Anomalously Low Proton Temperatures in the Solar Wind following Interplanetary Shock Waves— Evidence for Magnetic Bottles?

J. T. Gosling and V. Pizzo

High Altitude Observatory, National Center for Atmospheric Research
Boulder, Colorado 80302

S. J. Bame

Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87544

Occasionally, anomalously low values of the solar wind proton temperature $T_p$ are observed when the solar wind velocity $v$ is high. A large fraction of such measurements by the Vela 3 satellites follow the passage of interplanetary shocks by some 20-60 hours. Of 24 post-shock events in which $v$ exceeded 400 km sec$^{-1}$ and for which Vela 3 measurements are available, 12 exhibited plasma states of anomalously low $T_p$, high $v$. The proton density at the time of these observations typically was depressed below normal, and the velocity tended to be constant or falling. A very strong association with abnormally high (≥ 15%) concentrations of He$^{++}$/H$^+$ in the solar wind is noted for these anomalous proton temperatures, the usual temporal sequence of events at 1 AU being: (1) shock wave, (2) helium enrichment, and (3) low $T_p$, high $v$. It is suggested that these observations are consistent with a model for some shock wave disturbances that includes the ejection of new material (distinguished by the helium enrichment at 1 AU) into the solar wind at the time of large solar flares and the formation of a magnetic bottle configuration in the solar wind behind and within the ejecta. The anomalously low proton temperatures then result from the adiabatic cooling of the plasma within the magnetic bottle.

The positive correlation between solar wind flow speed $v$ and proton temperature $T_p$ is well documented in the literature [Strong et al., 1966; Hundhausen et al., 1967; Burlaga and Ogilvie, 1970]. A demonstration of this correlation is provided by Figure 1, which is a scatter plot in the $v, T_p$ plane of the 3-hour averages of the Vela 3 solar wind data obtained between July 1965 and December 1967. Several recent papers [Burlaga and Ogilvie, 1970; Hartle and Barnes, 1970; Hundhausen, 1973] have concentrated on an understanding of the general increase in proton temperature with increasing flow speed. Although differences in interpretation exist, there is agreement that the average increase in proton temperature with increasing flow speed probably represents a mapping outward from the corona of increasingly high coronal proton temperatures.

One of our concerns recently has been the interpretation of the relatively large scatter of plasma states evident in Figure 1 particularly at high flow speeds. That is, we have been concerned with the deviations from the average flow speed–proton temperature relationship. It is now clear that compressional heating caused by high-speed streams overtaking slower-moving plasma is responsible for a major part of the plasma states of excessively high proton temperature at moderate and high flow speeds [Burlaga and Ogilvie, 1970; Burlaga et al., 1971; Gosling et al., 1972; V. Pizzo, J. T. Gosling, and A. J. Hundhausen, unpublished manuscript, 1972; Hundhausen, 1973]. On the other hand, rarefational cooling in the trailing part of high-speed streams does not appear to be a major factor in explaining the anomalously low proton temperature states sometimes observed at high flow speeds [Gosling et al., 1972; V. Pizzo, J. T. Gosling, and A. J. Hundhausen, un-
Fig. 1. A scatter plot in the $v$, $T_p$ plane of all the 3-hour averages from Vela 3 for July 1965 through December 1967. The straight line separates out the anomalously low $T_p$, high $v$ plasma states under discussion. Those measurements falling below this line and following within 72 hours of interplanetary shocks have been circled.

Published manuscript, 1972). It is our purpose here to show that these anomalous states of low $T_p$, high $v$ preferentially occur some 20-60 hours after the passage of interplanetary shocks. The association with interplanetary shocks is particularly strong for those shocks that are followed by abnormally high ($\geq 15\%$) He$^{++}$/H$^+$ concentrations in the solar wind. We suggest that these anomalous $T_p$ states following some (but not all) interplanetary shocks are the result of adiabatic cooling in the expanding driver gas behind these shocks. Such unusual cooling can be interpreted as evidence for the existence of large magnetic bottle configurations behind these shock waves, as suggested by Gold [1960] and others a number of years ago and more recently in a slightly different form by Hundhausen [1971]. Our results are entirely consistent with the interpretation of low electron temperatures in the solar wind given recently by Montgomery et al. [1972].

**Observations**

In Figure 1 a straight line has been drawn in the $v$, $T_p$ plane connecting the points 350 km sec$^{-1}$, 0°K and 700 km sec$^{-1}$, $2 \times 10^6$ °K. This line is approximately parallel to the best-fit line for all the Vela 3 data [e.g., Hundhausen et al., 1970a; Gosling et al., 1972; V. Pizzo, J. T. Gosling, and A. J. Hundhausen, unpublished manuscript, 1972] and has been chosen to separate out the region of anomalously low $T_p$, high $v$ states. The choice of this particular line is somewhat arbitrary; slightly different lines could equally well have been drawn. Measurements performed within 72 hours following interplanetary shocks and falling below this line, as determined from a list of 48 shocks for this period derived from papers by Chao [1970], Hundhausen et al. [1970b], Hundhausen [1970], Burlaga and Ogilvie [1969], Ogilvie and Burlaga [1969], and Taylor [1969], have been circled. Of 90 measurements falling on or below the line, 36 (representing 12 separate events) occur within 72 hours after the passage of an interplanetary shock. Yet, less than 10% of the total Vela 3 data sample occurs within the 72-hour interval following interplanetary shocks. The correlation with interplanetary shocks is considerably greater at the higher velocities. For example, of 30 measurements falling below the line when the velocity exceeded 515 km sec$^{-1}$, 21 (representing 9 separate events) occur after interplanetary shocks. The conclusion seems inescapable that plasma states of anomalously low $T_p$, high $v$ are preferentially associated with the plasma behind interplanetary shock waves. We shall explore this association in more detail in the following paragraphs.

**Data**

The Vela 3 satellites were launched into nearly circular orbits 18 $R_E$ in radius about the earth in July 1965. The 3-hour averages of the proton component of the interplanetary solar wind data from July 1965 to December 1967 derived from measurements when the satellites were beyond the earth's bow shock have been published by Bame et al. [1971] and are the source of the present study. A large number of data gaps exist in the Vela 3 interplanetary coverage, owing to intermittent data transmission to the earth and the passage of the satellites into the earth's magnetosheath and magnetotail. For this reason the Vela 3 data lend themselves more readily to statistical studies of the interplanetary medium than to the intensive study of individual events, such as a single corotating high-speed stream or a flare-induced shock wave.
The distribution of delay times from the shock waves versus the anomalously low $T_p$, high $v$ states is shown in Figure 2. When more than one shock occurred within the 72 hours before an anomalous state, the delay time was calculated in relation to the last shock in the sequence. Often anomalously low proton temperatures were measured for more than 15 hours; hence some events contributed to more than one time interval in Figure 2. We note that Figure 2 indicates that the anomalous proton states occurred preferentially from 20 to 60 hours after the shock passage. We emphasize that this range is primarily a statistical result; seldom are the data sufficiently complete to allow one to state with precision when the anomalous states began or ended for any particular event.

There was a marked preference for the proton density to be low at the time of these low $T_p$, high $v$ measurements, as is shown in the histogram of Figure 3. Proton densities below 5 cm$^{-3}$ were preferred; densities between 2 and 3 cm$^{-3}$ were the most probable. These densities are considerably below the average Vela 3 solar wind density of 7 cm$^{-3}$ and the most probable density of 4.5 cm$^{-3}$ and are also lower than the densities normally encountered by Vela 3 at these velocities [Hundhausen et al., 1970a]. Said another way, the events under consideration exhibit plasma states of anomalously low $T$, and $n$, and high $v$.

The thirty-six 3-hour averages circled in Figure 1 and used in the construction of Figures 2 and 3 are summarized in Table 1. We note that 12 different events are represented in Table 1 out of a total of 24 shock events for which the velocity exceeded 400 km sec$^{-1}$ and for which postshock data were available. However, owing to the aforementioned data gaps, it is uncertain whether those events that did not exhibit anomalously low $T_p$, high $v$ states ever actually did so. Thus 50% is a lower-limit estimate of the percentage of postshock events that exhibited this phenomenon. It is also clear from Table 1 that the low $T_p$, high $v$ state in some events persists for $>15$ hours. Generally, it is true of those events for which we have listed only a few points in Table 1 (e.g., events 1, 3, 5, 8, 10, and 12) that data gaps severely limit our ability to distinguish the anomalous $T_p$, $v$ state at other times during the postshock event. Thus it is quite possible that these as well as some of the other six events actually persisted considerably longer than is apparent in the data.

The next to last column in Table 1 indicates the important positive association of these anomalous $T_p$, $v$ states with abnormally high He$^{++}$/H$^+$ ratios observed in the postshock solar wind between the time of the shock passage and the onset of the anomalous states. In fact, the correlation of anomalously low proton temperatures with helium enrichments is considerably better than the table indicates, for a variety of reasons. First, helium concentrations of 15% or greater relative to hydrogen are extremely
<table>
<thead>
<tr>
<th>Event Date</th>
<th>Shock Time, UT</th>
<th>Delay from Shock, hours</th>
<th>Proton Speed, km sec⁻¹</th>
<th>Proton Temperature, eV</th>
<th>Helium Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Jan. 21, 1966</td>
<td>0739</td>
<td>27</td>
<td>534</td>
<td>4.40 × 10⁴</td>
<td>?</td>
</tr>
<tr>
<td>2 March 23, 1966</td>
<td>0420</td>
<td>45</td>
<td>507</td>
<td>6.54</td>
<td>Gosling et al. [1972]</td>
</tr>
<tr>
<td>3 July 9, 1966</td>
<td>0000</td>
<td>60</td>
<td>541</td>
<td>10.4</td>
<td>Hirschberg et al. [1971]</td>
</tr>
<tr>
<td>4 Aug. 30, 1966</td>
<td>1112</td>
<td>27</td>
<td>653</td>
<td>10.4</td>
<td>Lazuta and Busek [1966]</td>
</tr>
<tr>
<td>5 Sept. 3, 1966</td>
<td>2129</td>
<td>24</td>
<td>475</td>
<td>4.78</td>
<td>Hirschberg et al. [1971]</td>
</tr>
<tr>
<td>6 Nov. 25, 1966</td>
<td>1339</td>
<td>27</td>
<td>428</td>
<td>3.90</td>
<td>Hirschberg et al. [1972]</td>
</tr>
<tr>
<td>7 Feb. 7, 1967</td>
<td>1640</td>
<td>33</td>
<td>578</td>
<td>12.9</td>
<td>Hirschberg et al. [1972]</td>
</tr>
<tr>
<td>8 Feb. 15, 1967</td>
<td>2345</td>
<td>33</td>
<td>462</td>
<td>3.81</td>
<td>4.19</td>
</tr>
</tbody>
</table>

**Table 1.** Properties of Solar Wind Plasma Associated with Low-Temperature Measurements.
Gosling et al.: Solar Wind Proton Temperatures

rare in the Vela 3 data; of 10,200 individual solar wind spectra obtained by the Vela 3 satellites between July 1965 and June 1967, only 43 showed helium concentrations of >15% [Hirshberg et al., 1972]. These 43 spectra were distributed among 16 separate events, 12 of which were shock events associated with major solar flares. Second, helium enrichments of >15% in the solar wind typically pass a satellite at 1 AU in 6 hours, according to Hirshberg et al. [1972]. Thus these large enrichments are easily and often missed by the intermittent temporal coverage provided by the Vela 3 satellites. It is possible, indeed likely, that those events for which no large helium enhancement is indicated in Table 1 actually had a helium enrichment association. Third, there is very good evidence that most, if not all, flare-associated helium enrichments of >15% are followed shortly thereafter by periods of anomalously low proton temperatures. For example, 6 of the 12 events noted by Hirshberg et al. are included in Table 1. Of their remaining 6 flare-associated events, 3 (the enrichments of March 28 and September 19, 1966) were followed within 48 hours by anomalously low Tp, high v solar wind states. These 3 events account for 7 of the uncircled points in Figure 1 falling below the diagonal line and to the right of 500 km sec⁻¹. They did not appear in our original list of 48 events, but all 3 enrichments have close associations with either a sudden commencement geomagnetic onset or a sudden impulse, usually reliable indicators of major solar wind discontinuities [Gosling et al., 1967; Gosling et al., 1968]. In addition, the helium enrichment of October 17, 1966, preceded protons with temperatures of 4 × 10⁴ K but also low velocities; postshock Vela 3 coverage terminated some 21 hours after the shock of January 13, 1967, and 3 hours after the helium enrichment on the same date; and the helium enrichment of September 2, 1966, was followed shortly thereafter by another shock and helium enhancement on September 3. This accounts for all 12 of the major helium events reported by Hirshberg et al. [1972].

Finally, in closing our discussion of Table 1 we note that the flow speed tends to be nearly constant or falls off slowly with time during the measurement of anomalously low proton temperatures.
The salient points of the observations can be summarized as follows.

1. Plasma states of low $T_p$, high $v$ are rarely observed in the solar wind at 1 AU. A disproportionately large fraction of those states that do occur come 20–60 hours after the passage of interplanetary shocks.

2. The proton density of the solar wind at the time of these anomalously low proton temperatures is depressed below that normally observed at these high velocities.

3. The velocity tends to be constant or to fall off slowly at the time of the events.

4. Interplanetary shocks are likely to be followed by anomalous $T_p$, $v$ states if they are also followed by abnormal concentrations of He$^{++}$. However, the highest He$^{++}$ concentrations usually occur before the low $T_p$, high $v$ states.

Montgomery et al. [1972] have recently reported observations of depressed electron temperatures $T_e$ in the solar wind. They find a very strong correlation of these measurements with the passage of interplanetary shocks past the Vela 5 and 6 and Imp 6 spacecraft. Statistically, the occurrence of depressed $T_e$ occurs simultaneously with the anomalously low proton temperatures reported here, i.e., approximately 20–60 hours after the shock passage. They also noted a threefold increase in the He$^{++}$/H$^+$ ratio for the one event for which such data were available and commented on the fact that $T_e$ tended to be somewhat depressed simultaneously with the $T_p$ depressions. Thus it is clear that abnormally low solar wind electron temperatures ($\sim 5 \times 10^4$ K) are also an important feature of the postshock plasma behind many interplanetary shocks.

It is common to associate interplanetary shocks with solar activity, particularly, large solar flares. Of the 12 events listed in Table 1, 8 have reasonably positive associations with class 2B or 3B flares. Further, the 3 additional high helium events that gave rise to anomalous proton temperatures also were related to class 3B (2 events) or 2B (1 event) flares. Thus we feel reasonably confident that most (and probably all) of the shock events under consideration here are related to major solar activity.

A considerable body of evidence now exists that supports the viewpoint that an amount of material approximately equal to the total ambient mass of the corona commonly is ejected into the solar wind at the time of large solar flares. (See Hundhausen [1971, 1972] for reviews of the 1-AU evidence.) This material, presumably of chromospheric origin, drives many of the shock waves observed at 1 AU. Hirshberg and her colleagues [e.g., Hirshberg et al., 1970] have suggested that this driver gas can be distinguished at 1 AU by its extraordinarily high helium content. Hundhausen [1971] has recently synthesized many of the solar wind observations relating to the geometry of shock wave disturbances in the qualitative sketch shown in Figure 4. Of particular interest to the discussion here are the relative positions of the shock and helium enrichment and the magnetic field configuration ahead of and behind the enrichment. Ahead of the helium concentration, field lines connect back to the sun. These field lines are associated with the ambient medium ahead of the disturbance; they are compressed and pushed aside by the disturbance but probably retain their connection to the sun. The field geometry behind the enrichment is less certain. The new material ejected into the solar wind at the time of the flare carries with
it new fields. It seems likely that these field lines may merge near the sun to form large magnetic bubbles or bottles. However, until recently there was virtually no evidence available bearing on the question of the field topology within and behind the flare ejecta, hence the question mark on Figure 4. We note that it is precisely within the postulated bottle region of the shock wave disturbance that the anomalous proton temperatures reported here are observed. In the following paragraph we will describe reasons why these observations can be construed as positive evidence for the existence of such bottles. Our reasoning closely parallels that of Montgomery et al. [1972].

Consider that the field lines in Figure 4 actually do close in the vicinity of the question mark. Such closure serves to insulate the material within the bottle from the surrounding plasma; in particular, thermal conduction from the lower corona, which is considerably more efficient along field lines than across them, is inhibited. Thus the thermal situation within a magnetic bottle should be considerably different from that outside a bottle. Usually, the solar wind at 1 AU is in reasonably good thermal contact with the solar corona along field lines that connect back to the sun. The thermal connection is provided by the electrons, which, with their low mass, are extremely good conductors of heat. The reasonably high (1-2 \times 10^5 \, ^\circ\text{K}) and relatively constant electron temperature normally observed at 1 AU [Montgomery et al., 1968] testifies to the efficiency of this thermal connection. That the solar wind protons share in this thermal connection has become increasingly apparent in recent years. The protons with their relatively large mass should conduct about 40 times less heat than the electrons. If electrons and protons are coupled to one another only by Coulomb collisions, one expects the protons to cool nearly adiabatically in their expansion out to the earth. However, models [e.g., Hartle and Sturrock, 1968] that treat the solar wind as a two-component fluid with only Coulomb coupling between the components predict proton temperatures at the earth that are more than an order of magnitude lower than those observed [Strong et al., 1966] and electron temperatures that are too high by about a factor of 2. Several people [e.g., Hundhausen, 1969; Montgomery et al., 1968; Fredricks, 1969] have suggested that this discrepancy between theory and observations can be removed by invoking a coupling between the electron and proton components of the plasma that is more efficient than Coulomb collisions. Hence the protons to some extent probably share the electron thermal connection back to the corona when such a connection exists, i.e., most of the time. It appears that this coupling of the proton temperature to the corona may be sufficient to explain the lack of extensive cooling found in the rarefactions of quasi-stationary high-speed streams (compare, e.g., the observations and adiabatic theory illustrated in Figure 12 of Gosling et al. [1972]). We do suggest, however, that adiabatic cooling of solar wind protons and electrons does proceed behind many interplanetary shocks precisely because the thermal connection with the solar corona is broken by a closed magnetic configuration. This hypothesis appears to be consistent with the observation of constant or falling velocity and abnormally low density at the time of anomalously low proton and electron temperatures in the solar wind. Further, the low temperatures tend to occur 20-60 hours after the shock and closely follow the high helium concentrations, in accord with the geometry sketched in Figure 4. Finally, the high helium concentrations have been interpreted by Hirschberg et al. [1972] and others as positive evidence that fresh material is indeed injected into the solar wind at the time of some solar flares, a seemingly necessary condition for the formation of magnetic bottles within the solar wind.

In closing, we emphasize that the observational details of the structure of the solar plasma driving interplanetary shock waves remain fragmentary. Our evidence for the high helium concentrations and anomalously low proton and electron temperatures has been derived primarily from data that suffer from an excess of gaps where no information about the interplanetary plasma was obtained. Further, the proton temperature data have been simplified by the use of 3-hour averages. Our approach has been statistical; it has led us to conclusions about overall shock wave geometries that are undoubtedly an oversimplification. Although we feel that Figure 4 with field line closure in the region of the question mark em-
bodies the essence of many flare-associated shock disturbances, individual events must differ considerably in complexity and detail from this sketch. For example, it may be that instead of one big magnetic bottle, many smaller bottles are formed behind the plasma ejecta and within the ejecta itself. It is also possible that the magnetic loops may not actually disconnect themselves from the lower corona. In this case the anomalously low temperatures at 1 AU might result from the fact that a small area of the sun (the corona above the active region) must thermally feed a very large part of interplanetary space. Finally, although we have indicated that a magnetic bottle configuration may be responsible for the observations of low temperatures 20–60 hours after shocks, we do not presently have the interplanetary field data to confirm or deny this interpretation.

Acknowledgments. We have benefited from discussions on this topic with our colleagues Drs. W. Feldman, J. Hirshberg, and A. Hundhausen. In addition, Dr. Hirshberg provided ample and constructive criticism of the manuscript itself.

The National Center for Atmospheric Research is sponsored by the National Science Foundation. The work at Los Alamos was performed under the auspices of the Atomic Energy Commission, the Vela 3 program being jointly administered by the AEC, ARPA, and the USAF.

* * *

The Editor thanks L. F. Burlaga and E. N. Parker for their assistance in evaluating this paper.

References


Taylor, H. E., Sudden commencement associated discontinuities in the interplanetary magnetic field observed by Imp 3, Solar Phys., 6, 330, 1969.

(Received October 11, 1972; accepted November 14, 1972.)