size somewhat comparable to the flare itself and be ejected, as a body, into the solar wind. It is interesting to ask from what level of the solar atmosphere the material in the plasma comes. If it comes from an area as small as that of

optical flares ($3 \times 10^{19} \text{ cm}^2$) then the density at the source must be of the order of $10^{13} \text{ particles cm}^{-3}$. Thus a chromospheric origin is demanded. The material would have to be heated up, the helium and hydrogen completely ionized, and then the material ejected. Because of the high temperature needed for complete ionization, the material cannot come from the same time and place as the H_{α} emission. A source higher in the corona and of larger size should also be considered.

The hypothesis that the plasma piston is associated with the source of the Type II radio emission is very attractive. The Type II emission is believed by most workers to be due to high energy electrons interacting with a flare-produced shock propagating through the corona (Wild et al., 1963). We wish to check if the identification of the plasma piston as the cause of the shock leads to reasonable values for the initial height in the corona, volume, and particle density of the piston plasma. Although the initial height of the source of the Type II emission is uncertain (Kuckes and Sudan, 1971) it is commonly estimated to be $0.2 - 0.3 R_{\odot}$ above the photosphere (Kundu, 1965, Kuckes and Sudan, 1971). The typical size of the Type II radio source is of the order of $6'$ of arc ($2.5 \times 10^{10} \text{ cm}$). The size of the Type II region can be used to estimate the initial volume of the piston. The resulting volume ($1.5 \times 10^{31} \text{ cm}^3$) leads to an estimate of about 2.5×10^8 particles/cc for the initial piston particle density. Using the coronal density model of van de Hulst (Billings, 1966) and multiplying by a factor of 2 to 10 to account for the condensations that occur over active regions (Newkirk, 1967), we find that the proper coronal densities occur at levels below about $0.5 R_{\odot}$ or so,

depending on the strength of the condensation. This is in good agreement with the level of the source of the Type II bursts. On this basis, the helium enriched plasma is tentatively identified as the piston that drives the shock causing the Type II radiation, and it is estimated that the height of origin is very roughly $0.3 R_{\odot}$ above the photosphere, i.e., well down into the region in which a general coronal increase of the relative abundance of helium is expected on the basis of theory.

Returning to the observations of the post-flare solar wind, the data show that a stream of high velocity solar wind is emitted for a day after the initial ejection of the plasma piston (Hundhausen et al., 1970a). This new long-term wind is not helium enriched and the process producing it is probably very different from the processes producing the initial part of the piston. The new wind may also sample a different level of the corona from either the initial piston or the normal solar wind.

With the preceding discussion in mind, the following model for production of helium enriched pistons is suggested for further study. The plasma either in the neighborhood of the H_{α} flare, or in the lower corona, is heated by the flare. The relative helium abundance may be enhanced either by local concentrations in the active region, or by widespread coronal diffusion mechanisms. The plasma blob is accelerated upward; the plasma is confined within the hot region by magnetic fields, so the helium does not leak out, and is not left behind. A shock, producing Type II radio emission, forms in front of the rising plasma. The blob is accelerated into interplanetary space, still expanding. Meanwhile, the corona in a very

broad area above the flare has been heated and begins to emit the new high-velocity solar wind, containing a normal percentage of helium. This new wind can help propel the helium enriched piston plasma through space.

In summary, before observations of the percentage of helium in the piston plasma can be compared quantitatively with theory, mathematical models dealing with the effect of postulated plasma acceleration mechanisms on the helium abundance in the piston must be developed. Although the flare pistons described in this paper showed $\text{He}/\text{H} \approx 15\%$, this must be considered a rough estimate of the helium abundance of the source regions. It can be expected, however, that further observations of flare piston plasmas will be important in testing postulated solar flare acceleration models and in determining the relative abundance of helium at various positions in the solar corona, and, in time perhaps, the relative helium abundance of the sun itself.

Acknowledgements

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Figure Captions

Figure 1. - An illustration of the variability of the relative helium abundance in the interplanetary plasma. The top spectrum indicates less than 1% helium, while the lower spectrum shows a solar wind containing 22% helium. The shift of the spectrum to the right is due to an increase in velocity (from Hirshberg et al., 1971).

Figure 2. - The distribution of solar wind $\frac{\text{He}}{\text{H}}$. Note that in the Vela data (solid line) only 48 of more than 10,300 spectra showed more than 15% helium. The HEOS data (shaded bars) indicates a larger percentage of helium enhanced spectra during the period of greater solar activity, leading to an increase in the average helium abundance. However, there is no shift in the position of the modal value, suggesting that the quiet regions of the Sun emit the same $\frac{\text{He}}{\text{H}}$, no matter what the stage of the solar cycle. Vela data from Robbins et al., 1970, HEOS data from Formisano et al., 1970.

Figure 3. - Neutron monitor data covering the period of August 17, 1965, when a major helium enhancement was observed in the absence of solar flares. The helium enhanced period (shown as a shaded block) follows a small Forbush decrease.

Figure 4. - Schematic representation of a flare disturbance propagating in the solar wind. The position of the earth is shown as for a central meridian flare. The sizes and shapes of the various regions are taken from theory or experiment whenever possible. The shape of the shock is derived from geomagnetic data (Hirshberg, 1968). The asymmetry of the shock is due to an asymmetry present in the data from which it was derived. The distance between the shock and piston is from theory (Hundhausen and Gentry, 1969), confirmed by the present study. The width of the helium region is from the present study. Effects of solar rotation have been omitted.

Table I

Major Flares, March 1966

<u>Date of Flare</u>	<u>Position of Flare</u>	<u>Date of Helium Enhancement</u>	<u>Slowing Ratio</u>
66-03-16	N22 E66	—	—
-19	N22 E35	03-23	{ 1.08 or 0.70
-20	N21 E18		
-21	N20 W10	—	—
-24	N18 W37	03-26	0.70
-25	N14 W54	03-28	1.01

Table II
Flares Causing Solar Wind Helium Enhancements $\geq 15\%$

Flare Date	Class	Position	Max. % He	Observed Velocity of Plasma	Mean Transit Velocity of Plasma	Slowing Ratio	Width $\times 10^6$ km	Number of Particles $\times 10^{39}$
66-03-20	3B	N20E15	31	436	575	0.76	1	1.3
66-03-24	3B*	N18W37	26	535	764	0.70	2.4	1.1
66-03-25	3B	N14W54	18	525	520	1.01	7	0.7
66-08-28	2B*	N23E05	16	653	594	1.10	—	—
66-08-31	2N	N24W30	17	439	488	0.90	8	2.6
66-09-2	3B*	N25W57	22	424	580	0.70	7.5	5.3
66-09-17	2B*	N25W65	17	520	745	0.70	32	8
66-10-14	2B	N20E42	16	358	577	0.62	0.8	0.3
67-01-11	3B*	S26W47	29	460	697	0.66	19	15
67-02-13	3B*	N20W10	22	559	667	0.84	1	0.8
67-05-23	2B*	N28E24	16	655	780	0.84	—	—
67-05-28	3B*	N27W36	17	625	644	0.97	—	—
AVERAGE						0.81		$\approx 4 \times 10^{39}$

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FIGURE CAPTIONS

Figure 1. Variation of relative helium abundance.

Figure 2. Comparison of helium abundance distributions.

Figure 3. Enhanced helium event of August 1965.

Figure 4. Solar flare disturbance.

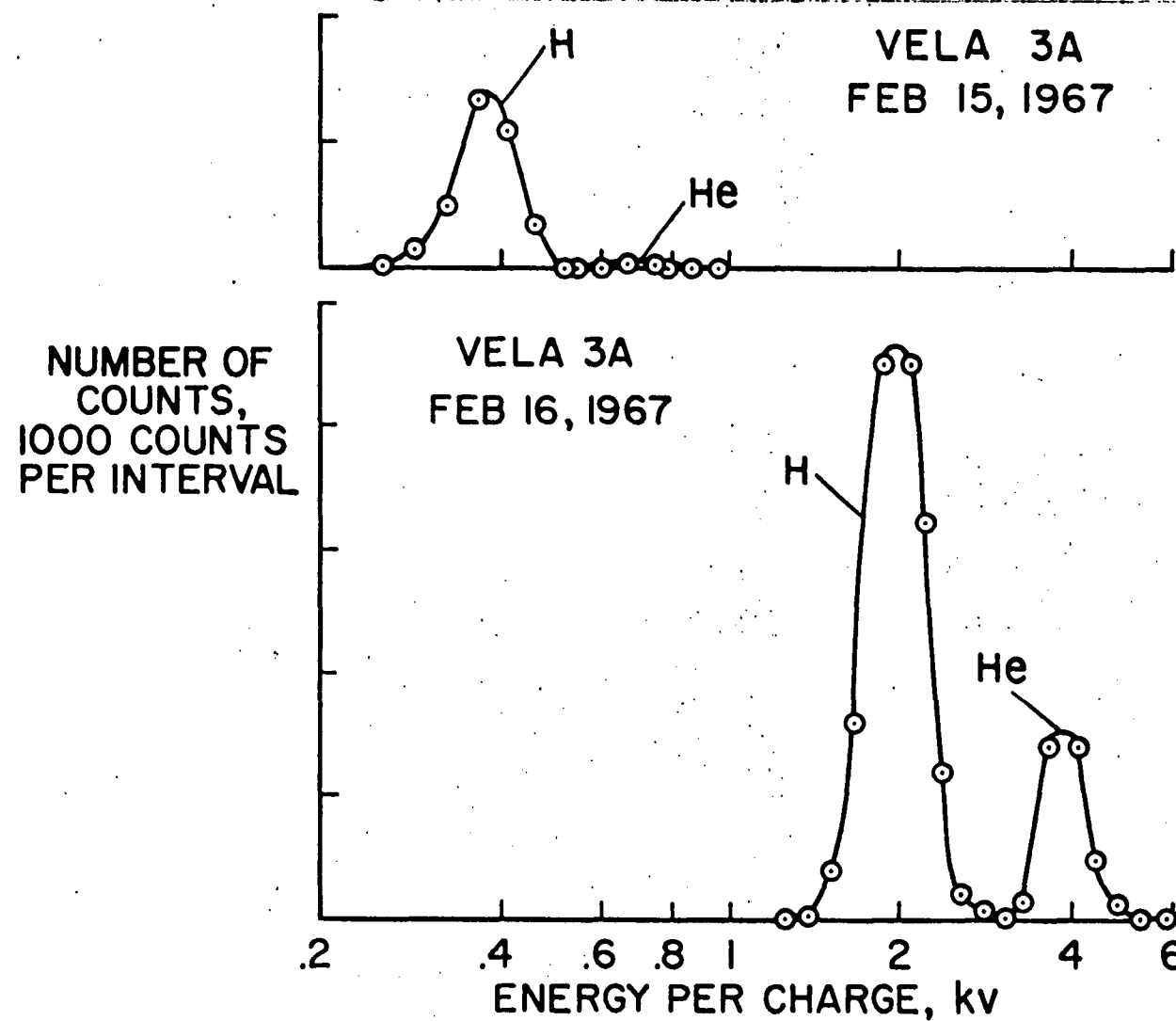


Fig. 1

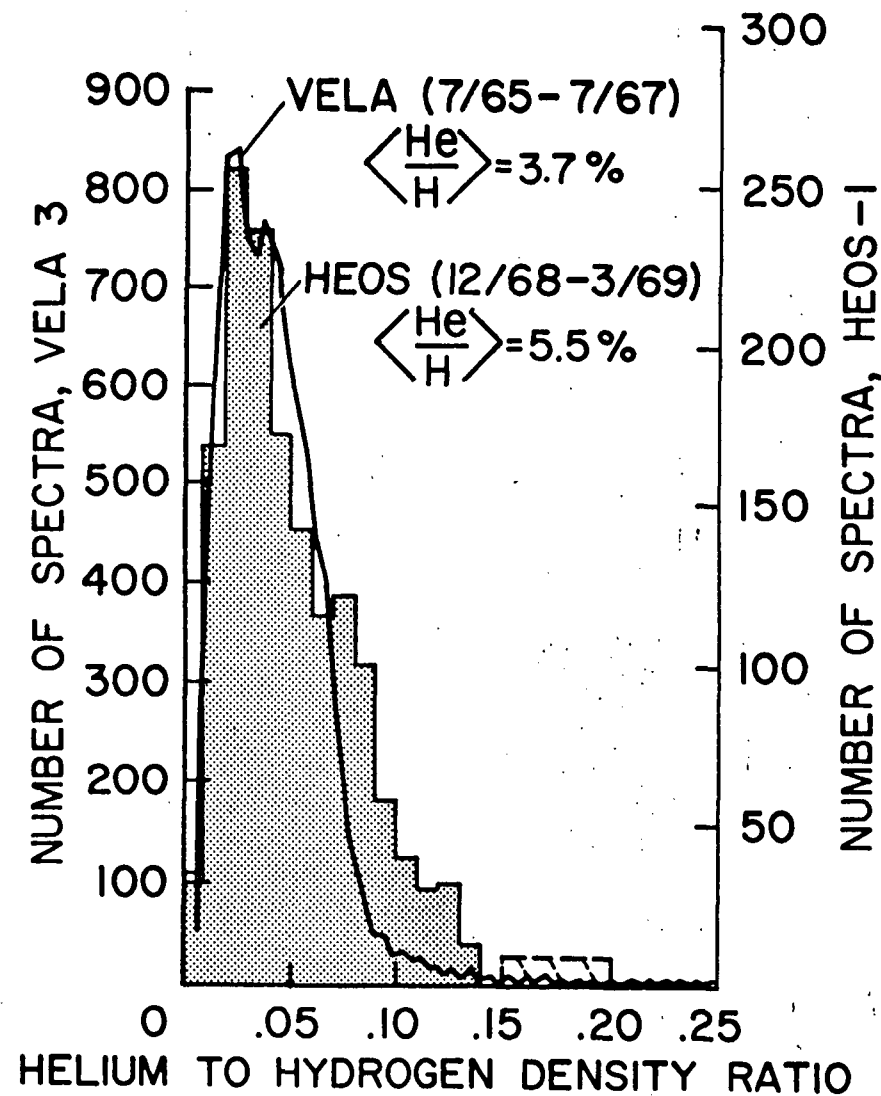


Fig. 2.

HELIUM EVENT OF AUGUST 1965

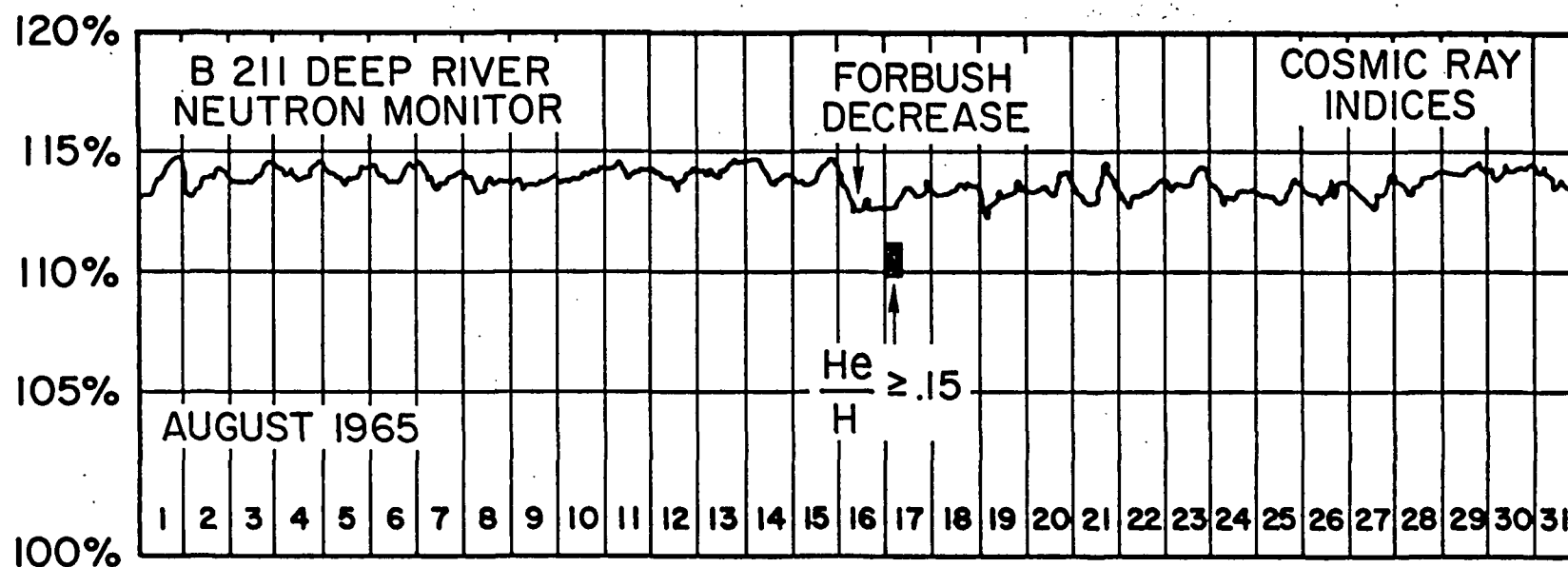


Fig. 3

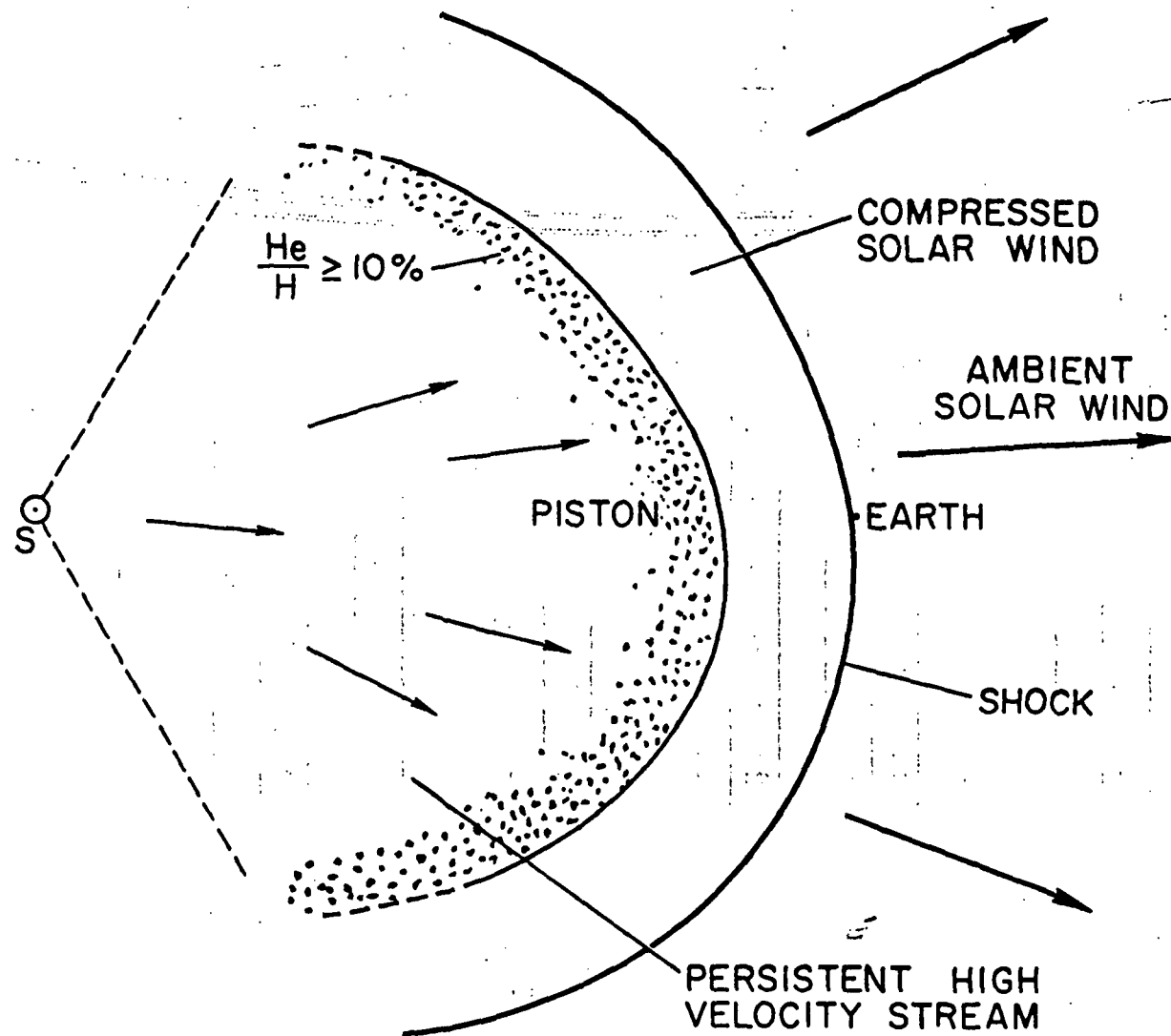


Fig. 4

SHOCK WAVES IN THE SOLAR SYSTEM

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ABSTRACT

Data acquired in space in recent years and the associated intensive efforts to understand their meaning have led to a virtual revolution in our concept of interplanetary space and of the role of gasdynamic processes including shock waves and electromagnetic forces in the transfer of solar material and energy to the Earth and elsewhere throughout the Solar System. This paper provides a review of the salient features of these phenomena as they are revealed by direct observation and theory.

Gasdynamic processes are now known to be essential for the maintenance of the quasi-stationary 2×10^6 °K temperature of an extended solar corona and the consequential development of an extremely tenuous solar wind that flows away from the Sun at all times at 300 to 800 km/sec throughout our part of the Solar System. In spite of the spherical appearance of the Sun, the solar wind flow is highly structured on a wide range of scales from large semipermanent rotating sectors, usually two or four in the plane of the ecliptic, to fluctuations, possibly of a magnetohydrodynamic turbulence nature, extending to the smallest scale to which measurements have been made. The sectors are characterized predominantly by outward or inward magnetic polarity and a spatial variation of gasdynamic properties that is remindful qualitatively of that observed at great distances

from a supersonic projectile or aircraft. Although the solar wind flow is directed nearly radially outward from the Sun, the sector boundaries rotate with the Sun in an approximately rigid body motion. The overtaking of slower parts of the solar wind by the faster plasma flow behind the sector boundaries leads to nearly discontinuous changes in flow properties that may be usefully approximated by magnetohydrodynamic tangential discontinuities, contact surfaces, and shock waves. Their arrival at Earth and periodic return with each solar rotation account, in ways not fully comprehended in detail, for many 27-day periodicities in geophysical observations of the upper atmosphere and geomagnetic field.

This supersonic plasma flow past Earth leads to containment of the geomagnetic field within a limited region of space, the magnetosphere, and to formation of a bow shock wave that resembles, in many ways, the bow wave that precedes a blunt-nosed object in hypersonic flight in the atmosphere. Recent investigations have revealed that Venus and Mars possess similar bow waves, although neither has a significant magnetic field and the solar wind interaction is with the ionosphere rather than the planetary magnetic field. The Moon, without significant field or atmosphere, provides still another type of interaction in which the solar wind plasma flows directly into the sunward hemisphere, where it is absorbed on contact without the development of a bow wave. Related interactions are presumed to occur for other major objects in the Solar System, but knowledge of them is more speculative since direct observations have not yet been made, and the surprises encountered in learning of the true nature of the interactions of the solar wind with Earth, Mars, Venus, and the Moon are sufficient to provide a sobering influence on our predictive abilities.

Equally important to these quasi-stationary features are the transient effects resulting from solar flares, gigantic outbursts in the lower atmosphere, the photosphere, of the Sun that release as much as 10^{32} ergs of energy during about a 1000 sec interval. This is a truly spectacular energy release by any terrestrial standard, being comparable to about 10^8 times the estimated energy of the Krakatoa explosion or of a 100 megaton hydrogen bomb; although it is, of course, dwarfed completely by the energy released by nova, supernova, quasars, and other astronomical phenomena involving the entire star. These eruptions on the Sun send out blast waves that travel both across the face of the Sun and out into the outwardly flowing solar wind of interplanetary space. Their arrival at Earth sets off a whole complex of related geophysical events including geomagnetic storms, polar aurora, ionospheric disturbances, and a whole host of more subtly related phenomena extending possibly all the way into the biological realm.

It is the purpose of this paper to provide a broad summary of these phenomena with particular attention to the role of shock waves, and with emphasis more on the nature and interrelation between the various phenomena as they are now understood than on precise details of specific theoretical models currently in vogue.

INTRODUCTION

In 1955, Gold [1] made the startling proposal that a collisionless shock wave must travel from the Sun to the Earth to account for the sudden commencement of a geomagnetic storm. Although the satellite era had not commenced at that time, it is nevertheless remarkable that such a proposal had not been made previously, as observations that could have been cited to support the idea had been accumulating

for nearly a century. Indeed, the circumstances surrounding the first observation provide at once a suitable introduction to this discussion and a fascinating story in the development of understanding of the diverse phenomena now studied collectively under the heading Solar-Terrestrial Relations.

On September 1, 1859, at about 11^h18^m G.M.T., the famous English solar astronomer, Carrington, was observing a large spot on the Sun. Upon seeing, for the first and only time in his career, an outburst of bright light within a large sunspot group, he noted the time and hastened to call someone to witness the event with him. Upon returning within 60 seconds, he wrote that he was mortified to find that it was already much changed and enfeebled. By 11^h23^m, all trace of the event was gone, and he could detect no change in the appearance of the Sun from that he had sketched just before the event took place.

At the same time, all three components of the Earth's magnetic field being recorded photographically at Kew Observatory became abruptly disturbed [2]. (See the traces of the magnetic records in Fig. 1.) About 18 hours later, a great geomagnetic storm commenced abruptly that surpassed in intensity and duration all previous observations. For several days, auroral displays of almost unprecedented magnificence were observed widely throughout the globe. In not a few instances, telegraph communication was interrupted, because of the current produced in the wires; and in some cases this proved so powerful that the batteries were disconnected and the wires simply connected with the Earth. We would now regard the geomagnetic disturbance on September 1 as due to the fleeting enhancement of ultraviolet light and X-rays; and the great storm beginning about 18 hours later as the effect of arrival of an interplanetary shock wave followed by the solar matter ejected from the Sun by Carrington's flare.

Fig. 1

THE ROLE OF SHOCK WAVES IN CORONAL HEATING AND THE ESTABLISHMENT OF THE STEADY-STATE SOLAR WIND

It is now well established that shock waves play an important role in not only dramatic transient events, such as that observed by Carrington, but also in the maintenance of the normal steady-state characteristics of the interplanetary medium. We may begin our discussion of the latter by examining the photograph of the solar corona shown in Fig. 2. taken from a high-flying jet aircraft at the time of the solar eclipse of May 30, 1965. From our point of view, the most significant thing about the corona, or extended upper atmosphere of the Sun, is its high temperature of the order of 2×10^6 °K throughout a region many times the size of the Sun. To provide a detailed understanding of how such an elevated temperature is maintained in the corona exposed on the lower side to the 5800° K of the photosphere, or visible surface of the Sun, and to the cold vastness of space on the other side has been an important objective in solar physics ever since Lyot, Edlén, and others perceived the high coronal temperatures about 30 years ago.

Fig. 2

Consideration of the temperature profile through the Sun and the corona, illustrated schematically in Fig. 3, shows, however, that it is not so much the high temperature of the corona that is anomalous as it is the comparatively low temperature of the photosphere. To understand this, let us recall that the energy created by nuclear fusion in the deep interior is transmitted outward through most of the Sun by radiative transfer. Near the photosphere, however, the density drops to such a level that the outgoing radiation escapes freely into space, and the temperature drops precipitously toward the relatively low value of about 5800° K required to radiate away 4×10^{33} ergs/sec from the surface of a sphere 7×10^{10} cm in radius

Fig. 3

(i.e., an energy flux rate of about 6×10^{10} ergs/cm² sec). After reaching a minimum temperature that may be as low as 4500° K, the temperature climbs rapidly in the chromosphere and reaches 10^6 °K at an altitude of about 3000 km above the photosphere, an average rise of about 1° K every 3 meters! It then continues to increase at a slower rate to a broad maximum of about 2×10^6 °K in the overlying corona. Because the atmosphere behaves much like a perfect gas in hydrostatic equilibrium in this region, the density displays a corresponding precipitous drop through the chromosphere followed by a much slower rate of decline in the hot corona.

Although serious consideration was at first given to the possibility that the corona was heated by the gravitational energy released by accretion of interstellar matter, it was soon concluded (see Kuperus [3] for a review) that the only process that can be taken seriously is the dissipation of mechanical energy rising from the lower layers of the Sun. While radiative transfer through a motionless gas is thought to be the dominant energy transfer process throughout most of the interior of the Sun, the results of calculations with such a representation indicate the temperature gradient to be steeper than the adiabatic gradient over a region extending downward from the photosphere for more than 10^{10} cm. The region is thus unstable to convective overturning; and the resulting motions assist in the energy transport and in the establishment of a temperature gradient intermediate between the adiabatic gradient and the radiative transfer solution. Although nearly all the energy flux of the Sun is radiated away from the photosphere, the gases there have been set into violent motion with vertical velocities of the order of 1 km/sec, and

horizontal velocities at least an order of magnitude larger, as illustrated in Fig. 4. Within cellular regions bounded by concentrated magnetic fields, marked by upsurging spicules, and covering the entire surface of the Sun, except possibly where inhibited by the even stronger magnetic fields of sunspots, these oscillations generate many classes of wave motion, including sound, gravity, and magnetohydrodynamic waves, and their combined counterparts that may occur in an ionized gas in a gravitational field. Of these, it has been concluded from an examination of their generation and transmission properties [3] that ordinary sound waves provide the dominant contribution to the flux of mechanical energy from the photosphere to the corona. Although many details remain to be clarified, there can be no doubt that these waves amplify and steepen into trains of shock waves as they propagate outward into regions of diminishing density, and that dissipation of these shocks provides the energy source to heat the corona. The level at which the major deposition of this mechanical energy occurs is controlled, moreover, by the strong $(T^{5/2})$ dependence on temperature of both the viscosity and thermal conductivity of an ionized gas. Since the energy thus passed upward into the corona exceeds that which the corona can release by radiation or by conduction back down to the chromosphere and photosphere, energy continues to flow outward into space from the corona. Although outward heat conduction may be dominant in the middle part of the corona, convection soon takes over and leads ultimately to the solar wind that flows past the orbit of Earth. Its properties are quite variable in time and space, but speeds between 300 and 800 km/sec and densities between 1 and 50 or more protons/cm³, and an equal number of electrons to insure charge neutrality, are representative.

Fig. 4

Theoretical studies of the heating of the solar corona and the development of the solar wind are customarily based on the assumptions that (a) the medium involved is a perfect monatomic gas with equation of state

$$p = \frac{\rho RT}{\mu} = 2 nkT \quad (1)$$

where p , ρ , n , and T are the pressure, density, ion number density, and temperature, μ is the mean molecular mass in atomic units (i.e., $\mu = 1/2$ for fully ionized hydrogen), $R = 8.31 \times 10^7$ ergs/gm °K is the universal gas constant, and $k = 1.38 \times 10^{-16}$ ergs/°K is Boltzmann's constant; (b) all large-scale motions are steady and spherically symmetric; and (c) the effects of small-scale and transient motions associated with the formation and dissipation of shock waves can be approximated in the analysis of large-scale motions by a heat addition term q_h in the energy equation

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left[r^2 \rho v \left(\frac{v^2}{2} + h - \frac{GM_{\odot}}{r} \right) \right] = q_h - q_r - \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \kappa \frac{\partial T}{\partial r} \right) \quad (2)$$

where $h = 5 RT = 5 kT/m$ is the specific enthalpy for a monatomic gas with specific heat ratio $\gamma = 5/3$, $m = 1.67 \times 10^{-24}$ gm is the mass of a proton, $G = 6.67 \times 10^{-8}$ cm³gm sec² is the gravitational constant, $M_{\odot} = 2 \times 10^{33}$ gm is the mass of the Sun, r is the heliocentric radius, q_h is the heating per gram by mechanical processes of shock dissipation, and q_r is the loss of energy by radiation. The coefficient of thermal conduction κ is usually taken to be given by

$$\kappa = 6 \times 10^{-7} \times T^{5/2} \text{ ergs/cm}^2 \text{ sec } ^\circ\text{K} \quad (3)$$

as derived for a fully ionized gas by Chapman [4], although the presence of a magnetic field such as exists in the solar wind vastly reduces the thermal conduction perpendicular to the direction of the magnetic field. Numerous processes contribute to the radiative losses of a unit volume of optically thin coronal matter, but the total radiative losses have been estimated by Orral and Zirker [5] to be given by

$$q_r = 1.76 \times 10^{-23} n^2 \text{ erg/cm}^3\text{sec} \quad (4)$$

Considerable uncertainty in the value of the coefficient exists, however, because of insufficient knowledge of relative abundances and oscillator strengths. The heating q_h due to dissipation of a train of shock waves is proportional to the increase in enthalpy during a shock and expansion cycle. For weak shock waves, Kopp [6] has shown that q_h may be approximated by

$$q_h = \frac{5 \rho R T}{2 P} (M_s - 1)^3 \quad (5)$$

in which P is the period of the shocks, and M_s is the shock Mach number, which depends in a complicated way on the temperature and Mach number of the average flow and the heliocentric distance. It is apparent that several aspects of the theory may be refined, but the solution of these equations together with the equations of continuity and motion

$$\frac{\partial}{\partial r} (\rho v r^2) = 0, \quad v \frac{\partial v}{\partial r} = - \frac{1}{\rho} \frac{\partial p}{\partial r} - \frac{GM_\odot}{r^2} \quad (6)$$

for steady radially symmetric flow provides the most comprehensive basis for theoretical analysis of the heating of the solar corona and development of the solar wind that is now available.

Fig. 5 shows results of a calculation of Kopp [6] for the temperature and various components of the energy flux as a function of distance from the Sun for a special case. The shock-wave period is taken to be 300 sec, and plausible values are used for the boundary conditions at the Sun, Earth, and infinity. Although the precise values depend on the choice of these parameters, and on the approximations used in evaluating various components of the energy equation, particularly q_h (see Kuperus [3] for a discussion), the general trends displayed here are representative, and the differences are not important for the present discussion. In this plot, the convective part of the energy flux is presented in terms of the three components, kinetic, thermal, and gravitational, indicated by the three terms on the left side of Eq. (2). Positive conductive flux represents the contribution of $-r^2 \kappa \partial T / \partial r$, and mechanical flux represents the contribution of the shock-wave train. Since the shock-heating model described above and used by Kopp with only minor modifications is not considered adequate in the chromosphere and the immediately overlying transition region extending upwards for about 10,000 km from the photosphere, the results for those regions are indicated by dashed lines. (An improved fluid theory of chromospheric heating by dissipation of fast magnetohydrodynamic shock waves has been given recently by Mäcke [7].) The dotted line represents Kopp's estimate of more realistic values for the temperature.

Fig. 5

In Kopp's classification, region I is the chromosphere in which mechanical heating is balanced by radiation, and heat conduction is unimportant because of the small temperature gradient. Region II is the lowermost part of the transition region between the chromosphere and the corona in which the temperature starts to rise suddenly, and thermal conduction competes with radiation. In region III, which is also part of the transition, thermal conduction becomes more important than radiation. The conductive flux is almost constant, and hence largely determines the temperature profile. In region IV, the temperature increases to the coronal maximum of about 2×10^6 °K. Mechanical heating is very important in this region. Heat conduction drops to zero at the upper boundary, and then reverses its direction from inward to outward in higher regions. Since the kinetic energy flux is insignificant in regions I through IV, these layers may be considered to be in hydrostatic equilibrium. Hydrodynamic expansion becomes important at about the lower boundary of region VI as the kinetic energy flux becomes noticeable, and the mechanical energy flux in the shock-wave trains becomes exhausted. Above this level, neither mechanical heating nor radiative losses play an important role in the energy budget. The temperature structure in region VI is thus determined by the interplay of thermal conduction and hydrodynamic expansion in a central gravity field. Far from the Sun, heat conduction probably becomes negligible and the remaining energy is conveyed outward primarily by adiabatic expansion of the solar corona.

The expanding solar plasma accelerates rapidly in region VI and surpasses the speed of sound $a = (\gamma p / \rho)^{1/2} = (\gamma RT / \mu)^{1/2}$ within a few solar radii of the Sun at the level where the ratio of kinetic energy flux to thermal energy flux is

$(1/3)^{1/2} = 0.58$. It continues to accelerate to supersonic speeds as it passes farther from the Sun to form the solar wind. Representative values for the properties of the solar wind near the Earth are summarized in Fig. 6 with their theoretical variation with distance r from the Sun expressed in AU. All these quantities display substantial variations with time and location. The chemical composition is principally fully ionized hydrogen with a small mixture, usually about 4 percent, but sometimes more than 20 percent, of helium nuclei. The expanding coronal plasma, being effectively a perfect electrical conductor, carries with it the relatively weak solar magnetic field, stretching the lines of force outward through the solar system and enhancing the magnetic field there while generally maintaining direct connection to the Sun. Because of the rotation of the Sun, the magnetic lines of force spiral in the plane of the ecliptic making, on the average, an angle of about 45° with the direction from the Sun to the orbit of Earth.

Fig. 6

It is generally presumed that the region of supersonic solar-wind flow terminates with a shock wave at some location between 50 and 100 AU, and that the flow beyond is subsonic. Ultimately, at great distances from the Sun, the solar wind must interact in some way with the interstellar gas, usually estimated to have properties similar to those listed in Fig. 6. Fluid considerations suggest the development of an interface, the heliopause, separating the solar and interstellar plasmas, and also a bow wave if this interstellar flow is supersonic. So little is known about the nature of the interaction and the properties of the gases involved, however, that even the existence of the terminal shock wave and heliopause must be regarded as hypothetical.

Returning our attention to conditions near the orbit of Earth, geophysical measurements including magnetic fluctuations, auroral, and ionospheric disturbances have long been known to display a recurrence pattern associated with the 27-day rotation period of the lower latitude regions of the Sun. These were used more than 40 years ago by Chapman [8] to infer the existence of long-lived jets of plasma emitted from limited regions of the solar surface; but satellite observations have shown that they are, in fact, the result of a rotating sector structure within the solar wind. Principal properties of this sector structure revealed by the data from IMP I satellite for the winter of 1963-64 are summarized in Fig. 7. The sketch on the left indicates schematically the boundaries of the four sectors and the predominant direction of the interplanetary magnetic field in each by plus (away from the Sun) and minus (toward the Sun) signs. Although the sector is defined in terms of the direction of the interplanetary field, Wilcox and Ness [9,10] have shown that it is a coherent entity with an organized semipermanent internal structure. The evidence is summarized on Fig. 7 in the form of superposed epoch plots of the velocity, density, and magnetic intensity as a function of position within the three larger 8-day sectors shown on the left. The abscissa represents azimuthal position within a sector with day 0 designating the day on which a sector boundary sweeps past the Earth. The remaining plot shows the corresponding results for the fluctuations of the geomagnetic field, as indicated by the 24-hour sum of Kp (an index running from 0 to 72 with increasing activity). The velocity, magnetic field intensity, and geomagnetic activity index all display roughly the same type of variation within a

Fig. 7

sector, with the maximum occurring one or two days after the passage of the sector boundary followed by a more or less monotonic decline throughout the remainder of the sector. The density variation is substantially different, however, with the maximum values occurring approximately coincidentally with the sector boundaries, and the minimum values occurring in the central parts of the sector. Continuing observation of the solar wind has revealed that a sector structure has continued to persist in the years since its discovery in the IMP I data, but that the number of sectors is sometimes two rather than four as illustrated here.

SHOCK WAVES IN SOLAR WIND FLOW PAST PLANETS AND THE MOON

The concept of a supersonic solar wind flowing outward from the Sun leads immediately to questions of how it flows around and interacts with the Earth, Moon, and planets. These matters have been investigated extensively, both theoretically and observationally, in recent years. The general behavior may be said to be quite well understood, although many details, particularly of transient effects, need to be clarified.

As recognized more than 40 years ago by Chapman and Ferraro [11], the solar plasma, with virtually infinite electrical conductivity, is held away from the Earth by the geomagnetic field. The shielded region, the magnetosphere, extends about 10 Earth radii in the sunward direction, and acts as an obstacle in the supersonic flow of the solar wind, as illustrated in Fig. 8. Although not conceived in the earlier work, a bow wave is now known to stand a few Earth radii upstream of the magnetosphere. In contrast to the early works, which were based on

Fig. 8

particle trajectory concepts, nearly all modern analyses of large-scale features of the interaction are based on the assumption that the average bulk properties of the flow can be described adequately by the continuum equations of magnetohydrodynamics of a perfect gas having infinite electrical conductivity, and zero viscosity and thermal conductivity. That this should be so is not at all obvious, since the mean free path of the particles, based on Coulomb interactions, is of the order of half the distance between the Sun and Earth. Indeed, theoretical justification is essentially qualitative at the present time, and usually consists of referring to randomizing and isotropizing effects of small-scale irregularities, perhaps a form of turbulence, that are always in the solar wind. Details of these processes are seldom discussed in depth, and it is fair to state that the real support for the use of the continuum fluid model is provided by the outstanding agreement between results calculated in this way and those actually measured in space.

In regions in which the flow properties vary in a continuous manner and the indicated derivatives exist, the equations of magnetohydrodynamics of a dissipationless perfect gas are

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0 \quad (7)$$

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p - \frac{1}{4\pi} \mathbf{B} \times \text{curl } \mathbf{B} + \rho \mathbf{g} \quad (8)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \text{curl } (\mathbf{v} \times \mathbf{B}), \quad \text{div } \mathbf{B} = 0 \quad (9)$$

$$\frac{Ds}{Dt} = 0, \quad s - s_0 = c_v \ln \frac{p/p_0}{(\rho/\rho_0)^\gamma} \quad (10)$$

in which s refers to the entropy, subscript o refers to conditions at an arbitrary reference location, and D/Dt refers to the substantial derivative $\partial/\partial t + (\underline{v} \cdot \underline{\nabla})$. If effects of gravity $\underline{g}$ are disregarded, flows described by these equations depend on two nondimensional ratios, the Mach number $M = v/a$ and the Alfvén Mach number M_A , where $A = (B^2/4\pi\rho)^{1/2}$ is the Alfvén speed and $\underline{B}$ is the magnetic field. Both M and M_A are normally much greater than unity, values of about 10 being representative for the solar wind flow approaching the Earth's bow wave.

These equations must be supplemented by the conservation equations relating conditions across possible discontinuities in the flow. At each element of such a surface, conservation of mass, momentum, energy, and magnetic field provides the relations

$$\left[\rho \tilde{v}_n \right] = 0, \quad \left[\rho \tilde{v}_n \underline{v} + \left(p + \frac{B^2}{8\pi} \right) \hat{n} - \frac{B_n \underline{B}_t}{4\pi} \right] = 0 \quad (11)$$

$$\left[\rho \tilde{v}_n \left(h + \frac{v^2}{2} \right) + \frac{\tilde{v}_n B^2}{4\pi} - \frac{B_n \underline{v} \cdot \underline{B}}{4\pi} \right] = 0 \quad (12)$$

$$\left[B_n \underline{v}_t - B_t \tilde{v}_n \right] = 0, \quad \left[B_n \right] = 0 \quad (13)$$

The square brackets indicate the difference between the enclosed quantities on the two sides of the discontinuity; $\tilde{v}_n = \underline{v} \cdot \hat{n} - \underline{v}_n$ is the normal fluid velocity component relative to the normal velocity $\underline{v}_n$ of the discontinuity surface; $\hat{n}$ and $\hat{t}$ are unit vectors normal and tangential to the discontinuity surface; and subscripts n and t indicate components of $\underline{v}$ and $\underline{B}$ in these directions. Five classes of

magnetohydrodynamic discontinuities, tangential, contact, rotational, and fast and slow shock waves, are known to be described by these equations [12]. All have been identified in the solar wind, and several are important in the flow field of the Earth and other major objects in the solar system [13,14].

For steady flow of the solar wind past the Earth, several important simplifications may be introduced beyond the obvious elimination of terms containing $\partial/\partial t$ or λ [15]. In the magnetosphere, $B^2/8\pi$ greatly exceeds p everywhere above a few hundred kilometers; and the dominant effect of the Earth is provided by the terms that remain when p and ρ are equated to zero, namely

$$\text{div } \underline{B} = 0, \quad \underline{\text{curl}} \underline{B} = 0 \quad (14)$$

where $\underline{B}$ now represents the geomagnetic field. The latter may be represented with sufficient accuracy for the present purposes by a magnetic dipole at the center of the Earth with such a strength that $|\underline{B}| = B_{\text{eq}} = 0.312$ gauss at the geomagnetic equator, and oriented so that the north geomagnetic pole is at 78.6° North latitude and 70.1° West longitude, near Thule, Greenland. Its properties are thus given by

$$\underline{B} = -B_{\text{eq}} (a_e/r)^3 (\hat{\theta} \sin \Theta + \hat{r} 2 \cos \Theta) \quad (15)$$

in which $a_e = 6.37 \times 10^8$ cm is the radius of the Earth, r is the geocentric distance, and Θ is the polar angle measured with respect to the north geomagnetic pole, and $\hat{r}$ and $\hat{\theta}$ are unit vectors in the r and Θ directions. The magnetopause, which bounds the magnetosphere and the flowing plasma, can be represented only by a tangential discontinuity, since that is the only solution of the steady-state

conservation equations for which $v_n = B_n = 0$. Arbitrary differences in ρ , $\underline{v}_t$, and $\underline{B}_t$ are allowed, but the sum of the gas and magnetic pressures $p + B^2/8\pi$ must be the same on both sides of this surface. The bow wave can be represented only by a fast shock-wave solution because the solar wind approaches the Earth with a mass flux $\rho_\infty \underline{v}_\infty$ that greatly exceeds that which can pass through any of the other types of discontinuities. In the flowing solar plasma, the terms containing $\underline{B}$ and $\underline{g}$ may be disregarded because of their smallness in the calculation of the fluid motion. The equations for the fluid motion thereby reduce to the much simpler ones of gasdynamics; and the distortion of the interplanetary magnetic field can be determined in a subsequent step by solving the remaining equations with $\underline{v}$ known from the gasdynamic results. The still difficult problem of solving the free-boundary problem for the shape of the magnetopause can be reduced to tractable form by introducing the Newtonian approximation for the pressure on the surface of an obstacle in high Mach number flow. Thus p is assumed to be given on the magnetopause by

$$p = K \rho_\infty v_\infty^2 \cos^2 \Psi \quad (16)$$

in which Ψ is the angle between the outward normal to the magnetopause and the free-stream velocity vector $\underline{v}_\infty$, K is a constant equal to 0.88 for high Mach number flow of a monatomic gas, although usually taken as unity in most applications of the type described here. Since the free-boundary problem thus arrived at coincides with that put forward from quite different concepts more than 40 years ago by Chapman and Ferraro, it is paradoxical, but true, that the theory of the geomagnetic boundary shape is much older than the idea of the solar wind.

The type of results that may be calculated in this way are illustrated in Fig. 8. Although the angle between the dipole axis and the direction of the solar wind varies by at least $\pm 35^\circ$ in the course of a year, calculations [16] have indicated that the alterations in the outer magnetosphere and the surrounding flow remain small, and can be disregarded for most purposes. In contrast, the size of the magnetosphere varies considerably in response to changes in the density and velocity of the solar wind, as indicated by the expression $D = a_e (B_{eq}^2 / 2\pi K \rho_\infty v_\infty^2)^{1/6}$ for the geocentric distance to the magnetosphere nose.

One prominent feature of Fig. 8 that cannot be accounted for by the approximate theory described above is the neutral sheet in the magnetosphere tail, across which the magnetic field reverses within a relatively short distance. This implies, of course, that an electrical current $\underline{J}$ flows across the magnetosphere tail. Thus, the condition $\underline{\text{curl}} \underline{B} = 0$ given in Eq. (14) must be replaced by $\underline{\text{curl}} \underline{B} = 4\pi \underline{J}/c$, where $c = 3 \times 10^{10}$ cm/sec is the speed of light. Difficulties of establishing the amount of current that flows have hindered the development of a rational theory of the magnetosphere tail.

The degree to which this approximate hydromagnetic theory is actually capable of accurately predicting the location of the magnetopause and bow wave of the Earth, and the conditions in the flow, is indicated in Fig. 9 [17]. This figure shows a comparison of data from Pioneer 6 as it traversed the indicated escape trajectory following launch on December 16, 1965 during a period of exceptionally low geomagnetic activity. Upon emerging into the incident solar wind after passing the bow wave, an unusually steady stream of particles with a

Fig. 9

number density of 11 protons/cm³ (and presumably an equal number of electrons) was observed coming from an apparent direction about 6° west of the direction to the Sun with a speed of about 280 km/sec. The magnetic field had an intensity of about 3.5 gamma, and was directed approximately along the ideal "garden-hose" angle of about 45° to the Sun-Earth line. These values were used together with assumed values of 8 and 5/3 for M_∞ and γ to calculate $\underline{v}$, ρ , and $|\underline{B}|$ along the portion of the trajectory from the magnetopause to somewhat beyond the bow wave. The most apparent feature of the comparisons is the nearly perfect agreement between the calculated and measured locations of the magnetopause and the bow wave. All the flow parameters agree reasonably with the theory, although some notable discrepancies appear in each plot. It is difficult to fully assess the implications of these, however, because of uncertainties and incompleteness of the data. The experimental values for the density, for example, are judged by the experimenter to contain a 50 percent uncertainty. The observational values for the velocity are not actually for the bulk velocity, as considered by the theory, but for the speed of the ions that produce the greatest current per unit energy increment in the plasma probe. To help assess the effects of the difference, an additional theoretical curve is included on the velocity comparison to show the values for the speed c_M of the most numerous particles per unit speed and solid-angle increments under the assumptions that the velocity distribution is Maxwellian in a reference frame moving with the local bulk velocity of the flow. Values for c_M are computed using the expression

$$c_M = \left[v + \left(v^2 + 8kT/m \right)^{1/2} \right] / 2 \quad (17)$$

in which v and T refer to the values for velocity and temperature indicated by the magnetohydrodynamic solution. It is, moreover, quite possible that some of the observational variations not duplicated by the theory are the consequence of changes in the interplanetary conditions when Pioneer 6 was behind the bow wave, and could be reproduced by the theory if the interplanetary conditions were better known.

If we now turn our attention to Venus, Mars, and the Moon, we find that data acquired in recent years disclosed two essentially different types of interaction from that described for the Earth. None of these objects has a significant magnetic field to withhold the solar wind as does the Earth, but Venus and Mars have sufficiently dense and electrically conducting upper ionospheres to prevent the solar wind from flowing directly into either the planetary surface or the lower absorbing levels of the atmosphere. The solar wind is thus deflected around the ionosphere, and a bow wave is formed upstream of the planet, similar in many ways to that associated with the Earth. Aside from evident differences in the underlying physical processes at the bounding surface between the ionosphere and the solar wind, the ionopause, the principal differences between the flow fields around these planets and the Earth is the size of the cavity. As illustrated in Fig. 10, the ionopause is wrapped much closer around Venus or Mars than the magnetopause is around the Earth, the nose being at an altitude of about 500 km for Venus and 155 to 175 km for Mars, compared with about 60,000 km for Earth. It has been shown [18] that a satisfactory theory for the solar wind flow past Venus or Mars can be constructed in a way exactly analogous to that for the Earth by

Fig. 10

replacing the magnetic relations of Eq. (14) with the simple relation indicating hydrostatic support of the ionosphere

$$\nabla p = \rho g \quad (18)$$

that remains when γ and B are equated to zero in Eq. (8). Solar wind flow past the Moon is different again, because of the lack of either a sensible magnetic field or ionosphere to deflect the incident flow. As a consequence, no bow wave forms, and the principal features of the flow field are associated with the closure of the lunar wake, or cavity, in the solar wind. While exact details depend on the orientation of the interplanetary magnetic field (see [19] for a recent analysis and discussion of previous work), it is evident that any shock wave that may form will be downstream of the Moon and relatively weak.

SHOCK WAVES IN INTERPLANETARY SPACE

Even before Gold's proposal of interplanetary shock waves, classical studies of solar-terrestrial relationships pointed to the existence of two classes of interplanetary disturbances (Fig. 11). One is a large plasma cloud of indefinite form and size expelled from the Sun by a flare or other explosive event. Its existence was inferred from the frequent observation of a flare followed a few days later by a geomagnetic storm. One characteristic feature of such an event is depicted in the upper right of this figure in which is shown, in idealized form, the time variation of the horizontal component of the geomagnetic field observed in low and middle latitudes. The sudden commencement (s.c.) of many geomagnetic storms was originally thought to be the result of the impact of the plasma cloud

Fig. 11

on the geomagnetic field. Following Gold, however, the tendency has been to associate it more with the effects of a shock wave traveling through the solar wind in advance of the plasma cloud. The second class of major discontinuity in the solar wind is a long-lived structure rotating with the Sun. Such an irregularity had long been suspected because of a pronounced tendency for geomagnetic storms to recur in approximately 27-day intervals with each complete solar rotation, as indicated schematically in the sketch in the lower right, and was usually assumed to have the form of a rotating beam of plasma expelled from an active region on the Sun much like water from a rotating garden sprinkler. With the realization of the permanent existence of the solar wind and the presence of the sector structure in it, the 27-day recurrence pattern of geomagnetic disturbances, and also some patterns with shorter periods, is now related to the passage of a sector boundary. Whether or not a shock wave forms in front of a sector boundary depends on the Mach number and Alfvén Mach number of the normal component of the relative motion of the plasmas on the two sides of the sector boundary. According to Hundhausen [20], a search of data obtained in space disclosed no evidence of such a bow wave preceding the sector boundary in the vicinity of the Earth's orbit.

Observations indicative of the passage of an interplanetary shock wave are presented in Fig. 12 [21]. Values for the proton temperature, number density, flow direction, and speed deduced from Vela 3A satellite data are shown with the trace of the horizontal component of the geomagnetic field at Guam, a representative low-latitude location. They show that, almost simultaneously with the

Fig. 12

occurrence of the initial horizontal field increase of about 15 gamma at Guam, the data from Vela 3A at 19.1 Earth radii, 56° solar ecliptic latitude, and 350° solar ecliptic longitude indicate that the speed of the solar wind increased from 340 to 385 km/sec, the density from 9 to 23 protons/cm³, and the average temperature from 3×10^4 to 8×10^4 °K. Gosling et al., [21] analyzed these changes in terms of a gasdynamic shock having properties given by Eqs. (11) through (13) with the terms containing $\tilde{B}$ and $\tilde{g}$ omitted, and showed that they are consistent with an interpretation of the discontinuity as a low Mach number shock wave traveling at a velocity of 70 km/sec through the ambient solar wind in which the speed of sound is about 30 km/sec. They also examined the possible relationship of this event to a 2B solar flare that began about 2253 UT on January 18 and gave rise to a low-energy (~ 5 MeV) solar proton event at the Earth's orbit. If this flare was the cause of the events displayed in Fig. 12, the mean transit velocity of the disturbance from the Sun to the Earth was 1670 km/sec, a speed substantially in excess of the 410 km/sec speed of the shock wave past the satellite, but not at all uncommon in comparison with many similar previous determinations. The obvious implication is that the shock wave was decelerated as it propagated through the solar wind. Qualitatively, this is the expected result for a blast wave originating at the Sun with a sudden release of energy by a flare, and with little or no energy addition thereafter.

Although a flare is a localized event on the solar surface, mathematical difficulties are sufficient that most theoretical attention has concentrated on the propagation of spherically symmetric disturbances. In the pioneering work

of Parker [22], solutions of Eqs. (7) through (13) with $\underline{B}$ and $\underline{g}$ neglected were obtained by similarity techniques that assume basic dependence on the parameter $\eta = tr^{-\lambda}$, where t is time and r is the heliocentric distance. Any feature of these solutions at position r_0 at time t_0 moves with time as $r = r_0 (t/t_0)^{1/\lambda}$. The solutions are connected to the ambient medium by assuming a strong shock at the leading edge of the disturbance.

The dashed lines of Fig. 13 indicate the density vs. position (normalized to the shock location) for two of Parker's shock waves for $\gamma = 5/3$ and an ambient density proportional to r^{-2} . The solution labeled "driven wave" corresponds to $\lambda = 1$; the density rises monotonically behind the shock to a singularity at $r = 0.84$. This wave moves with constant speed, and has an energy that increases linearly with time. It represents the wave pushed (or driven) ahead of a steadily expanding plasma cloud or "piston" located at the singularity. The solution labeled "blast wave" corresponds to $\lambda = 3/2$; the density falls monotonically behind the shock wave, and the wave moves with steadily decreasing speed and with constant energy. It represents the disturbance produced by a sudden release of energy at the Sun, and modified thereafter by interaction with the ambient medium. Parker's assumption of infinite shock strength has been improved upon by several authors (see [13] for a recent review) to obtain similarity solutions valid to first order in the ratio of the ambient solar wind speed to the shock speed. Even these solutions are basically strong-shock-wave solutions, however, whereas observations reveal that most interplanetary shocks are of lesser strength. The applicability of the similarity solutions to solar wind conditions is therefore questionable.

Fig. 13

Hundhausen and Gentry [23] have overcome this difficulty by numerically integrating the adiabatic fluid equations for spherically symmetric shocks of arbitrary strength to obtain solutions that include effects of solar gravity, but neglect magnetic forces. Two of their solutions for $\gamma = 5/3$ and an ambient solar wind speed of 400 km/sec and density of 12 protons/cm³ at the Earth's orbit are included in Fig. 13. The solution labeled "driven wave" shows a monotonic density rise behind the shock wave until a contact discontinuity, which separates the compressed ambient solar wind from the gas ejected in the initial disturbance at $t = 0$, is reached; and then a decline to a minimum at about the position of the singularity in the similarity solution, followed by rising density in the direction of the Sun in the new "steady state" set up in the driver gas. The wave moves with nearly constant speed, and has an energy that increases linearly with time. It is thus analogous to the driven wave of similarity theory, and represents a wave pushed by a continuous output of driver gas from the Sun. The numerical solution labeled "blast wave" in Fig. 13 shows a monotonic decrease in density for some distance after the shock, with an eventual increase to the original ambient profile (approximately proportional to r^{-2}) at $r \approx 0.6$ AU. This wave moves with steadily decreasing speed and has a constant total energy. It is thus analogous to the blast wave of similarity theory, and represents a wave produced by a short duration explosion at $t = 0$, followed by a return to ambient conditions. As with the similarity solutions, the properties of this wave depend only on the total energy in the initiating explosion. The numerical blast waves differ from those of similarity theory in that the density rarefaction following the shock does not extend all the way back to the Sun.

Since the optical emission from nearly all solar flares comes from an area less than 10^{-3} of a hemisphere, the theoretical models described above for spherically symmetric disturbances can only roughly approximate reality. To improve on this aspect of the theory, De Young and Hundhausen [24] have made numerical integrations of the gasdynamic equations corresponding to Eqs. (7) through (13) with terms containing B neglected, for flare ejecta confined initially to the portion of a thin spherical shell at $r = 0.1$ AU and moving away from the Sun as a constant energy axisymmetric disturbance in the spherically symmetric moving plasma of the solar wind. Fig. 14 shows the results of a specific calculation for the shape of the resulting shock front at several times after introduction of flare ejecta in a cone of half-angle $\Theta = 15^\circ$ with a total energy of 2.8×10^{30} ergs, values representative of a moderate solar flare. This wave, of the blast-wave class, slows and expands laterally as it moves away from the Sun, and passes the orbit of Earth 67.6 hours after initiation at 0.1 AU. The transverse expansion becomes important when the wave is beyond about 0.4 AU (the orbit of Mercury) because interaction with the ambient medium has considerably slowed and weakened the shock; the high pressure produced behind the front can then produce lateral expansion at a significant fraction of the shock propagation speed. Similar calculations for other Θ at 0.1 AU show that the shock shapes at the orbit of Earth are substantially more widespread for $\Theta = 30^\circ$ and 60° , as would be anticipated, but almost identical for $\Theta \leq 15^\circ$. For the latter, the shock is nearly spherical with radius of about 0.5 AU centered at about 0.5 AU, approximately as described by Hirshberg [25] on the basis of a statistical study of

Fig. 14

geomagnetic sudden commencements and solar flares and by Taylor [26] from an analysis of magnetometer data measured in space as eight "possible shocks" passed the IMP 3 spacecraft (no unambiguous identification was possible owing to the lack of plasma data). It may be concluded from these results that, for the small initial angles characteristic of most solar flares, the shock shape, speed, and transit time from the Sun to the Earth depend primarily on the energy of the initial disturbance and the properties of the interplanetary plasma, and not upon such details as the initial angular extent or distribution of energy within the initiating event.

Although most interplanetary shock waves are produced by solar flares, most flares, including many large flares, do not produce shock waves observable at the orbit of Earth. Hundhausen [20] has investigated the possible causes for such a selection, and arrived at an interesting relation between the mass and energy output required of the flare if a shock wave is to be observable at the orbit of Earth. From data from 19 shock waves, he estimated the mass and energy at 1 AU, added 1.92×10^{15} ergs/gm to each value for the energy to account for the work done against solar gravity in transit from the Sun, plotted the resulting values for the energy of the flare against the mass in the disturbance as shown in Fig. 15, and observed that the data point for each shock wave was slightly above a dashed line indicating the gravitational energy. From this, and the statistical result that most flares do not produce shock waves at 1 AU, he concluded, as indicated schematically in the insert on Fig. 15, that most solar flares have an energy-mass ratio less than that required for escape against solar gravity; and the

Fig. 15

observed shock waves are produced by the relatively small number of flares that have a sufficiently high energy-mass ratio. Although complicating consequences of magnetic forces, heat conduction, and small-scale unsteady processes may be anticipated, Hundhausen concludes from his analysis that solar gravity is a dominant factor in limiting the escape of flare ejecta into interplanetary space.

Although a solar flare may have an area that is only 1/1000 that of the entire Sun, the energy and mass supplied to the solar wind are not insignificant, for short periods of time. For example, a solar flare with mass and energy losses of 10^{17} gm and 10^{32} ergs may be compared with representative total coronal mass and energy loss rates of 10^{12} gm/sec and 3×10^{27} ergs/sec [3]. Such a flare thus ejects as much mass and energy into the solar wind plasma as is normally done by the entire Sun in about a day. Since several such flares may occur in a day at times of maximum solar activity, and only a few times a year during periods of minimum activity, it is evident that flares make significant contributions to the long period variations observed in the solar wind and related geophysical phenomena during the 11-year solar cycle. On the other hand, it should be recognized that the energy released by flares appears insignificant in comparison with the total energy output of the Sun, primarily by radiation in the visible range, of 4×10^{33} ergs/sec.

SOME TERRESTRIAL CONSEQUENCES OF SOLAR ACTIVITY

Reference has been made at several places in this paper to geomagnetic and auroral variations that occur in response to solar activity and through the intervening mechanisms provided by blast waves and other irregularities in the

solar wind. The statistical recognition of such correspondences has been well established for more than a century, and the processes involved are now intensively studied using measurements made both in space and on the ground. A great variety of other phenomena are also known or suspected to be linked to solar activity, but the degree of confirmation varies widely. For example, the development of radio at the beginning of the century made clear both the existence of the ionosphere and the degree to which it is controlled by the Sun. Rockets and spacecraft have disclosed more recently that this responsiveness is not confined to the electrical properties of the upper atmosphere, but extends to many other features including temperature, density, and the operative chemical processes. Long-standing efforts to relate meteorological variations in the lower atmosphere to solar activity have not met with equal success, however, in spite of the discovery of many possible correlations. Although it seems likely that effects of solar activity are not negligible, weather processes are so complex that recognition and confirmation of specific relations is an extremely difficult task.

The search for possible effects of solar activity on biological processes is perhaps the most questioned, and yet most intriguing, aspect of solar-terrestrial studies. As long ago as 1801 W. Herschel drew attention to the relationship between the price of wheat and solar activity. Others have drawn attention to a great variety of effects that can be correlated with solar activity. Some, such as the thickness of annual growth rings of trees in selected areas, are now sufficiently established that they are used to estimate solar activity for a few thousand years into the past. Estimates for remoter times are being made by similar studies of

corals. Others, such as the 11-year cycles in the population of certain animals, fish, and insects including the massively destructive locusts and grain moths in Asia and Africa and the cotton leafworms in the United States, have been noted [27], but the runs of data are often marginally long for reliability. It is tempting to associate the more plausible of these with the 11-year solar cycle, but the existence of many other prominent biological rhythms, and particularly those with only slightly different periods such as the 10-year cycle in the population of Canadian hare and lynx deduced from the approximately 10-fold fluctuations in the number of skins purchased per year since about 1800 by the Hudson's Bay Company [28], gives reason for caution. Still others, such as a remarkable correlation between the number of publications per year of Sydney Chapman and the annual sunspot number [29], portrayed in Fig. 16, are interesting, but probably better associated with frivolity, anniversary, or commemoration.

For me, in this day of constant search for relevancy in all fields of inquiry, the most provocative correlations with solar activity are those pertaining to human mortality rates associated with certain diseases or failures of body functions. In a recent review [30] of his work dating back to 1915, Chizhevskii has presented Fig. 17 to show, for example, that the number of deaths in Russia due to cholera in the years between 1823 and 1923 averaged from 5 to 10 times greater in years of maximum solar activity than in years near the solar minimum. Other data, such as the mortality rates for cerebrospinal meningitis in New York, relapsing fever in Russia, and diphtheria in Denmark shown here in Fig. 18 were also presented to display prominent 11-year cycles that can be correlated with

solar activity, although sometimes with other phases between the times of the maxima. More positively indicative of a link between mortality rates and solar activity are the increases indicated in Fig. 19 of 10 to 20 percent in death rates in Copenhagen from diseases of the central and peripheral nervous systems, cardiovascular diseases, and respiratory diseases in the days immediately following violent geomagnetic fluctuations such as are now known to result from solar flares. While modern medicine has greatly reduced and modified the mortality rates, as evident in the diphtheria mortality curve of Fig. 18, the suggested relations are so sweeping that they deserve reinvestigation in the light of present knowledge of the physical mechanisms involved.

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FIGURE CAPTIONS

- Fig. 1. Magnetic records at Kew, England showing effects of Carrington's flare, 11^h15^m, Sept. 1, 1859.
- Fig. 2. Photograph of solar corona during eclipse of May 30, 1965, from NASA CV-990 aircraft at 38,000 feet.
- Fig. 3. Representative temperature T and number density n profiles for the Sun.
- Fig. 4. Schematic representation of the mechanical energy transfer processes from the convection zone to the corona.
- Fig. 5. Calculated and estimated temperature and energy fluxes in an expanding shock-heated solar corona [6].
- Fig. 6. Principal features of the solar wind throughout the Solar System.
- Fig. 7. Schematic representation of the sector structure based on the direction of the interplanetary magnetic field, and the associated superimposed epoch analyses of the velocity, density, magnetic field magnitude, and geomagnetic activity index as a function of position within the sectors [9,10].
- Fig. 8. Principal features of solar wind plasma flow past the Earth and its magnetosphere.
- Fig. 9. Comparison of Pioneer 6 measurements with calculated results for $M_{\infty} = 8$ and $\gamma = 5/3$.
- Fig. 10. Types of interaction of the solar wind with the Earth, Moon, Venus, and Mars.

- Fig. 11. Schematic drawings of two types of major irregularities in the solar wind and their geomagnetic consequences.
- Fig. 12. Solar wind and geomagnetic measurements indicative of the passage of an interplanetary shock wave. Uncertainties in the values of the interplanetary quantities are indicated by the vertical error bars on each data strip [21].
- Fig. 13. Theoretical density profiles in the solar wind when a spherically symmetric shock wave passes the Earth [22,23].
- Fig. 14. Calculated shape of an interplanetary shock wave at several times after initiation by a thin shell of flare ejecta in a 15° half-angle cone at 0.1 AU [24].
- Fig. 15. Energy-mass relationship for 19 interplanetary shock waves; and its significance to the ability of a solar flare to produce an interplanetary shock wave [20].
- Fig. 16. Yearly number of Sydney Chapman publications and yearly means of sunspot relative numbers [29].
- Fig. 17. Cholera mortality in Russia between 1823 and 1923 and yearly means of sunspot relative numbers. The curves indicate the values for years preceding (negative) and following (positive) the year of maximum activity of each 11-year solar cycle [30].
- Fig. 18. Selected yearly mortality rates and yearly means of sunspot relative numbers that suggest a relationship with the 11-year solar cycle [30].
- Fig. 19. Mortality rates in Copenhagen and means of worldwide magnetic disturbance index for 68 solar rotations. The curves indicate the values for days following the 27-day recurring peak of magnetic disturbance associated with solar rotation [30].

11h15m, SEP 1, 1859

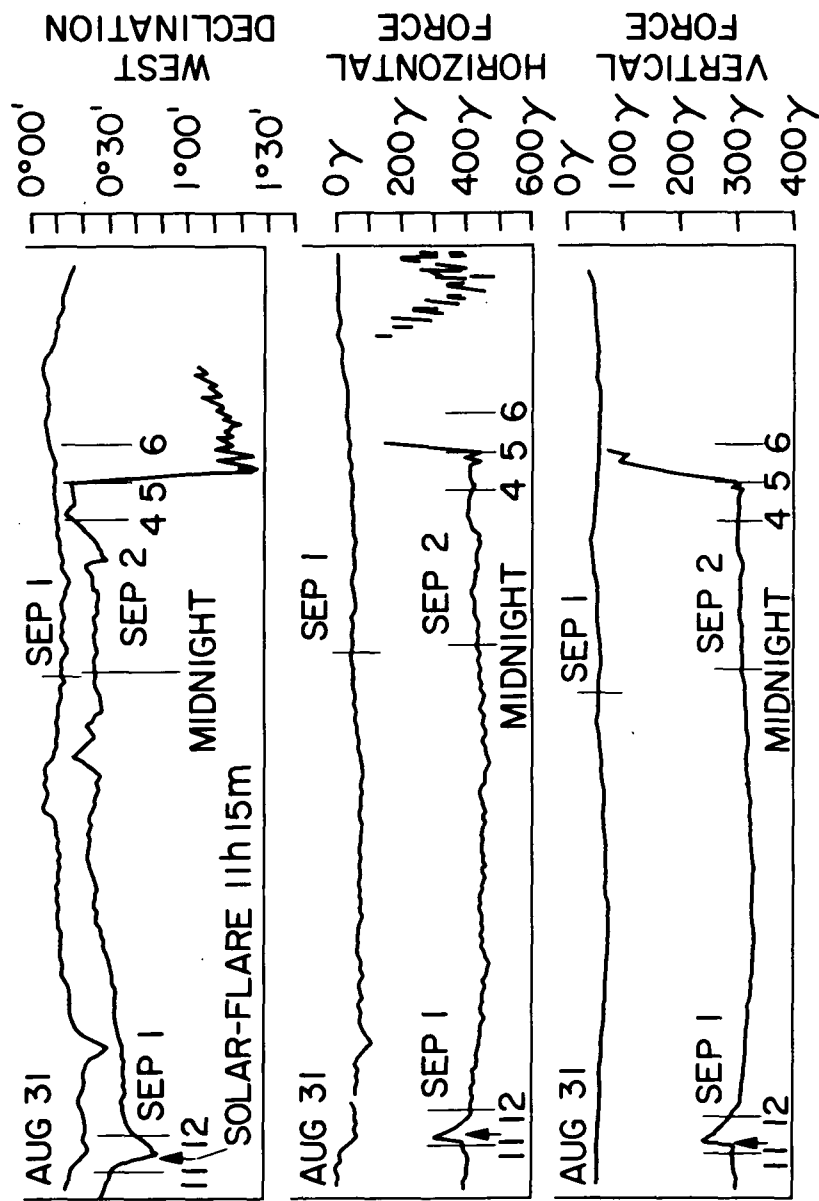


Fig. 1



Figure 2.

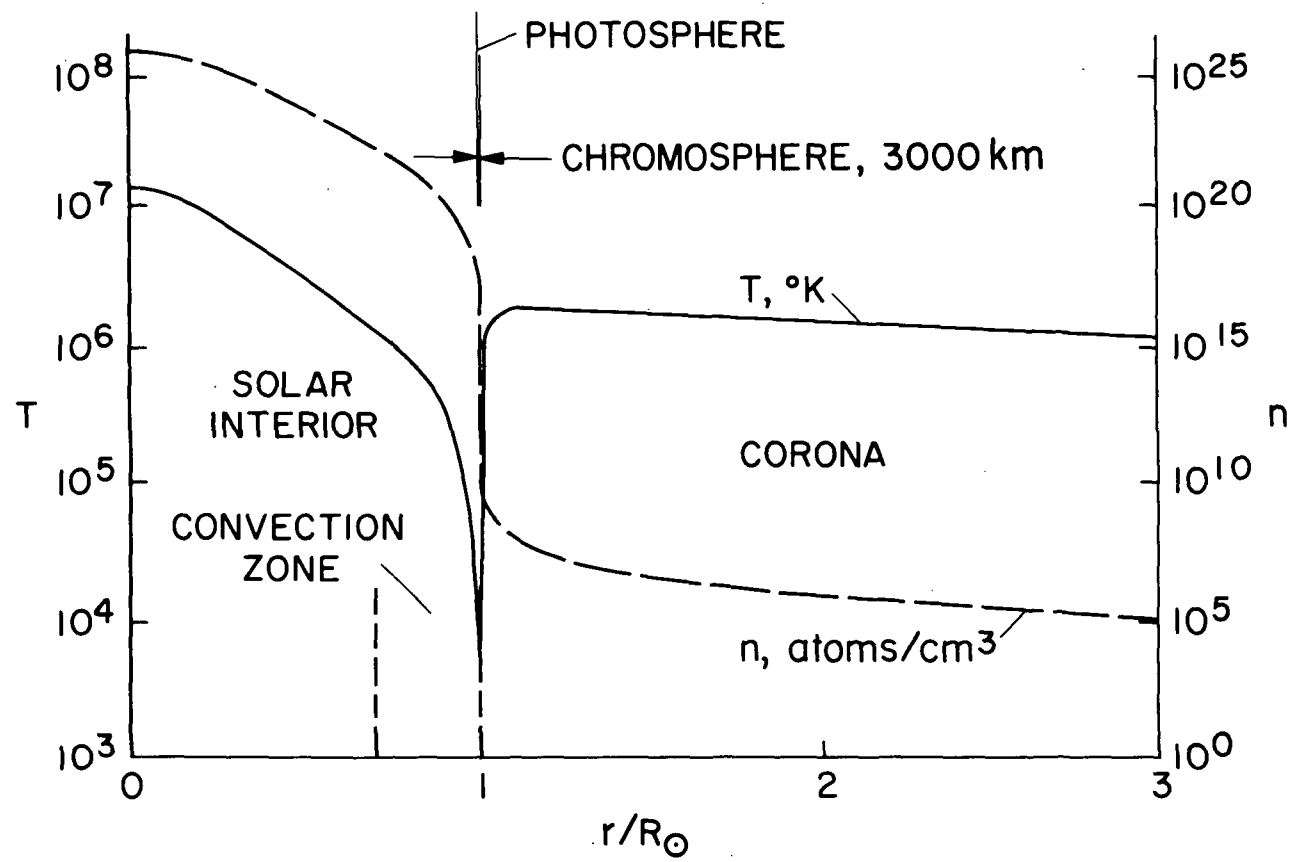


Fig. 3

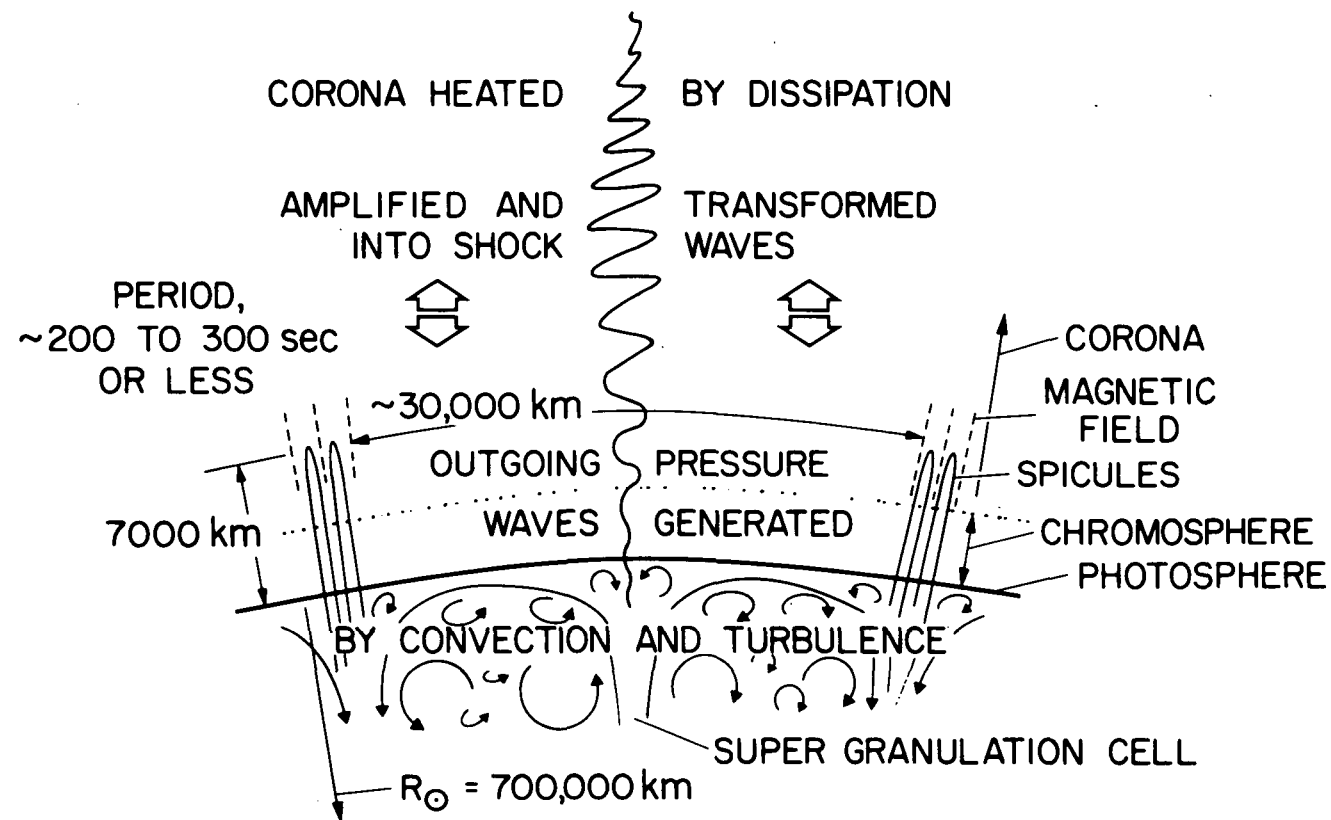


Fig. 4

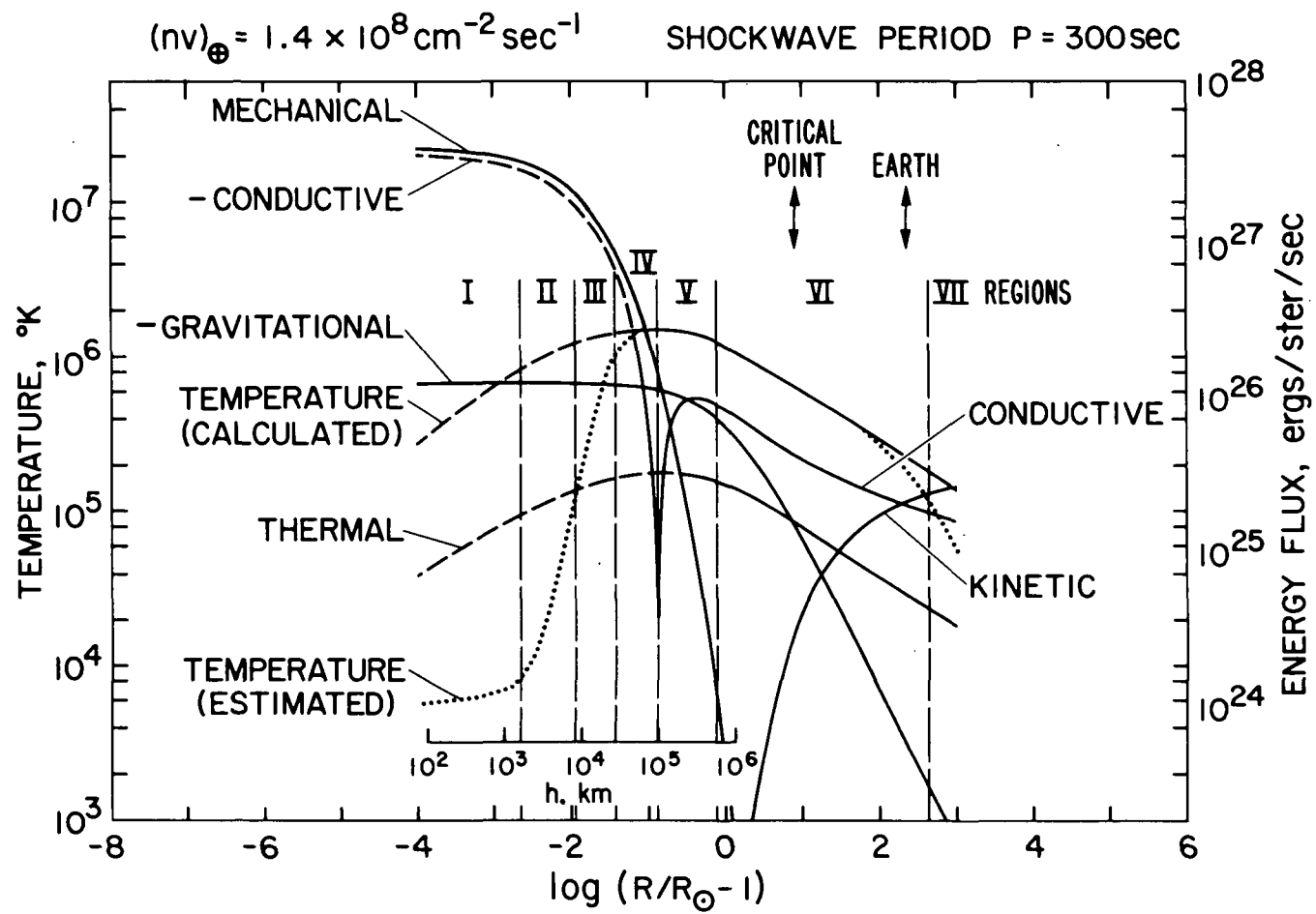
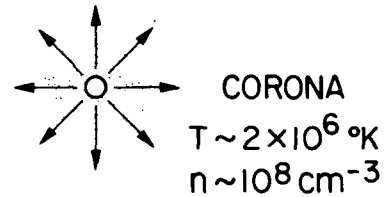


Fig. 5

$$\left(\begin{array}{l} n_2 \sim 4n_1 \\ v_2 \sim v_1/4 \\ T_2 \sim 10^6 \text{ } ^\circ\text{K} \\ B_{r2} \sim B_{r1} \\ B_{\theta 2} \sim 4B_{\theta 1} \end{array} \right) \begin{array}{l} \textcircled{2} \\ \textcircled{1} \end{array}$$

HELIOPAUSE ? TERMINAL SHOCK ?

SUN
 $T \sim 5800 \text{ } ^\circ\text{K}$, $n \sim 10^{16} \text{ cm}^{-3}$



SOLAR WIND
 FROM MARS TO VENUS

$0.7 < r < 1.5 \text{ AU}$

$n \sim 10r^{-2} \text{ cm}^{-3}$

$v \sim 500 \text{ km/sec}$

$T \sim 10^5 \times r^{-4} \text{ } ^\circ\text{K}$

$B_r \sim 3.5r^{-2} \text{ gamma}$

$B_\theta \sim 3.5r^{-1} \text{ gamma}$

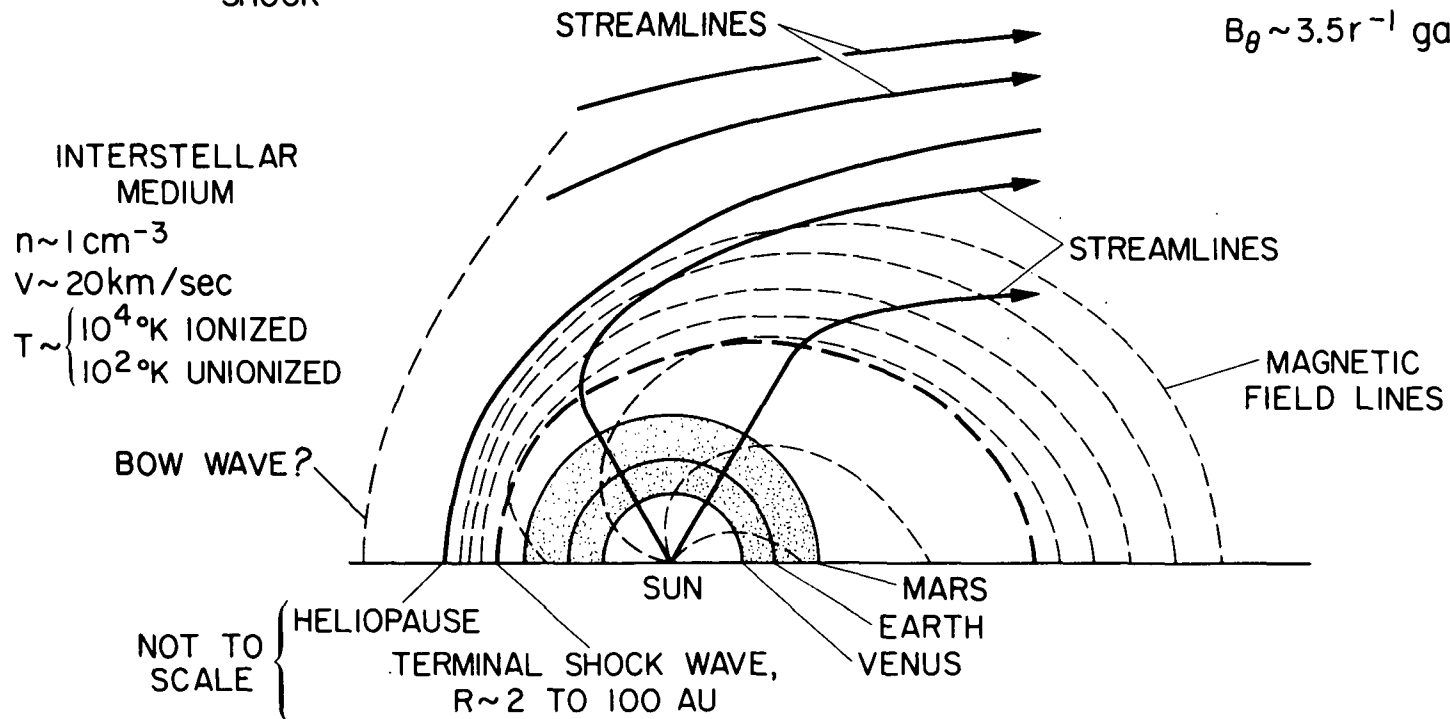


Fig. 6

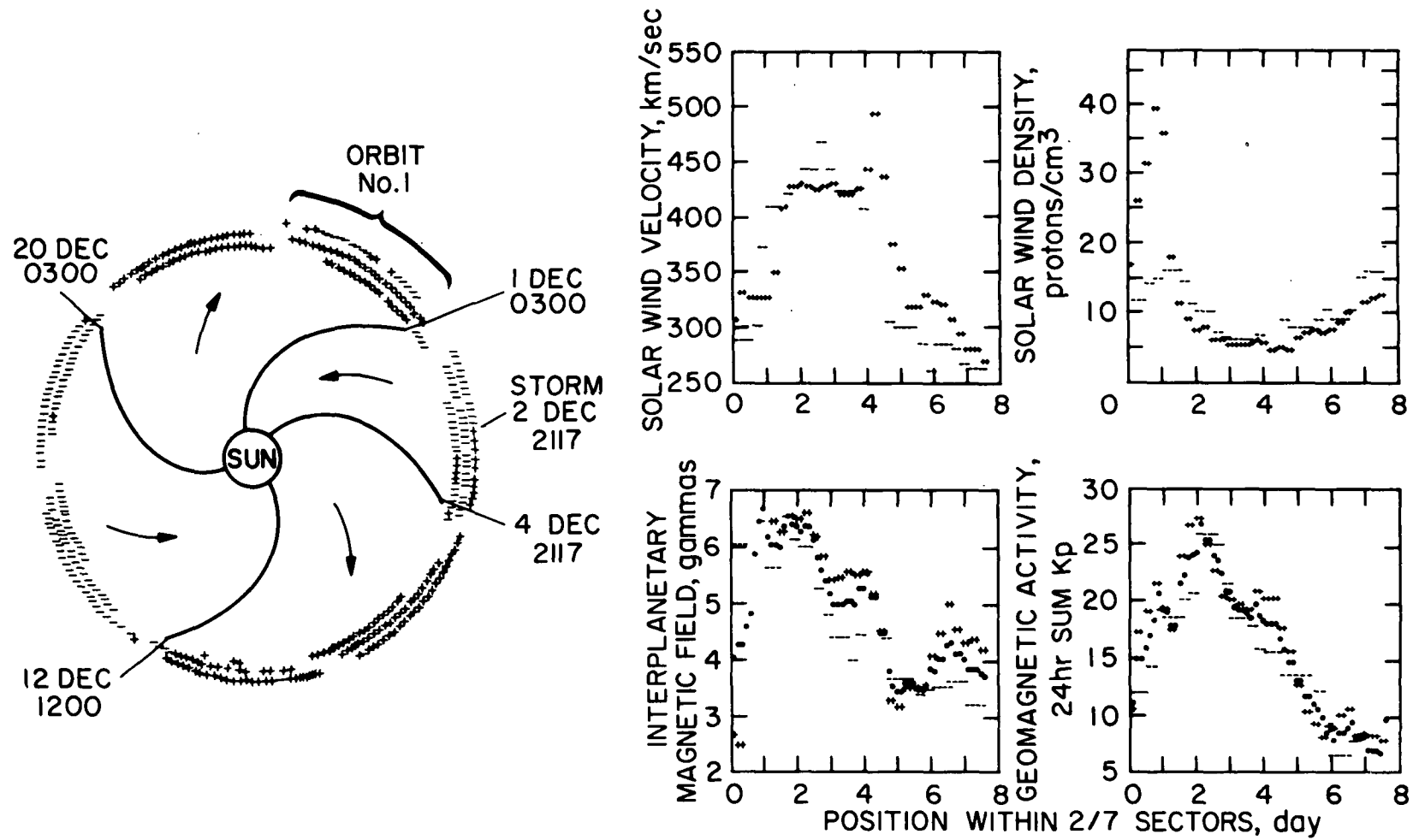


Fig. 7

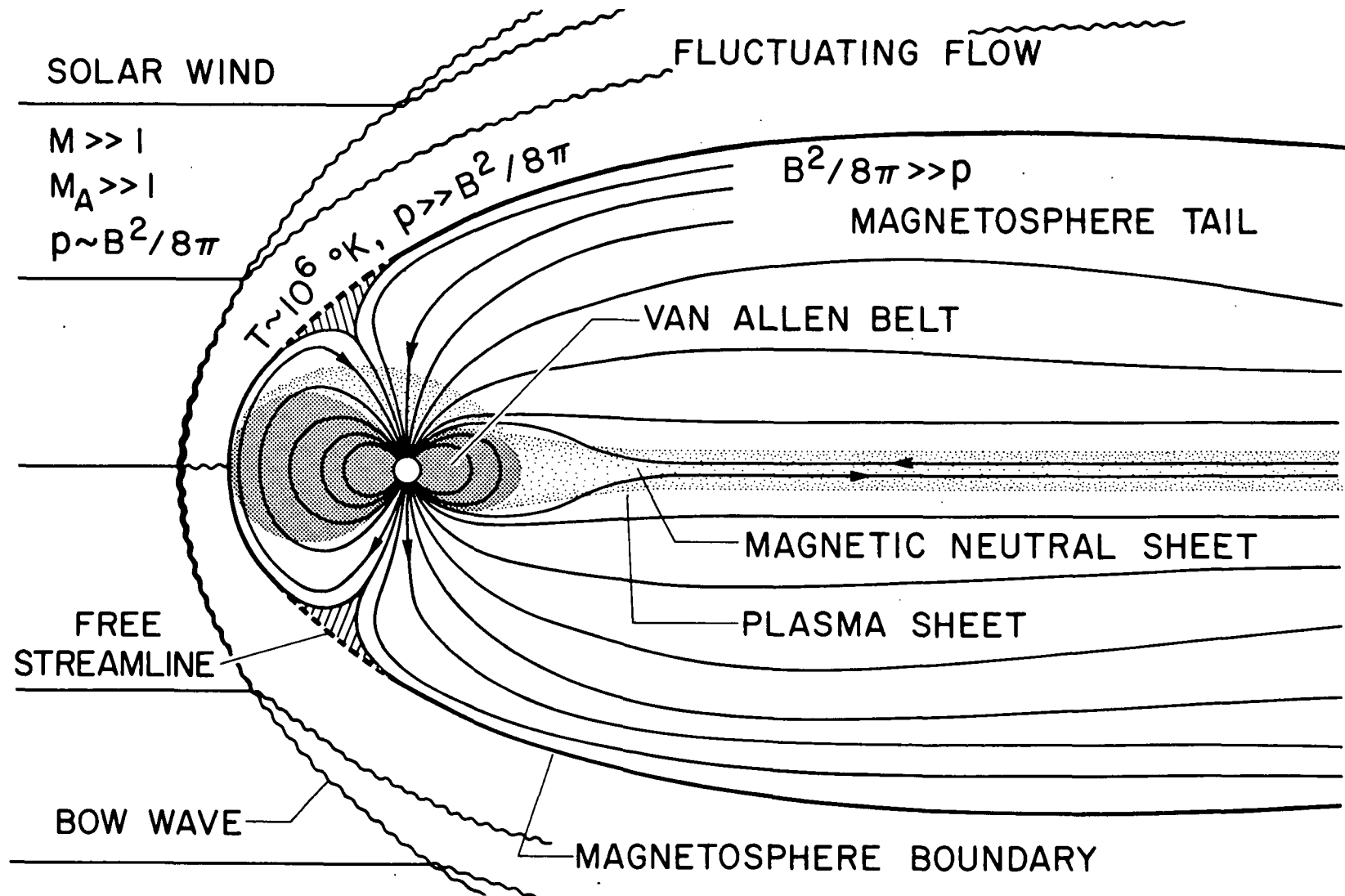


Fig. 8

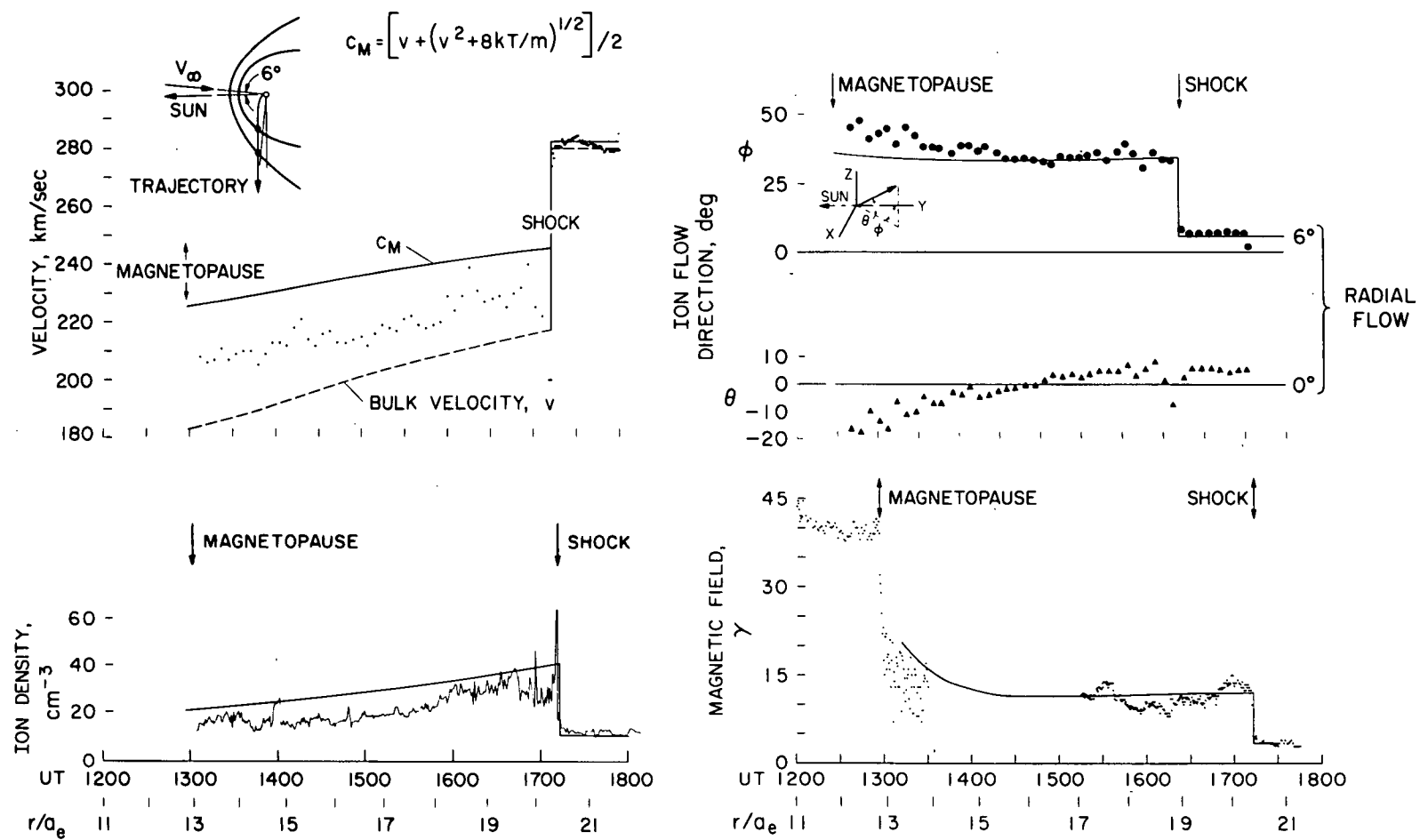


Fig. 9

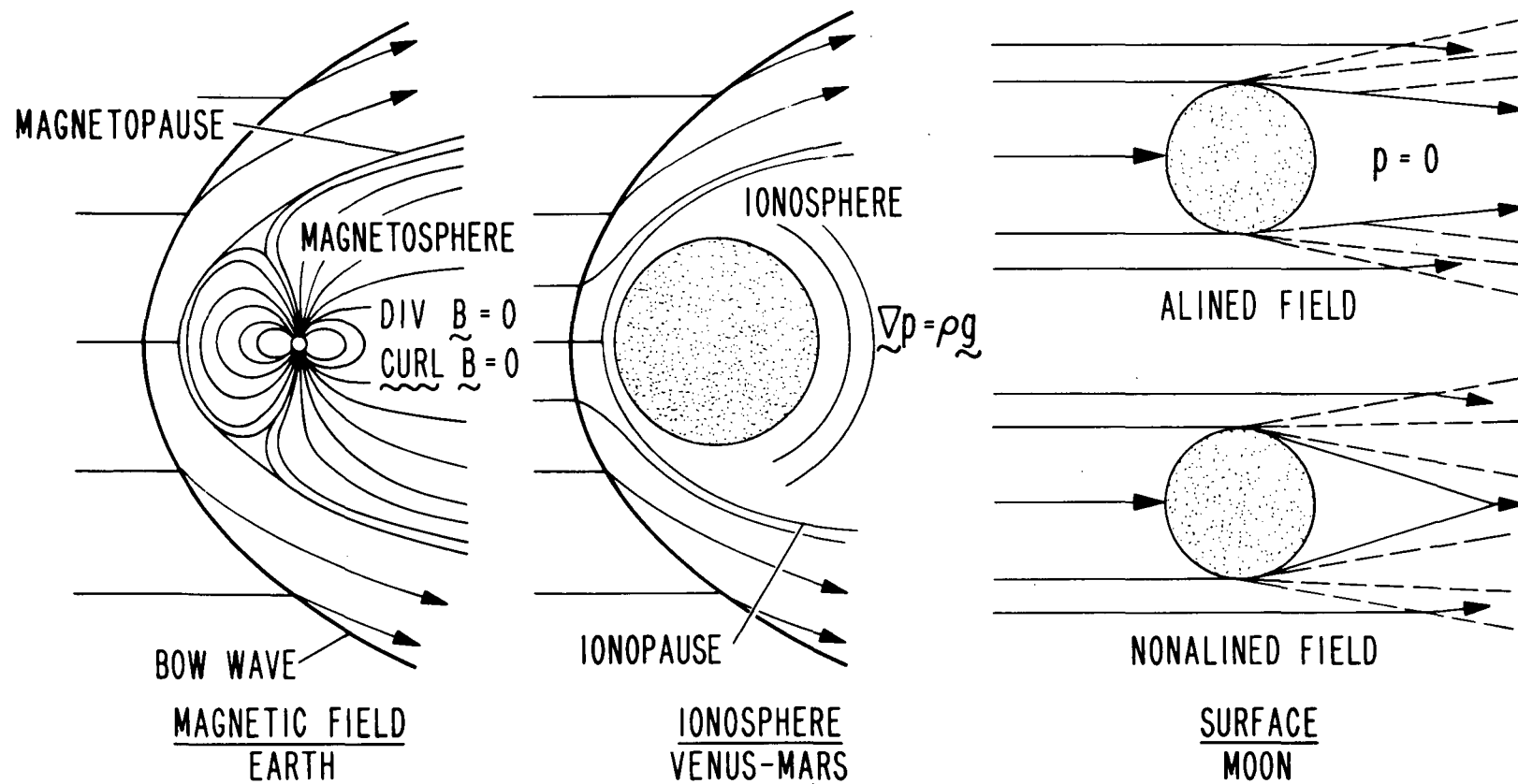
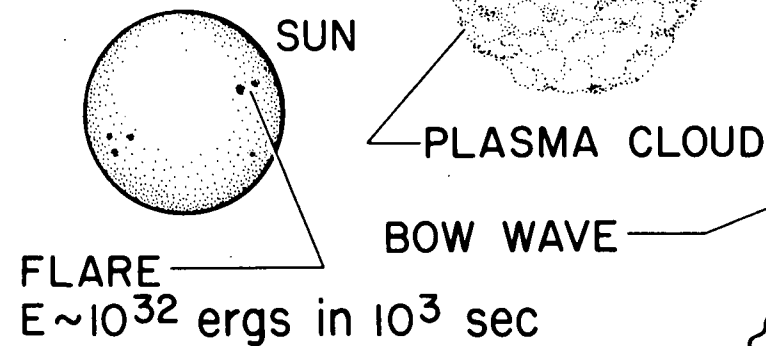
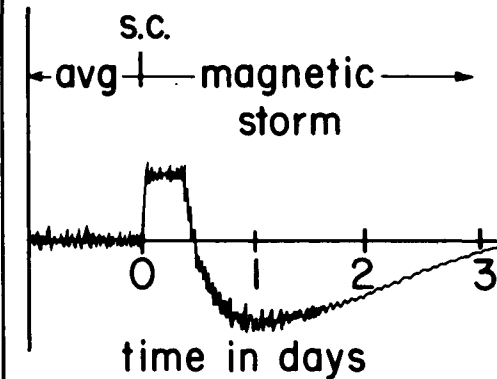


Fig. 10

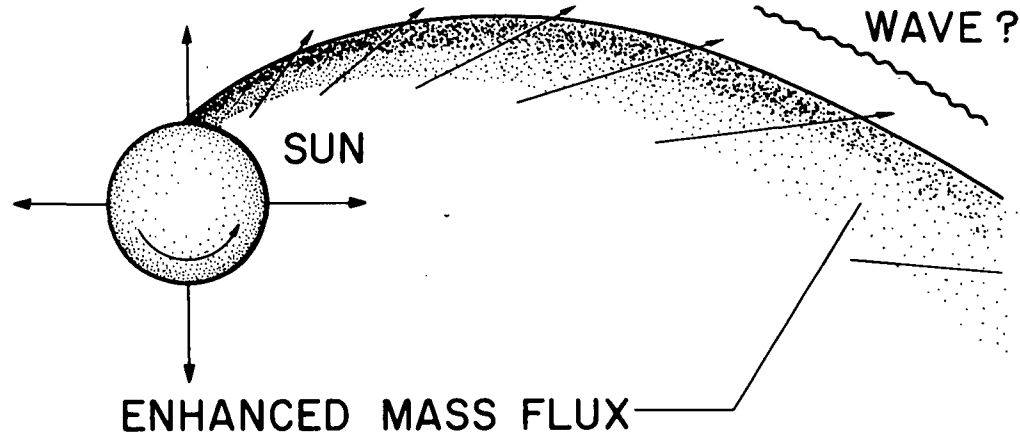
FLARE INDUCED BLASTS



GEOMAGNETIC FIELD CHANGES



LONG-LIVED ROTATING BEAM



GEOMAGNETIC DISTURBANCE INDEX

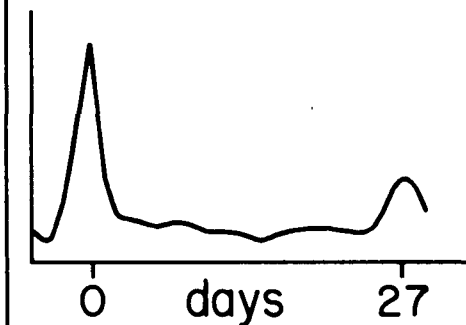


Fig. 11

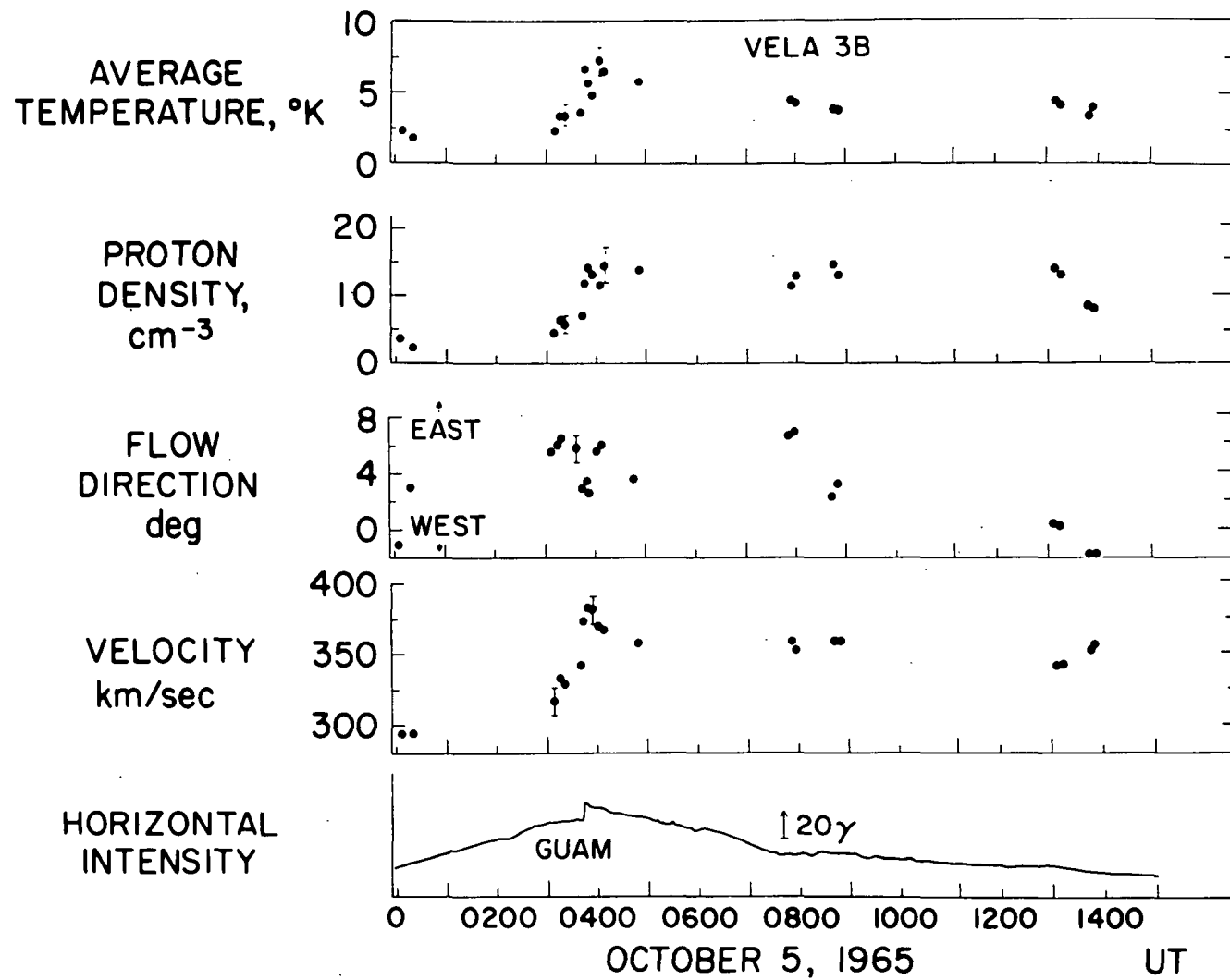


Fig. 12

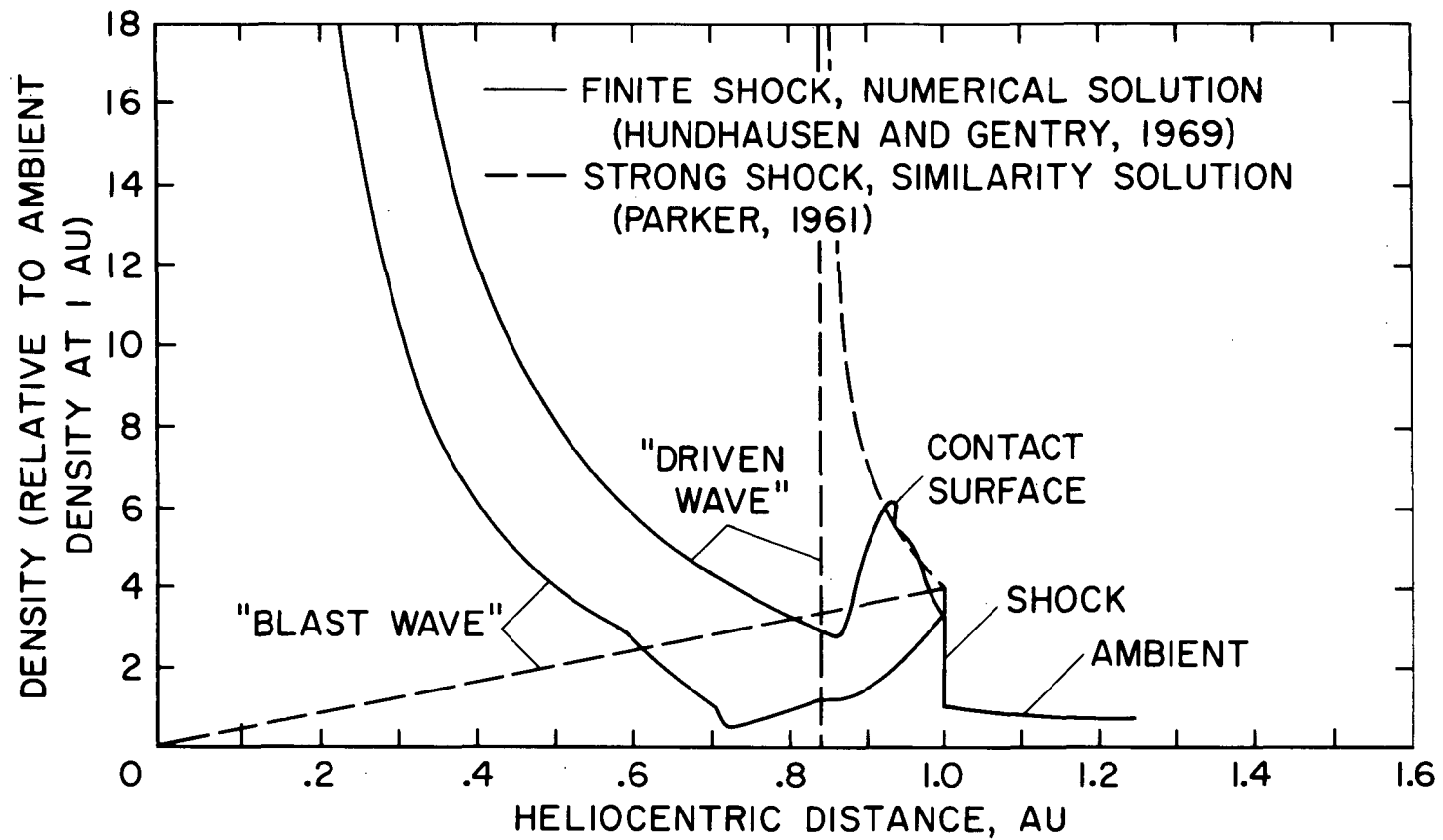


Fig. 13

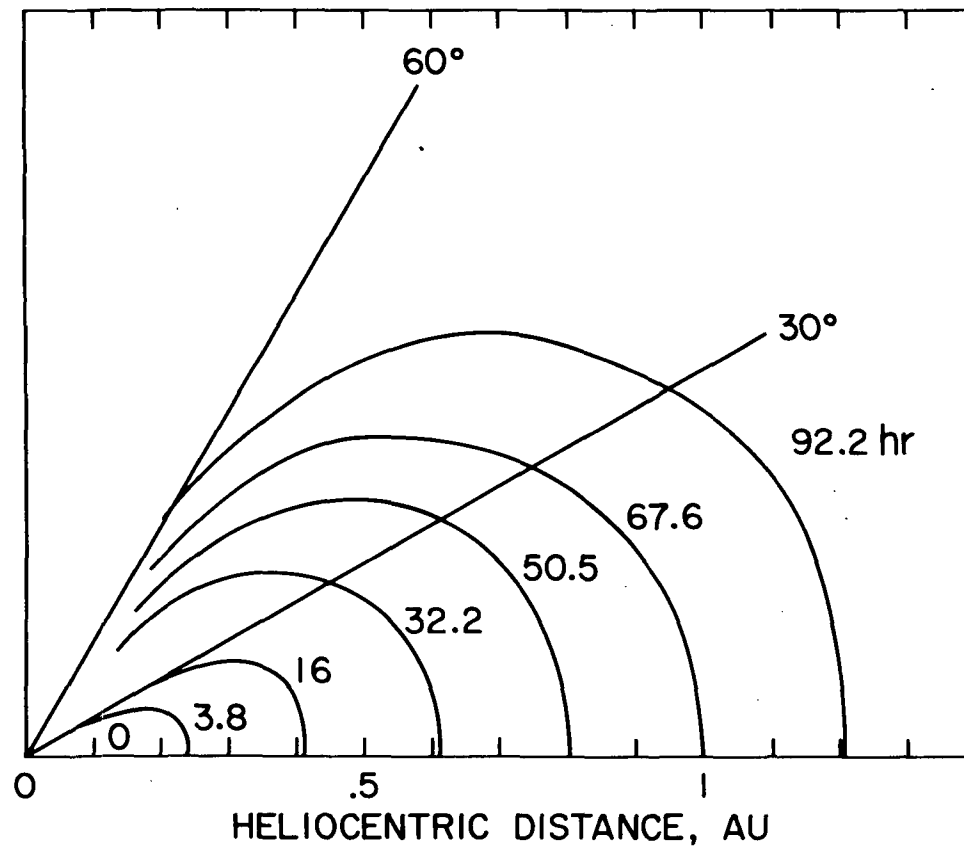


Fig. 14

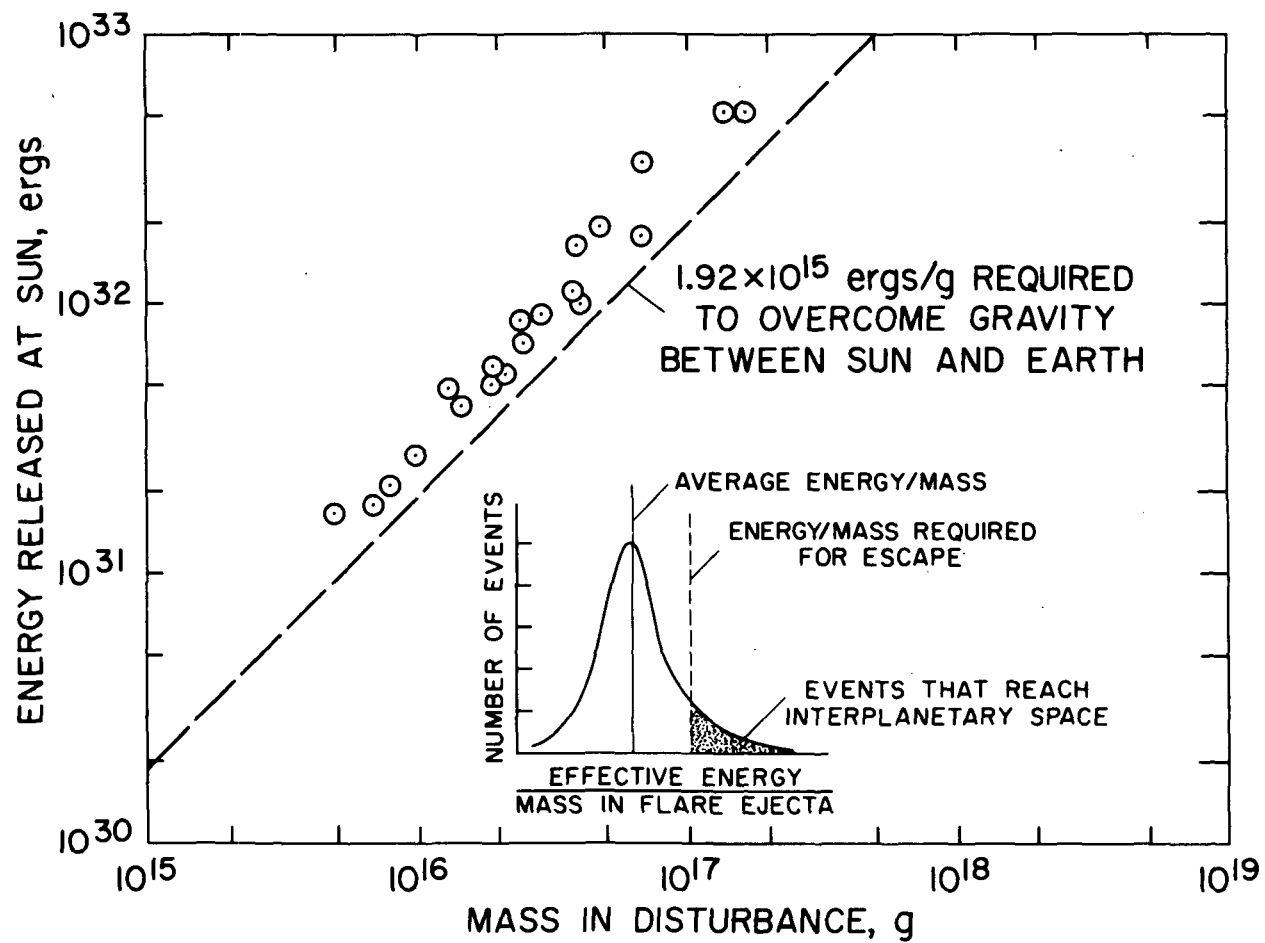


Fig. 15

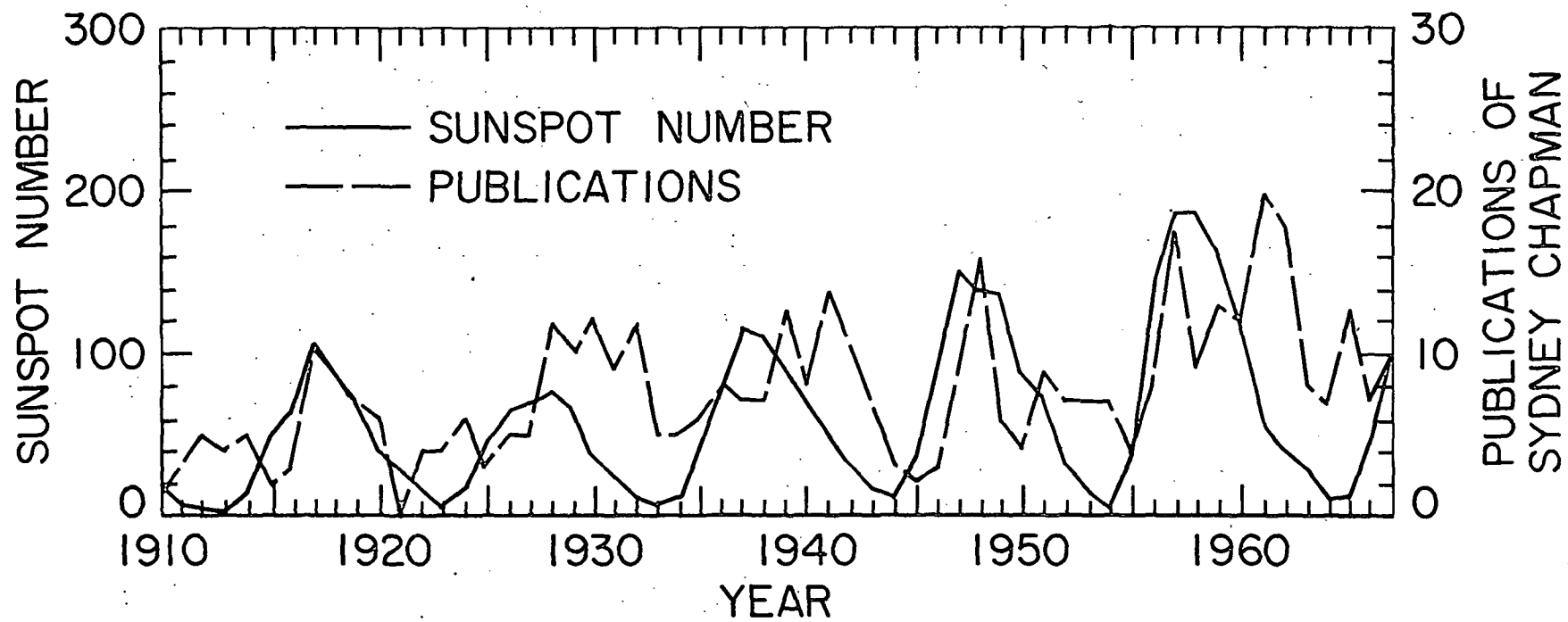


Fig. 16

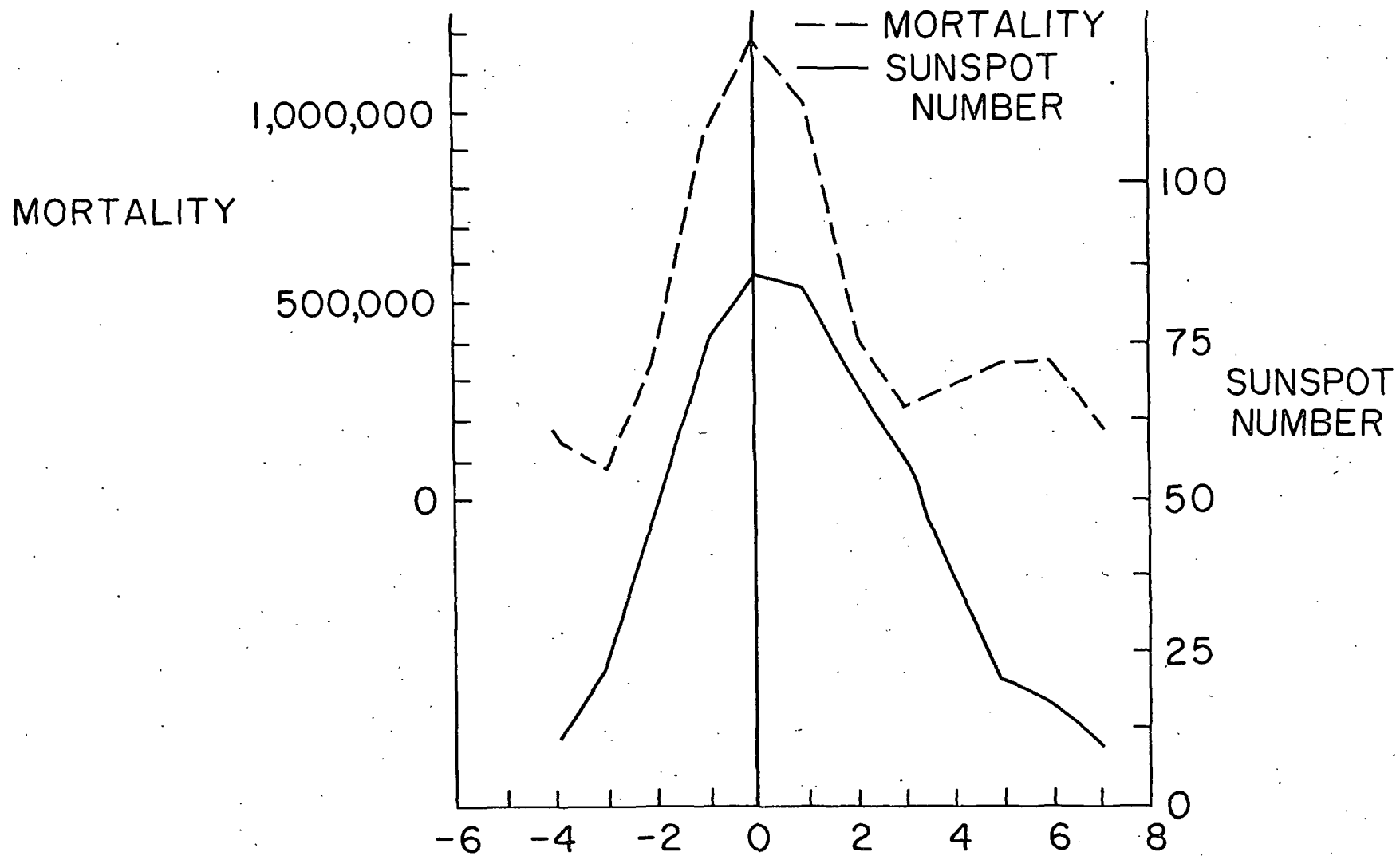


Fig. 17

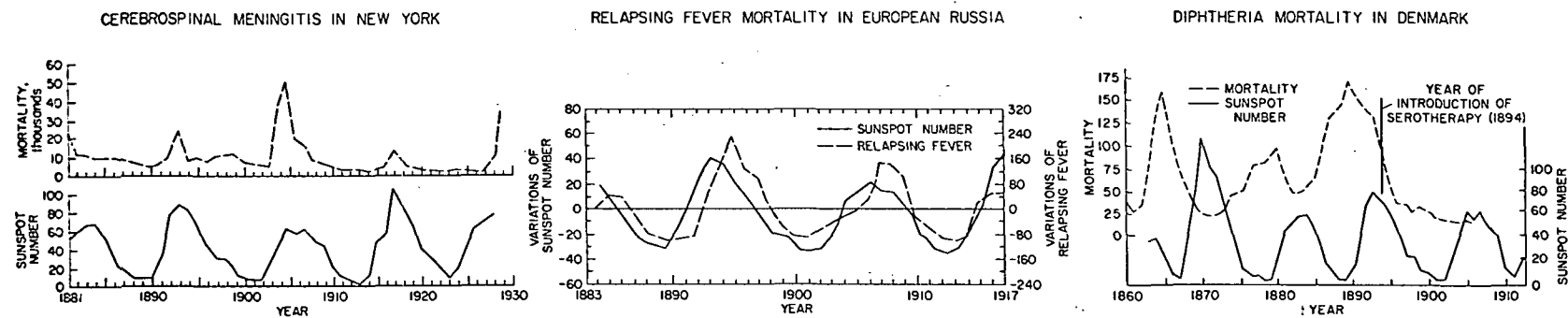
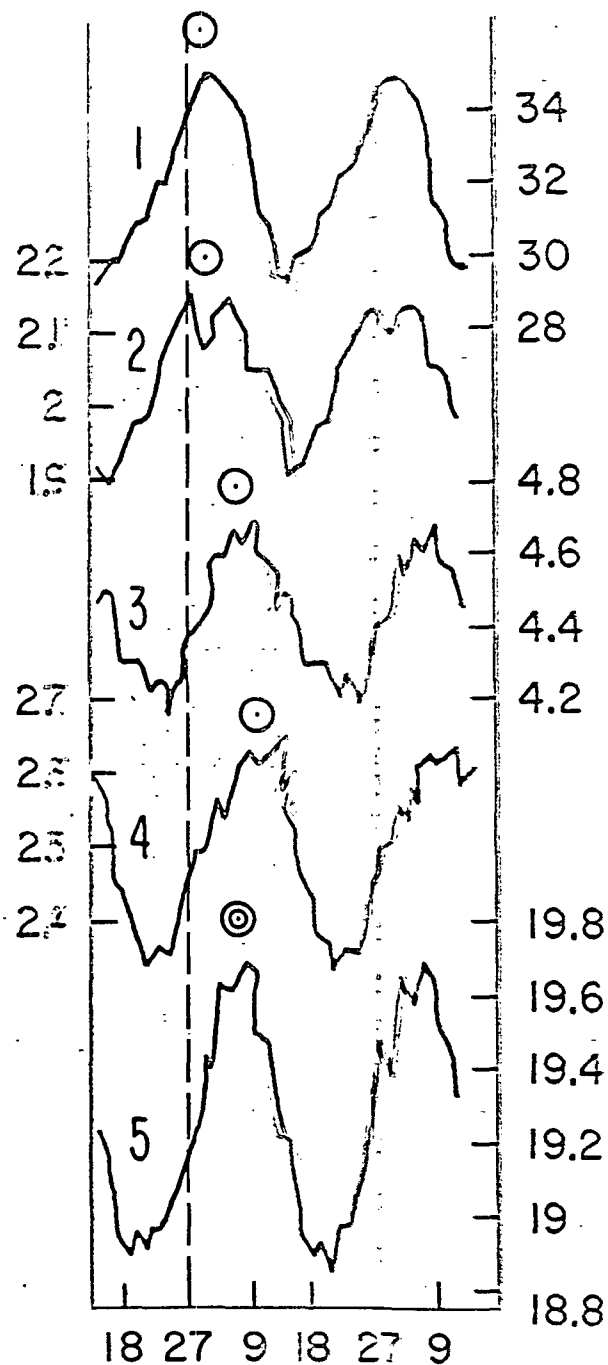


Fig. 18



WORLDWIDE
GEOMAGNETIC DISTURBANCES

DISEASES OF
CENTRAL AND PERIPHERAL
NERVOUS SYSTEM,
3720 CASES

CARDIOVASCULAR DISEASES
AND SENILITY,
8099 CASES

RESPIRATORY DISEASES,
4579 CASES

ALL CAUSES
EXCEPT MURDER,
35,244 CASES

Fig. 19