SOLAR WIND HELIUM ENHANCEMENTS FOLLOWING MAJOR SOLAR FLARES

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ABSTRACT The observations of solar wind helium enhancements following major solar flares are reviewed, and the hypothesis that helium enhancements often mark flare piston plasma is confirmed. Helium enhancements were observed during each of the three periods (March 1966, July 1966, August/September 1966) of major solar activity that occurred from October 1965 to October 1966. No enhancements were seen during the long quiet periods that occurred that year. During 1966-67, He/H $\geq$ 10 percent after 13 major flares, as listed. In 12 of the cases cited, He/H $\geq$ 15 percent in at least one plasma spectrum. Eight of the flares produced prompt solar cosmic ray protons. At 1 AU, the helium-enhanced plasma pistons had slowed so that the velocity was 80 percent of the mean transit velocity, in general agreement with theoretical models of the propagation of flare disturbances. A qualitative model, in which the piston plasma is accelerated from the flare site deep in the corona, is discussed briefly. If the model is valid in general outline, the piston plasmas provide samples of material from the lower levels of the corona.

INTRODUCTION

The average relative helium abundance in the solar wind has been found to be of the order of 4 to 5 percent [*Neugebauer and Snyder,* 1966; *Wolfe et al.,* 1966; *Robbins et al.,* 1970; *Ogilvie and Wilkerson,* 1969; *Formisano et al.,* 1970]. However, individual spectra show He/H varying from less than 1 percent to greater than 25 percent. The causes of this variation are not yet understood. We have proposed that periods of enhanced helium abundance mark the piston plasmas accelerated into space by solar flares [*Hirshberg et al.,* 1970]. In this paper, we discuss evidence that supports our hypothesis and briefly consider a model that might produce a helium enhancement of the flare piston plasma.

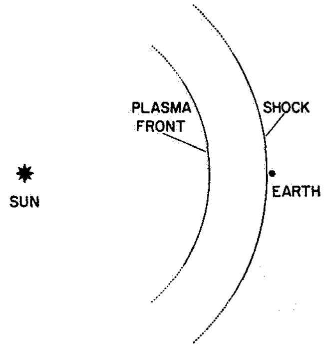

Figure 1. *Schematic representation of the propagation of solar flare disturbances.*

OBSERVATIONS

The propagation of flare plasma in space is shown schematically in figure 1. The shock due to the flare disturbance will be detected at earth several days after the flare. The velocity, temperature, density, and magnetic field intensity of the plasma will all increase discontinuously across the shock. However, the ratio of He/H will remain unchanged, since the region behind the shock simply consists of compressed ambient solar wind. The discontinuity between the compressed plasma and the flare piston itself, appears several hours after the shock has passed. If the helium enhancement marks the

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plasma piston, it will occur behind the discontinuity between the piston and the ambient wind. The pattern we expect, then, is a flare, followed several days later by a shock with no change of helium, and then, some hours after that, a helium enhancement.

This expected pattern can be compared to the observations shown in figure 2 from *Hirshberg et al.* [1970]. A 3B flare had been observed on February 13, 1967, at 20°N, 10°W. No other major flares occurred within a week before this flare, or for 5 days afterward. A shock discontinuity was observed by Vela 3A in earth orbit at about midnight, February 15. The velocity, temperature, density, and magnetic field intensity all increased postshock, while the relative helium abundance remained virtually unchanged. However, about 9 hr after the shock had passed, we see a marked increase in helium to an abundance of more than 20 percent. Similar patterns have been reported for the helium enhancements of 10 to 15 percent on April 17, 1968 [*Gosling et al.*, 1967], 12 percent on July 11, 1966 [*Lazarus and Binsack*, 1969], 17 percent on May 30, 1967 [*Ogilvie et al.*, 1968], and 18 percent on January 14, 1967 [*Bame et al.*, 1968], and for the series of flares of August/September 1966 [*Hirshberg et al.*, 1971].

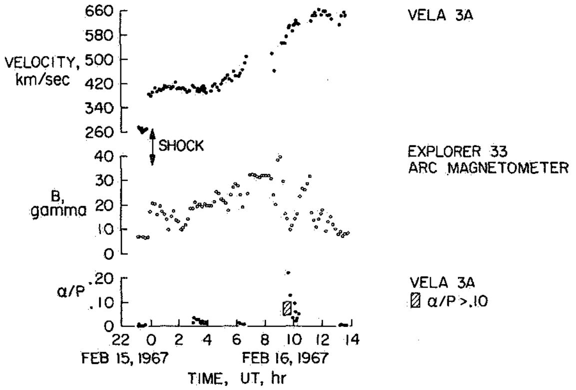

Figure 2. *Interplanetary disturbance caused by the 3B flare, 13 Feb. 1966. Note shock discontinuity 2351, Feb. 15. The postshock* He/H *does not increase appreciably until 9 hr later, when* He/H ~ *20 percent is detected. The helium enhancement marks the flare piston plasma [figure from Hirshberg et al., 1970].*

Although there are many examples of helium enhancements appearing at earth several days after major solar flares, the possibility that this apparent association between flares and helium enhancements is simply a coincidence must be dealt with [*Ogilvie and Wilkerson*, 1969]. To do this we will discuss the observations made during the year from October 1965 to October 1966. During this period the interplanetary medium was observed by plasma probes on Vela 3A and 3B in earth orbit and by MIT's plasma probe on Pioneer 6, in solar orbit.

The solar cycle was very close to minimum in October 1965, but the sunspot number was increasing rapidly throughout the following year. Solar flare activity was characterized by long periods of quiet, interrupted by a few short periods of intense solar activity. The helium enhancements that occurred during the periods of intense flare activity are discussed below.

The first major period of solar activity of the new solar cycle occurred in March 1966. This activity has been preceded by a long quiet period. In the seven months before the March activity, only one flare (66-01-17, N19 E27) was listed as 3B by any observatories, and that flare was listed by only one observatory. Then, at the end of March, plage region 8207 became extremely active and produced five flares that were reported as 3B by at least one observatory, including the major proton flare of March 24.

The solar wind during this period was being monitored by Vela 3A and 3B, which collected data on the relative helium abundance during the 2 years from July 1965 to July 1967. During these two years, *Robbins et al.* [1970] reports that over 10,000 spectra were collected, 2 percent of which showed He/H > 10 percent. In their study, only 48 spectra show He/H ≥ 15 percent. Because of the rarity of such spectra, we will take He/H ≥ 15 percent as a criterion for saying that a helium enhancement has been observed by the Vela probes. With this criterion in mind, we note that the plasma probe collected 3,178 spectra during the quiet sun period between October 1965 and March 1966. There was not a single spectrum showing a helium abundance as large as 15 percent. Then, at the end of March, during the period of solar activity, six spectra showed He/H ≥ 15 percent. If we define an enhancement as a period during which at least one spectrum shows ≥ 15 percent helium, and no spectra show < 10 percent helium, we find three distinct periods of enhancement during the end of March. These enhancements contributed to the high average helium abundance of 6 percent during the period March 21 through 30, as discussed by *Hundhausen* [1970]. The three separate enhancements were attributed to the three major flares of March 20, 24, and 25 [*Hirshberg et al.*, 1971, in preparation]. The first helium enhancement could have been due to either the major flare of March 19 or March 20; however, the second was more likely.

There was no ambiguity in the assignment of the second and third enhancements to the proton flare of March 24, and the major flare of March 25, respectively.

The second period of major solar activity of the new solar cycle occurred during the first half of July, 1966. An intensive study of these events has been made [*Annals of the IQSY,* 1969]. There were three class 2B flares, on July 7, 8, and 9. The proton flare of July 7 was the largest of the three. The solar wind plasma was observed by Vela 3B in earth orbit, and Pioneer 6 in solar orbit 43.7° west of the earth. The flare of July 7 was a central meridian flare as seen from Pioneer. During the period when the flare plasma was expected both satellites detected plasma with velocities greater than 550 km/sec. Unfortunately, the Velas spent most of the period of interest (July 9-13) within the magnetospere. Data were collected only during a 4½-hr period on July 10 and for less than an hour on July 11. The observed helium abundances were low (1-4 percent). However, helium enhancements typically pass the detector in a matter of a few hours. Thus a helium enhancement at earth could have easily been missed because of the poor data coverage. The observational situation at Pioneer 6 was more fortunate. On this vehicle, helium could be detected only when the proton component of the solar wind was relatively cold. On July 11, the temperature of the protons was low enough, and a relative abundance of helium of 12 percent was reported by *Lazarus and Binsack* [1969]. The enhancement was probably due to the July 9 flare. A helium enhancement, then, was seen at Pioneer 6 but not at earth. The failure to detect the enhancement at earth may well have been due to poor data coverage.

The third major period of solar activity occurred in August/September 1966. The activity has been described by *Švestka and Simon* [1969] who list two proton flares (August 28 and September 2) and several additional class 2 flares (August 26, and August 31, and a limb flare on September 4). The plasma from the flares could be expected to arrive at earth between August 30 to September 9. This period has been discussed in detail elsewhere [*Hirshberg et al.,* 1971]. The plasma was observed by Vela, which had collected 1,231 spectra between the March 1966 events and these events of August/September. Having missed the July enhancement, Vela has not detected a single spectrum with He/H $\geq$ 15 percent during the 5-month period between March and August. In contrast, between August 30 and September 9, 1966, Vela collected 134 spectra, eleven of which (8.2 percent) showed He/H $\geq$ 15 percent while 28 (22 percent) showed abundances greater than 10 percent.

There were four distinct periods of helium enhancement. For the details of making specific flare-enhancement identifications, see *Hirshberg et al.* [1971]. The resulting identifications are shown in table 1. The two proton flares of August 28 and September 2 are both associated with helium enhancements, as is the major flare of August 31. The second enhancement listed in the table could not be reasonably associated with a flare major in H_α. It is listed as due to a class 2 flare on August 30. The method of making that assignment will be discussed below. Returning to the major flares and their helium enhancements, the observed velocity of the helium enriched solar wind is given in the fourth column. The average transit velocity, calculated by assuming the plasma left the sun at the time of the beginning of the flare, is shown in the next column. We define a "slowing-ratio" as being the ratio of the observed velocity to the transit velocity. A slowing ratio of greater than 1 indicates that the plasma has speeded up on its way to the earth. The slowing ratios are shown in the final column of table 1. The helium enriched plasma due to the August 28 flare seems to have been

Table 1. *Flares and associated solar wind helium enhancements, Aug./Sept. 1966 [adapted from Hirshberg et al., 1971]*

Flare	Class	Helium enhancement	Observed velocity, km/sec	Average transit velocity, km/sec	Slowing ratio
1966 Aug. 28	2B	Aug. 31	653	596	1.1
(Aug. 30)	(2)	Sept. 1	576		
Aug. 31	2N	Sept. 3	439	475	0.9
Sept. 2	3B	Sept. 5	424	580	0.7

speeded up, perhaps by the plasma from a later flare [*Hirshberg et al.,* 1971]. The slowing ratios for the last two events are more typical of other observed flare-helium events. Slowing ratios to be expected for solar flare shocks are estimated from theory to be of the order of 0.8 [*Hundhausen and Gentry,* 1969]. If we assume that slowing ratios of 0.8 are fairly typical for flare pistons, then we can hunt for a flare to assign to the second helium enhancement shown in table 1. The flare chosen was described as class 2 by *Zirin and Lackner* [1969].

Summing up, the year from October 1965 to October 1966 is characterized by long periods of quiet sun, broken by a few periods of intense solar activity. During the quiet time, the percentage of helium in the solar wind remained relatively low. Enhancements were detected following solar activity. Although one enhancement was tentatively attributed to a less important flare, all other enhancements during that year were associated with major H_α flares.

After September 1966, solar activity increased to the point where there were no more long quiet periods. However, major flares were still fairly well isolated in time, and He/H $\geq$ 15 percent was not seen often. Other flare-enhancement associations have been reported for the period between October 1966 and May 1967 [*Bame et al.,* 1968; *Hirshberg et al.,* 1971, in preparation; *Ogilvie et al.,* 1968], but will not be reviewed in detail here.

In table 2 we have listed 13 flares that have been reliably associated with helium enhancements during the period from July 1965 to July 1967. The second column of the table shows the class of the flare. Most of the enhancements were due to the largest and brightest flares. A star indicates that solar protons were observed in space [*Lin,* 1970]. Every class 3 flare with prompt solar cosmic rays was followed by a helium enhancement. Column 3 shows the *maximum* percentage of helium observed during each enhancement. The *average* value of He/H during the enhancements seen by Vela was of the order of 15 percent. The final column shows the slowing ratio of the plasma pistons. The average slowing ratio is 0.8, in general agreement with theoretical calculations of the propagation of flare plasma [*Hundhausen and Gentry,* 1969].

MODELS

One of the most interesting questions that these observations bring up is the problem of the cause of the flare helium enhancement. At the present state of observational and theoretical knowledge, we cannot come to any definitive conclusion on this question. However, we shall describe a qualitative model that appears reasonable and that may serve as a basis for further study.

Table 2. *Flares and associated solar wind helium enhancements, July 1965-July 1967. See text for references.*

Flare date	Class of flare	Maximum percent of He	Slowing ratio
66–03–20	3B	31	0.8
66–03–24	3B	26	0.7
66-03-25	3B	18	1.0
66–07–9	2B	12	0.8
66–08–28	2B	16	1.1
66–08–31	2N	17	0.9
66–09–2	3B	22	0.7
66–09–17	2B	17	0.7
66–10–14	2B	16	0.6
67–01–11	3B	29	0.7
67–02–13	3B	22	0.8
67–05–23	2B	16	0.8
67–05–28	3B	17	1.0

The relationship between He/H observed at 1 AU and the relative helium abundance in the solar corona is not yet well understood. In addition, we do not know either the mean value of He/H in the corona or its distribution. It has long been recognized that the percentage of helium in the solar wind would be lower than that in the corona since helium is more difficult to accelerate into the wind than hydrogen [*Brandt,* 1966]. The distribution of helium in the corona and wind has been discussed in several recent theoretical papers. The basic approach is to consider 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. It will lead to regions of the solar atmosphere that are relatively enhanced or depleted in helium. Since the heavy elements diffuse toward regions of high temperature, the lower corona will have He/H large relative to that of the cool chromosphere [*Jokipii,* 1966; *Delache,* 1967; *Nakada,* 1969]. There also will be a tendency for the helium to settle out of the upper corona, again producing a relative helium enrichment in the lower corona [*Nakada,* 1970; *Yeh,* 1970; *Geiss et al.,* 1970]. This tendency for solar atmospheric stratification will be opposed by mixing. However, unless the mixing is very strong, we may expect some enhancement in the relative abundance of helium at a few tenths of a solar radius above the photosphere. In addition, the same mechanisms operating in the vicinity of an active region may cause local areas of enhanced helium abundance.

With these regions of probable coronal helium enhancement in mind, it is interesting to consider the model to produce flare piston plasma that has been suggested by *Axford* [1970]. Briefly, observations of solar flare disturbances in the interplanetary medium indicate that the flare piston plasma is ejected from sun with a sizable amount of its energy in the form of directed motion [*Akasofu,* 1966; *Hirshberg,* 1968]. Axford has proposed a mechanism for producing the directed motion. He suggests that the source of the flare piston plasma is in the lower corona. The flare heats a blob of plasma, which is then very buoyant and therefore rises rapidly through the corona. Magnetic fields confine the plasma within the blob. These same fields would also confine the helium so that it could not leak out and be left behind, as it would by a solar wind type of accelerating mechanism. If this model is valid in general outline, the flare pistons described in this paper are samples of plasma from the lower regions of the corona.

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DISCUSSION

E. C. Roelof I hate to raise the spectre again of the corotating versus the radial shock, but three of the events that you have identified as having the helium driver gas following the shock are precisely the three events in 1967 which Lin and I did analyze and decided were corotating events. Those are the slides I did not show on Monday. Those were January 11, February 13, and May 28, 1967.

Now, there is obviously disagreement here. I would like to point out that there is the alternative explanation; the matter has to be settled somehow and if these are corotating events then simply what is happening is that you are not seeing a driver gas but merely a helium enriched stream from the region that produced the flare, which I feel is also quite a reasonable interpretation.

J. Hirshberg It seems to me that that picture would not give the slowing ratio which was shown in all those three events, that there is no particular reason to have that 0.8 slowing ratio. If you're dealing with solar wind, then it should be speeding up on the way out, not slowing down.

J. Geiss I wonder if I'm the only one that doesn't know what Axford's greasy balloon is.

J. Hirshberg Well, Axford has suggested that you suddenly heat up some material above the flare and then it pops out like a cork, and this he has referred to earlier in the conference as a greasy balloon. I am suggesting the balloon has a lot of helium in it.

Unidentified Speaker I think that we should not consider with a teaspoon in mind the large excess of Alpha particles which appear in solar flares. I think this is one of the major problems in plasma physics, to understand how it is possible to increase by such a large factor the concentration of Alpha particles in respect to protons.

Dr. Dryer I guess you know what I'm going to ask, Joan. Did you look at all of the–let me ask this question first, what was the time interval generally between the arrival of the shock and then the arrival of the piston, in hours?

J. Hirshberg Well, in many of these events, like the March events and August events, there were so many shocks and discontinuities that I couldn't assign a particular shock to a given helium enhancement. In the early events we seemed to get about 10 hours.

Dr. Dryer Yes. Did you ever make any effort to see if there might possibly be a reverse shock that might follow the piston?

J. Hirshberg No.

Dr. Dryer You didn't make the effort, or there were none?

J. Hirshberg I didn't make the effort.

Dr. Dryer Did you have magnetic field data?

J. Hirshberg No.