SOLAR FLARES AND SOLAR WIND HELIUM ENRICHMENTS: JULY 1965–JULY 1967

J. HIRSHBERG
Ames Research Center, National Aeronautics and Space Administration, Moffett Field, Calif., U.S.A.

S. J. BAME
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, U.S.A.

and

D. E. ROBBINS
Manned Spacecraft Center, National Aeronautics and Space Administration, Houston, Texas, U.S.A.

(Received 6 October, 1971)

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 $He/H \geqslant 15\%$ that were observed among 10300 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 ($He/H \geqslant 15\%$) 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 AU is, of necessity, closely related to He/H in the solar corona from which the wind arose. Although the relation-

Solar Physics **23** (1972) 467–486. *All Rights Reserved*

ship 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 January 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 February 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 ($He/H \geqslant 15\%$) 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 Hα. 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 10314 spectra that showed no evidence of disturbance during the 256 s required for the observation of a complete spectrum. For discussions of the data analyses 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.

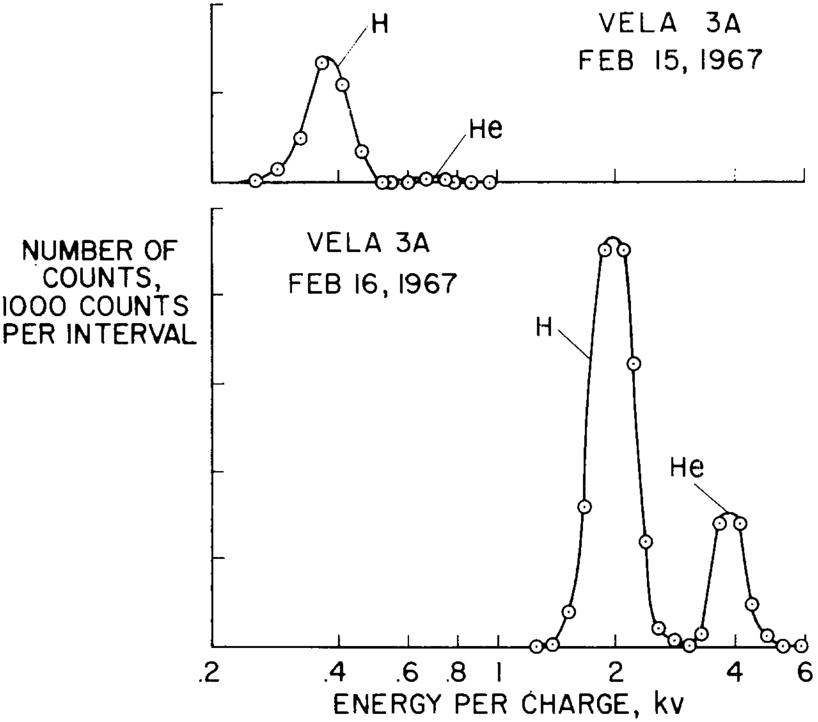

Fig. 1. An illustration of the variability of the relative helium abundance in the interplanetary plasma. The top spectrum indicates less than 1% helium, while the lower spectrum shows a solar wind containing 22% helium. The shift of the spectrum to the right is due to an increase in velocity (from Hirshberg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

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 December 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.

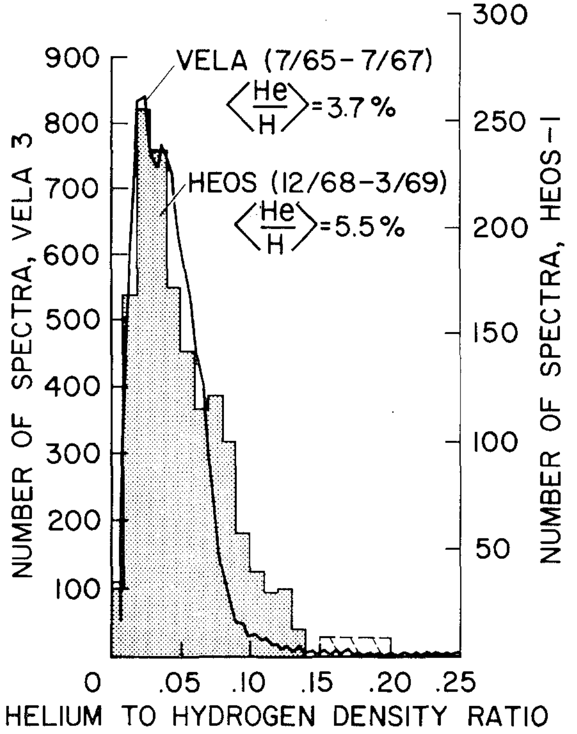

Fig. 2. The distribution of solar wind He/H. Note that in the Vela data (solid line) only 48 of more than 10300 spectra showed more than 15% helium. The HEOS data (shaded bars) indicates a larger percentage of helium enhanced spectra during the period of greater solar activity, leading to an increase 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 He/H, no matter what the stage of the solar cycle. Vela data from Robbins *et al.* 1970, HEOS data from Formisano *et al.*, 1970.

Returning to the Vela data, during the period 1965–67 values of $\mathrm{He/H} \geqslant 15\%$ 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 10300 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 $\mathrm{He/H} \geqslant 10\%$. 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 January 11, 1967 (Bame *et al.*, 1968), and February 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 3235 spectra between September 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 h 14 min, when a spectrum indicating 31% helium was observed. The next 3 spectra, taken over a span of 13 min, all show 20% or more helium. The velocities of the four enhanced helium spectra were 436^{+0}_{-4} km/s. Normal percentages of helium were observed 80 min 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/s. 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/s, 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 h 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 h 4 min of the same day. The velocity of the helium enhanced (26%) spectrum was 535 km/s. 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 UT, after a data gap of 11 h, plasma was observed with 18% helium. The enhancement lasted approximately 3½ h. The velocity of the helium enriched plasma was 525 km/s. The enhancement is attributed to the 3B flare of March 25 (N14, W54). Then the apparent mean velocity of the plasma was 520 km/s, 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.

TABLE I

Major flares, March 1966

Date of flare	Position of flare	Date of helium enhancement	Slowing ratio
66-03-16	N22 E66	–	–
-19	N22 E35	03-23	1.08 or
-20	N21 E18		0.76
-21	N20 W10	–	–
-24	N18 W37	03-26	0.70
-25	N14 W54	03-28	1.01

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 concluions 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 September 19th, 1966 until 17 h 53 min, when a helium abundance of 13% was observed. The next spectrum (17 h 57 min) showed 17% helium. An extremely long period of high helium followed. During the period between the first appearance of high helium and September 20 at 11 h 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 h. The velocity of the plasma in the first spectrum to exhibit high helium abundance was 520 km/s. This gives a width of 32×10^6 km to the region.

A class 2B flare had occurred in McMath plage 8496 on September 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 September 17, then, is the only flare that can reasonably be associated with the September 19 enhancement. It produced solar cosmic ray protons (Lin, 1970). This flare identification yields an apparent mean velocity for the plasma of 745 km/s, giving a slowing ratio of 0.7.

October 17, 1966

No He/H > 15% were seen during the first 16 days of October 1966. On October 13 helium abundances of the order of 1% or lower were observed. Then no more data was taken until 13 h 55 min, October 17, when data collection started with an observation of 13% helium. During the next 38 min, 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/s. 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 October 14. The mean transit velocity of the plasmas was 577 km/s, 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/s. The enhancement is attributed to the 2B proton flare of May 23 (N28, W34). 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 – August 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/s) 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 4300 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.

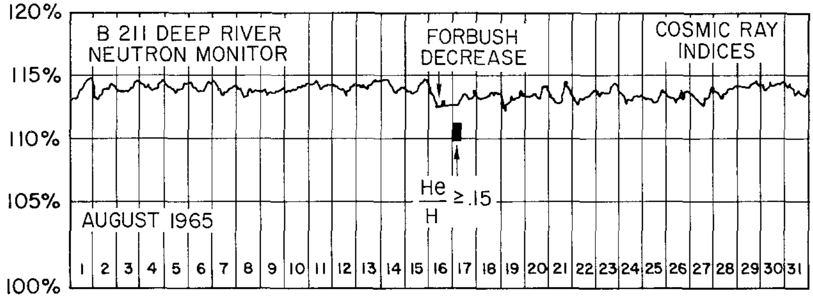

Fig. 3. Neutron monitor data covering the period of August 17, 1965, when a major helium enhancement was observed in the absence of solar flares. The helium enhanced period (shown as a shaded block) follows a small Forbush decrease.

Minor enhancements

Three other minor periods of helium enhancement not associated with major flares in Hα 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 h 39 min normal helium abundances were observed. Then 19% helium was observed at 6 h 44 min and 14% in the next spectrum 42 min later. The next spectrum, taken $1\frac{1}{4}$ h 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 h 55 min. The preceding spectrum (13 h 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 h 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 sporatic 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 $\mathrm{He/H} \geqslant 15\%$ 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, August–September 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

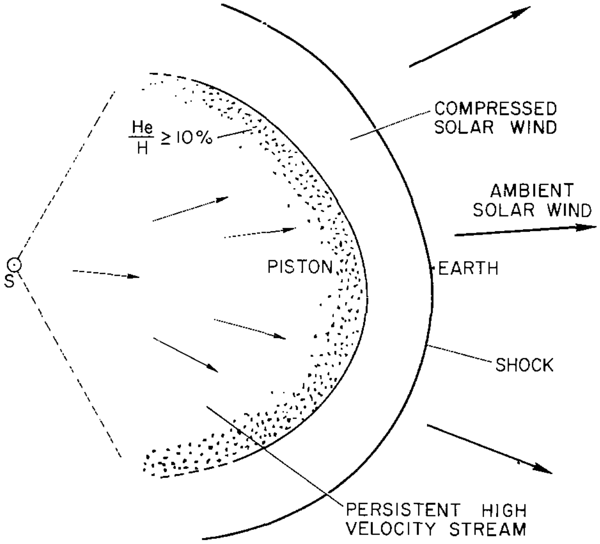

Fig. 4. Schematic representation of a flare disturbance propagating in the solar wind. The position of the Earth is shown as for a central meridian flare. The sizes and shapes of the various regions are taken from theory or experiment whenever possible. The shape of the shock is derived from geomagnetic 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.

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 s. (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, e.g., 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 Hα 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 hould be accumulated on this point. There is, of course, an east-west effect for solar proton events and we note that two of the 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).

TABLE II

Flares causing solar wind helium enhancements $\geqslant 15\,\%$

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	546	629	0.81		$\approx 4 \times 10^{39}$

In the estimates that follow we shall approximate the shape of the plasma front as $\frac{1}{4}$ 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/s to a low of 358 km/s, with an average of 546 km/s. This is considerably higher than the 400 km/s 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 AU 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/s for 27 interplanetary shocks, in excellent agreement with the 546 km/s plasma piston velocity found in the present study. There are three disturbances that appear in both studies (3-20-1966, 1-11-1967, 2-13-1967).

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/s to 780 km/s with an average of 629 km/s. 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/s. 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 AU. This is in excellent agreement with the 0.13 AU 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 h. 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 1000–2000 km/s at 0.1 AU, 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 He/H that should be considered to signal the end of the enhancement. Figure 2 shows that the most common value of He/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 He/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} AU to 0.2 AU). Since the range is so large and the number of events so small, the average value (9×10^6 km or 0.06 AU) is not expected to have much physical meaning. The largest width was found for the case of the flare of September 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 He/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 February 13, 1967 was also accurately determined and was only 1×10^6 km.

The average He/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

$$N = \varrho w A ,$$

where w is the width, ϱ the density and A the cross-sectional area. For A, we use $\frac{1}{4}$ the area of a sphere of radius 1 AU (7.1×10^{26} cm^2). 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 AU (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 January 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} g, or about $\frac{1}{4}$ 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 AU 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 the 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 (Jokippi, 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 polytrope index $\alpha<\frac{4}{3}$), and an upper region in which the solar wind is more nearly adiabatic ($\alpha>\frac{4}{3}$) (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 $\alpha>\frac{4}{3}$ (compared to the fully adiabatic case $\alpha=\frac{5}{3}$), 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 then 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 many 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 1000 km/s or more at 0.1 AU. This is considerably faster than the maximum velocity possible (800 km/s) 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 He/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 (3×10^{19} cm^2) then the density at the source must be of the order of 10^{13} 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 Hα 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 (2.5×10^{10} cm). The size of Type II region can be used to estimate the initial volume of the piston. The resulting volume (1.5×10^{31} 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 Hα 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 $\mathrm{He/H} \approx 15\%$, 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

It is a pleasure to acknowledge interesting discussions with Dr A. J. Hundhausen. We also wish to thank Mr G. Hosinsky of Anacapri Observatory for information on solar activity in April 1965.

The plasma data were part of the Vela nuclear detection satellite program, jointly administered by the Advanced Research Projects Agency of the Department of Defense and the U.S. Atomic Energy Commission, and managed by the United States Air Force. The work was begun with the partial support of the National Aeronautics and Space Administration under Contract NAS2-5355, administered by Ames Research Center and under Grant NGR 05-020-330. The work was completed during the tenure of a National Research Council Senior Research Associateship by one of us (J.H.).

References

Alloucherie, Y.: 1970, *J. Geophys. Res.* **75**, 6899.
Bame, S. J., Asbridge, J. R., Hundhausen, A. J., and Strong, I. B.: 1968, *J. Geophys. Res.* **73**, 5761.
Billings, Donald E.: 1966, *A Guide to the Solar Corona*, Academic Press, New York.
Brandt, John C.: 1966, *Astrophys. J.* **143**, 265.
Delache, P.: 1967, *Ann Astrophys.* **30**, 827.
De Young, D. S. and Hundhausen, A. J.: 1971, *J. Geophys. Res.* **71**, 2245
Dryer, Murray: 1972, *Proceedings of the Conference on the Solar Wind*, Asilomar, Calif., 21–26 March, 1971, to be published.
Formisano, V., Palmiotto, F., and Moreno, G.: 1970, *Solar Phys.* **15**, 479.
Geiss, J., Hirt, P. and Leutwyler, H.: 1970, *Solar Phys.* **12**, 458.
Hirshberg, J.: 1968, *Planetary Space Sci.* **16**, 309.
Hirshberg, J., Alksne, A., Colburn, D. S., Bame, S. J., and Hundhausen, A. J.: 1970, *J. Geophys. Res.* **75**, 1.
Hirshberg, J., Asbridge, J. R., and Robbins, D. E.: 1971, *Solar Phys.* **18**, 313.
Hundhausen, A. J.: 1970, *Rev. Geophys. and Space Phys.* **8**, 729.
Hundhausen, A. J. and Gentry, R. A.: 1969, *J. Geophys. Res* **74**, 2908.
Hundhausen, A. J., Asbridge, J. R., Bame, S. J., Gilbert, H. E., and Strong, I. B.: 1967, *J. Geophys. Res.* **72**, 87.
Hundhausen, A. J., Bame, S. J., and Montgomery, M. D.: 1970a, *J. Geophys. Res.* **75**, 4631.

Hundhausen, A. J., Bame, S. J., Asbridge, J. R., and Sydoriak, S. J.: 1970b, *J. Geophys. Res.* **75**, 4643.

Jokippi, J. R.: 1966, in R. J. Mackin, Jr., and M. Neugebauer (eds.), *The Solar Wind*, Pergamon Press, N.Y.

Kane, S. R., Winckler, J. R., and Hofmann, D. J.: 1968, *Planetary Space Sci.* **16**, 1381.

Kuckes, A. F. and Sudan, R. N.: 1971, *Solar Phys.* **17**, 194.

Kundu, Mukul R.: 1965, *Solar Radio Astronomy*, John Wiley and Sons, Inc.

Lanzerotti, L. J. and Robbins, M. F.: 1969, *Solar Phys.* **10**, 212.

Lazarus, A. J. and Binsack, J. H.: 1969, *Ann. I.Q.S.Y.* **3**, 378.

Lin, R. P.: 1970, *Solar Phys.* **12**, 266.

Nakada, M. P.: 1969, *Solar Phys.* **7**, 302.

Nakada, M. P.: 1970, *Solar Phys.* **14**, 457.

Neugebauer, M. and Snyder, C. W.: 1966, in R. J. Mackin and M. Neugebauer (eds.), *The Solar Wind*, Pergamon Press, N.Y.

Newkirk, G.: 1967, *Ann. Rev. Astron. Astrophys.* **5**, 213.

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

Ogilvie, K. W. and Wilkerson, T. D.: 1969, *Solar Phys.* **8**, 435.

Parker, E. N.: 1963, *Interplanetary Dynamical Processes*, Interscience Publishers, N.Y.

Robbins, D. E., Hundhausen, A. J., and Bame, S. J.: 1970, *J. Geophys. Res. Space Phys.* **75**, 1178.

Švestka, Z. and Simon, P.: 1969, *Solar Phys.* **10**, 3.

Sweet, P. A.: 1969, *Ann. Rev. Astron. Astrophys.* **7**, 149.

Taylor, Harold E.: 1969, *Solar Phys.* **6**, 320.

Valdez, Jesusa and Altschuler, Martin D.: 1970, *Solar Phys.* **15**, 446.

Vernov, S. N., Lyubimov, G. P., Kontor, N. N., Pereslegina, N. V., and Chuchkov, V. A.: 1970, Preprint, Moscow State University.

Wolfe, J. H., Silva, R. W., McKibbin, D. D., and Mason, R. H.: 1966, *J. Geophys. Res.* **71**, 3329.

Wilcox, John M. and Ness, Norman F.: 1965, *J. Geophys. Res.* **70**, 5793.

Wild, J. P., Smerd, S. F., and Weiss, A. A.: 1963, *Ann. Rev. Astron. Astrophys.* **1**, 291.

Yeh, Tyan: 1970, *Space Sci.* **18**, 199.