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Non-Adiabatic Expansion of Low-Temperature Solar Wind Radial Temperature Gradients

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Abstract. The occasional observation of very low temperatures in the solar wind at 1 AU are of great interest temperatures in the solar plasma dropping on average, to one third and one tenth of the value for the ambient solar wind, for electrons and protons, respectively. In explanation of this phenomenon, a hypothetical magnetically closed structure in the solar wind is tested assuming two different sets of conditions. The first considers the structure, hereafter called "blob", expanding radially outwards from the sun but not adiabatically. The second involves a rapid pressure equalization across the boundary of the moving blob. To test these models, we used a set of semi-empirical specific heats, different for protons and electrons, and applied semi-empirical temperature gradients in the ambient solar wind, different for fast and slow flow.

Contrary to an older model, which assumed a pure adiabatic expansion and used the Hartle-Barnes theoretical temperature gradients, the result, after this test, showed that the modified blob model could reasonably support the observations, suggesting additionally a possible blob-origin at a distance of the order of ten solar radii.

Key words: Solar wind temperature – Radial temperature gradients

Introduction

Theoretical treatment of the hydrodynamic conditions in the solar wind, its heat conduction and especially the prediction of its temperature (Parker 1963; Whang and Chang 1965; Hartle and Sturrock 1968; Hartle and Barnes 1970; Yeh 1971; Hundhausen 1972; Hollweg 1976) is supported by experiments in space but these also reveal new aspects of solar wind properties (Montgomery et al. 1968; Burlaga and Ogilvie 1970; Gosling et al. 1972; Feldman et al. 1975).

One surprising phenomenon, the detection of "very cold" solar wind plasma, has attracted a systematic analysis (Gosling et al. 1973; Montgomery et al. 1974; Gosling and Roelof 1974; Geranios 1978). These observations, made by Vela 5, 6 and IMP 6 satellites, after the passage of an interplanetary shock front or solar wind stream, last on the average 10–40 h, or even longer. During this period both the electron and proton temperatures are anomalously low. It is generally believed (above mentioned authors) that this effect could possibly originate from regions in the solar wind which are surrounded by closed or nearly closed interplanetary magnetic field lines. Therefore, these regions are thermally isolated from the relatively hot corona and are cooling down in relation to the plasma embedded in open field lines, as they expand away from the sun.

Theoretical models, proposed by Whang and Chang 1965; Hartle and Sturrock 1968; Hartle and Barnes 1970, express the parameters of the solar wind analytically assuming good thermal contact between the solar plasma and the solar corona along the interplanetary magnetic field lines. Consequently, observations of cold plasma suggest an interruption of this thermal conduction.

Due to the expansion and convection of such regions, "blobs", by the solar wind, at an average speed of 400 km/s, by 1AU they grow to a large size, of about 0.1–0.4 AU. (Originally, the expression "blob" was used by Barouch and Burlaga (1975), for a region in which the interplanetary magnetic field strength is high.) It is assumed that blobs started expanding somewhere between the sun and the earth. By assumming that they have followed a certain law during their expansion, for example an adiabatic expansion, we could estimate the place of their origin.

A method shown in principle in Fig. 1, described elsewhere (Geranios 1978), is based on the fact that at the origin the temperature inside the blob should be equal with that outside. The inner temperature falls progressively down to the measured value at 1 AU, 5.5×10^4 °K and 1.5×10^4 °K for electrons and protons respectively.

Using the Hartle and Barnes temperature gradients for electrons and protons in the ambient solar wind provided by the two-fluid model (Harthe and Barnes 1970) and the above observed low temperatures, we calculated independently for each main plasma component the radial distance from the sun of the apparent origin of the blobs. At this distance, the particles under consideration should be thermally decoupled from the corona. For the calculations we used two different models of the type of expansion:

(a) pure adiabatic expansion in radially streaming solar wind, and

(b) rapid pressure equalization across the boundary,

hereafter called model I and model II. The blob-formation distances thus calculated showed large discrepancies between electrons and protons, a fact which is inconsistent with what we might expect: that in the cold, expanding region, part of the solar wind, both electrons and protons should stay together (charge neutrality) (Geranios 1978). Therefore, under these conditions the closed magnetic loop or blob model is unlikely to

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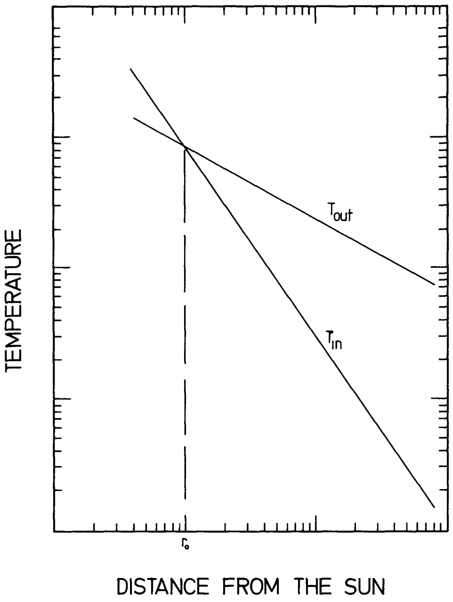

Fig. 1. The temperature variation of the solar wind plasma outside the blob, T_{out}, and inside, T_{in}, as this structure expands, moving radially outward from the sun towards the earth ($T_{out} > T_{in}$). The formation distance of the blob (r_o) is determined by the intersection of T_{out} and T_{in}, straight lines on a log-log scale

be the major cause of the electron and proton temperature depressions.

In this paper we attempt a new explanation of the anomalous solar wind temperature effect with the calculation of empirical specific heat coefficients, different for electrons and protons. In addition, we give empirical electron and proton temperature gradients, discriminating fast from slow solar wind (Helios-1, Rosenbauer et al. 1977).

Calculation of Semi-Empirical Specific Heats for the Low-Temperature Regions

Inside the blob we assume a radial, spherically symmetric temperature variation within the plasma and time independent expansion

$$T_i/T_o=(r/r_o)^{-2(\gamma_1-1)} \tag{1a}$$

T_i, T_o are the temperatures of the plasma at radial distances r and r_o, respectively, and γ is the ratio of the specific heat at constant pressure to that at constant volume. For an adiabatic expansion $\gamma=5/3$, as in a fully ionized gas with three degrees of freedom (Spitzer 1962). To apply Eq. (1a) with $\gamma=5/3$ to the electron and proton temperatures, the region under study should be completely thermally isolated from the neighbouring plasma. But this is an ideal condition. For a more realistic case we assume that

(1) the expansion is not purely adiabatic, so γ should be lower than 5/3, and

(2) γ is different for electrons and protons.

With these restrictions we calculate the new values (γ_1^e) for electrons and (γ_1^p) for protons, using

(a) the boundary conditions of the Hartle-Barnes model, and

(b) the experimentally measured temperatures at 1 AU (Geranios 1978):

at $r_o=2R_o$, $T_o=1.2\times10^6$ °K for protons
$T_o=1.5\times10^6$ °K for electrons,
and
at $r=1$ AU, $T_i=1.5\times10^4$ °K for protons,
and
$T_i=0.5\times10^5$ °K for electrons.

R_o, being the radius of the sun.

Equation (1a) gives

$$\gamma_1=(2-A)/2$$

where $A=\ln(T_i/T_o):\ln(r/r_o)$ and with substitution of the above boundary values we have

$\gamma_1^p=1.53$ for protons, where $A_p=-0.94$

and

$\gamma_1^e=1.37$ for electrons, where $A_e=-0.73$

yielding $\gamma_1^e<\gamma_1^p<\gamma_{ad}$.

Subscripts 1, 2 refer to models I, II. For model II we also use the same boundary conditions and as the electrons of the solar wind are much hotter than the protons, the total pressure of the ambient solar wind is represented by the electron pressure. The corresponding equation for this model is:

$$T_i/T_o=(r/r_o)^{-(\gamma_2-1)(\varepsilon+2)/\gamma_2} \tag{1b}$$

(Geranios 1978) $\varepsilon=0.316$, being the electron temperature gradient (Hartle and Barnes 1970), according to which we obtain

$$\gamma_2=(\varepsilon+2)/(\varepsilon+2+A)$$

and we have

$\gamma_2^p=1.68$ for protons, and
$\gamma_2^e=1.46$ for electrons.

Models Using an Empirical Model for the Ambient Solar Wind

Measurements of solar wind electron and proton temperatures at different distances from the sun (0.3–1.0) AU, performed by Helios-1, revealed radial gradients not only different from those theoretically predicted, but also different for slow and fast solar wind speed (Rosenbauer et al. 1977). The data for the electron and proton temperature gradients are obtained from temperature and solar wind speed measurements for the period 14 December 1974–15 April 1975, during which Helios-1 approached the sun up to a radial distance of 0.309 AU, after its launch on 10 December 1974. The caluclated gradients take into account that the solar wind is distinguished into slow and fast, $V_s<550$ km/s, $V_f>550$ km/s. An example of temperature gradients is given below (all are unitless exponents)

Electrons $\varepsilon_f=0.8$ for fast,
Electrons $\varepsilon_s=0.5$ for slow solar wind.
Protons $b_f=0.35$ for fast,
Protons $b_s=0.62$ for slow solar wind.

Generally, for fast solar wind, ε_s tends to the value of 0.5, while for slow solar wind, ε_f tends to 1 (Philipp 1978). Figure 2

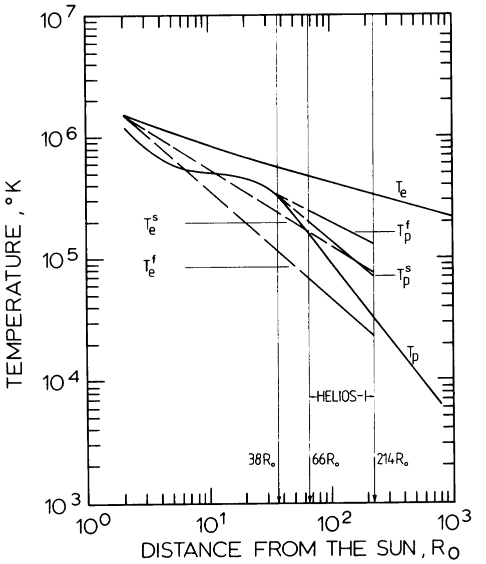

Fig. 2. Comparison between theoretically calculated H-B temperature gradients and those experimentally derived. T_e, T_p refer to the Hartle-Barnes two-fluid model. T_e^f, T_e^s, T_p^f, T_p^s are the calculated gradients for electrons and protons respectively for fast and slow solar wind. $38\,R_o$ is the distance at which the H-B model predicts a break-down of the gradient T_p. $66\,R_o$–$214\,R_o$ is the distance explored by Helios-1

compares the theoretical gradients with the empirical ones used. Applying these four temperature gradients and assuming that they are constant over the range 2–$214 R_o$, having similar values for the period August 1969–May 1974 (the period during which the low temperature regions are detected), we test the two models I and II. We used the same value suggested by Hartle and Barnes (1970) for the proton temperature gradients for $2R_o$–$38R_o$. For the calculated proton temperature gradients we used 16000 approximately hourly temperature-speed data covering a period of three years (December 1974–December 1977), measured by Helios-1.

For each of the 30 very low temperatures analysed (Geranios 1978), detected by the IMP and VELA satellites at 1 AU (Feldman et al. 1975), we measure the temperature before and after the low temperature period (two values of T_a), and the minimum temperature (T_i). These values are shown in Table 1.

We classify the 30 events observed (Table 1) into two categories,

(1) fast solar wind, and

(2) slow solar wind.

(The cases related to fast solar wind are marked in Table 1 with f.) All coefficients involved in the calculations are shown in Table 2.

Model I

For protons we have

$$T_a/T_o=(38/r_o)^{-a}(r/38)^{-b_{f,s}} \quad \text{for } 38R_o \leqq r \leqq 214R_o \tag{2}$$

and

$$T_a/T_o=(r/r_o)^{-a} \quad \text{for } 2R_o \leqq r < 38R_o \tag{3}$$

both

$$\text{for } 2R \leqq r_0 < 38R_o.$$

Table 1. Temperatures before (T_1) and after (T_2) very low temperature observations, minimum temperature T_m, recorded by IMP and VELA satellites. Subscript e refers to electrons, p to protons. Letter f denotes fast solar wind

No.	T_m^e	T_1^e	T_2^e	T_m^p	T_1^p	T_2^p	V
	$\times 10^4$ °K						(km/s)
1	–	–	–	0.8	19	15	490
2	5.0	11.8	12.0	2.5	7.5	14	375
3	4.2	17.0	26.7	3.5	15	50	700 f
4	7.5	14.2	10.0	2.0	29	16	415
5	6.8	9.5	10.0	0.8	7	3	370
6	4.5	22.0	12.0	4.0	30	10	500
7	6.5	15.5	12.2	1.2	10	7.5	365
8	7.5	21.5	14.5	–	–	–	710 f
9	4.5	11.5	8.0	1.8	18	7	455
10	3.3	9.5	15.1	3.7	25	14	620 f
11	5.0	13.0	16.5	3.0	18	8	495
12	6.0	15.0	17.0	2.0	16	24	370
13	–	–	–	0.3	16	10	430
14	5.0	8.0	13.0	1.5	17	13	400
15	5.0	10.0	18.0	2.0	14	18	380
16	5.0	10.8	7.6	1.8	12	16	440
17	4.5	15.6	10.3	1.0	18	12	430
18	8.3	25.5	20.8	0.8	42	11	525
19	6.6	30.0	14.5	1.0	4.7	3.7	350
20	5.0	19.0	15.1	0.8	10.7	16	455
21	6.1	13.6	23.9	1.6	9	33	–
22	5.8	20.6	15.1	1.3	20	16	635 f
23	5.6	13.5	10.6	0.8	4.7	3	370
24	5.6	10.6	15.1	0.8	3	16	300
25	5.3	27.5	13.1	0.8	44	13.5	600 f
26	1.4	7.3	7.0	3.1	20.5	10.2	–
27	4.4	13.8	25.0	1.3	22	12	420
28	6.6	16.0	24.0	1.3	6	36	–
29	5.0	20.0	24.0	2.5	51	41	565 f
30	6.3	15.6	14.4	1.7	18	13.6	600 f
31	4.6	13.3	13.5	1.6	7.8	16.7	400
32	–	–	–	2.1	19	16	600 f

Table 2. Polytropic indices (γ) and electron and proton temperature gradients (ε and b) for fast (f) and slow (s) solar winds

	Electrons	Protons
Model I	$\gamma_1^e=1.37$	$\gamma_1^p=1.53$
Model II	$\gamma_2^e=1.46$	$\gamma_2^p=1.68$
Fast	$\varepsilon_f=0.8$	$b_f=0.35$
Slow	$\varepsilon_s=0.5$	$b_s=0.62$
Theoret.	$\gamma_{ad}=1.67$	$a=0.349$
	$\varepsilon=0.316$	$b=1.272$

(From here, r denotes distance from the sun, variable, and r_o denotes location of the blob-origin, indices f, s apply to fast, slow solar wind cases, Table 1.)

$a=0.349$ (Hartle and Barnes 1970)

T_a is the temperature outside the blob at the sistance r. Using Eq. (1 a) we have, for fast and slow solar wind, respectively.

$$r_o=(T_i/T_a)^{1/(C^p-a)}38^{(a-b_{f,s})(a-C^p)}\,r^{(b_{f,s}-C^p)/(a-C^p)} \tag{4}$$

for

$38R_o \leqq r \leqq 214R_o$, and $\quad 2R_o \leqq r_0 < 38R_o$

$C^{p,e} = 2(\gamma_1^{p,e} - 1)$.

For each of the two categories we obtain

$$r_o = r(T_i/T_a)^{1(C^p - a)} \quad \text{for } 2R_o \leqq r < 38R_o, 2R_o \leqq r_o < 38R_o. \tag{5}$$

A third case, which does not apply here is

$$r_o = r(T_i/T_a)^{1/(C^p - b_{f\ s})} \quad \text{for } 38R_o \leqq r \leqq 214R_o, 38R_o \leqq r_o \leqq 214R_o.$$

For electrons, the corresponding equations are

$$T_a/T_o = (r/r_o)^{-\varepsilon_{f,s}} \tag{6}$$

and using Eq. (1a) we have

$$r_o = r(T_i/T_a)^{1/(C^e - \varepsilon_{f,s})} \quad \text{for fast and slow speeds.} \tag{7}$$

Model II

For protons we use Eq. (1b)

$$T_i/T_o = (r/r_o)^{-d_{f,s}}$$

and with

$$T_a/T_o = (38/r_o)^{-a}(r/38)^{-b_{f,s}}$$

gives for

$38R_o \leqq r \leqq 214R_o$, $\quad 2R_o \leqq r_o < 38R_o$

$$r_o = (T_i/T_a)^{1/(d^p_{f,s} - a)} 38^{-(a - b_{f,s})/(d^p_{f,s} - a)} r^{(b_{f,s} - d^p_{f,s})/(a - d^p_{f,s})} \tag{8}$$

for fast and slow solar wind, respectively.

$$d^{p,e}_{f,s} = (\gamma_2^{p,e} - 1)(\varepsilon_{f,s} + 2)/\gamma_2^{p,e}$$

p applies to protons and e to electrons.

In the range 2–38R_o for fast *or* slow solar wind we have

$$r_o = r(T_i/T_a)^{1/(d^p - a)} \quad \text{for } 2R_o \leqq r_o < 38R_o. \tag{9}$$

Similarly, for electrons we obtain, for $2R_o \leqq r \leqq 214R_o$

$$r_o = r(T_i/T_a)^{1/(d^e_{f,s} - \varepsilon_{f,s})}$$

for fast and slow solar wind.

for $2R_o \leqq r_o < 38R_o$.

Substitution of r by 214 (the distance of the observation) and of the measured temperatures T_i and the two T_1, T_2, which are the outside temperatures T_a (Table 1), into the above equations gives the possible ranges inside which the blobs might originate (Table 3). These ranges correspond to T_1–T_2 in Table 1. For the cases in Table 1 related to fast solar wind the possible ranges for electrons are at much larger distances than 1 AU for model I, while for model 2 they are at much shorter distances than one solar radius. This result is due to the apparently very large radial gradient used (0.8).

The frequency distributions of these distances are shown in Fig. 3. Here, the whole of the electron and proton distributions are overlapped, suggesting a mean distance of the origin of the blobs of protons and electrons around 10R_o for both models. The large width of the frequency distributions is due mainly to the large uncertainties in the temperature measurements and to the logarithmic scale used in the ordinates.

Results

Blob models which have previously been considered as possible candidates for the explanation of the phenomenon of very low

Table 3. Distance ranges where blob apparently originated, calculated for the two models, separately for electrons and protons

No.	Model I		Model II	
	Range of r_o^e (R_o)	Range of r_o^p (R_o)	Range of r_o^e (R_o)	Range of r_o^p (R_o)
1	–	1.3– 1.8	–	0.9– 1.3
2	5.6– 6.0	9.8–23.6	10.2–10.8	7.9–20.1
3	$\gg 214R_o$	5.1–27.6	$\ll 1R_o$	7.2–33.4
4	15.2–64.5	2.6– 5.9	23.3–78.7	1.9– 4.6
5	42.9–53.1	5.2–17.3	56.0–67.0	4.0–14.4
6	0.3– 3.6	6.5–30.5	0.7– 7.1	5.1–26.5
7	5.7–15.1	5.6– 8.4	10.4–24.0	4.3– 6.7
8	$\gg 214R_o$	–	$\ll 1R_o$	–
9	4.3–19.5	4.3–16.4	8.2–29.0	3.3–13.6
10	$\gg 214R_o$	14.5–32.8	$\ll 1R_o$	18.7–39.1
11	1.5– 4.0	8.9–27.9	3.4– 7.7	7.1–24.0
12	2.8– 4.7	3.4– 5.9	5.7– 8.9	2.5– 4.6
13	–	0.4– 0.8	–	0.3– 0.5
14	4.0–30.2	3.6– 5.3	7.7–41.8	2.7– 4.1
15	1.0–11.9	5.0– 7.2	2.5–19.2	3.8– 5.6
16	8.6–37.4	5.1– 7.7	14.7–49.9	3.9– 6.0
17	1.2– 6.8	1.9– 3.4	2.8–12.0	1.4– 2.5
18	2.0– 4.7	0.4– 2.8	4.3– 8.8	0.3– 2.0
19	0.4– 8.0	12.6–17.6	1.1–13.9	10.2–14.7
20	0.8– 2.1	1.6– 2.9	2.1– 4.6	1.2– 2.1
21	–	–	–	–
22	$\gg 214R_o$	4.6– 6.3	$\ll 1R_o$	6.5– 8.7
23	5.5–15.0	9.2–17.3	10.0–23.3	7.3–14.4
24	3.4–15.0	1.6–17.3	6.8–23.3	1.2–14.4
25	$\gg 214R_o$	0.8– 4.0	$\ll 1R_o$	1.3– 5.8
26	–	–	–	–
27	0.2– 1.8	2.1– 4.9	0.5– 4.0	1.5– 3.7
28	–	–	–	–
29	$\gg 214R_o$	3.1– 4.2	$\ll 1R_o$	4.6– 6.0
30	$\gg 214R_o$	7.7–11.5	$\ll 1R_o$	10.5–15.1
31	2.4– 2.6	4.1–11.9	5.1– 5.3	3.1– 9.7
32	$\gg 214R_o$	9.6–12.3	$\ll 1R_o$	12.9–16.0

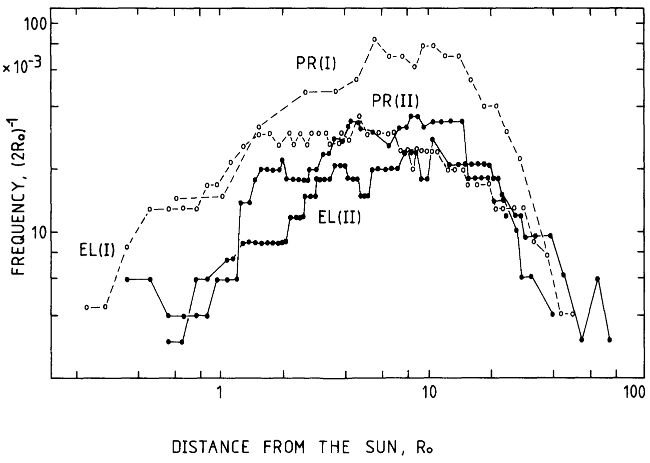

Fig. 3. The frequency of occurence of blob formation distances r_o versus R_o with the same calculated γ's as in Fig. 2 and the experimentally estimated temperature gradients for protons and electrons according to models I and II. The distinction between fast and slow solar wind is also taken into account

temperatures in the solar wind plasma under conditions of adiabatic expansion could not explain the temperature depressions (Geranios 1978).

In the paragraph here concerning specific heat calculations, which are different for protons and electrons, we have changed the condition of diabatic expansion, which the models tested previously were based on. Due to the fact that up to distance of at least 2/3 of 1 AU the temperature of protons and electrons in the solar wind have been measured by the heliocentric satellite Helios-1, we can calculate the radial temperature gradients.

The new test of the blob model is based on the assumption that the mean temperature gradient during the observed low temperature periods (August 1969–May 1974) is the same as the gradient during the period of Helios measurements, and is valid from 2–214 R_o. For protons, we assume a validity in the range 38–214 R_o, and for the distance 2–38 R_o we apply the same gradients as suggested by the Hartle-Barnes model.

The new information, that, the variation of temperature with distance is not unique but different for slow and fast solar wind (Rosenbauer et al. 1977) suggested two acceleration mechanisms for the solar plasma and led us to calculate two different values of radial temperature gradients for each component. Comparison with the theoretically derived values generally shows lower values for protons but higher for electrons

Protons $b_f = 0.3\, b_{HB}$
Protons $b_s = 0.5\, b_{HB}$
Electrons $\varepsilon_f = 2.5\, b_{HB}$
Electrons $\varepsilon_s = 1.5\, b_{HB}$

The calculated values of the proton radial temperature gradient are generally in agreement with the suggestions of Eyni and Steinitz (1978). According to their analysis, the slow solar wind ($V < 500$ km/s) shows a gradient of -0.8, while for the fast ($V > 500$ km/s) solar wind, there is no evidence for cooling of protons because the gradient is less steep. The discrepancy between our calculated gradient (-0.62) and that calculated by Eyni and Steinitz (-0.8) may be due to the

(1) different periods of analysis (possible temporal effects)

(2) restricted distance range used by Eyni and Steinitz (0.707–1.01 AU), and

(3) strong dependence of temparature on speed, which we have taken into account.

The result after treating the blob model with experimental temperature gradients which are different for low and high solar wind speed, while the adiabatic expansion of the blob is not retained, suggests that the blob might provide an explanation for the depressed temperature regions as shown in Fig. 3. According to this Figure, the suggested formation distance for these regions (blobs), for both models, fluctuates around 10 R_o.

Due to the fact that nearly all calculated polytropic indices γ_1^e, γ_1^p, γ_2^e, and γ_2^p are close to the value 5/3 which characterizes an adiabatic expansion, an independent adiabatic model as the explanation of the very "cold" solar wind would also work.

Discussion

The result shown in Fig. 3 suggests that it is not unreasonable that blobs are formed at heliocentric distances of 10 R_o. Following the recognition of bidirectional anisotropies in solar wind protons and electrons, observed by Explorer 34, 41 and Vela 5B, 6A and 6B, aligned with the interplanetary magnetic field lines, Palmer et al. (1978) suggested the existence of large-scale magnetic bottles behind interplanetary shocks. The mean duration of the bidirectional anisotropies was nine hours, representing a spatial extension of the region characterized by these anisotropies of about 0.13 AU. During these periods, a decrease of high-energy cosmic ray flux takes place, as in our case, when an interplanetary shock wave is identified simoultaneously with a very low temperature plasma (Geranios 1978). The main difference is that in their model the magnetically closed region is attached to the sun, while in our case it is detached from the sun. In addition, during the 4th International Solar Wind Conference, it was reported (Pilipp et al. 1978) that low temperatures coinside with interplanetary magnetic sector boundaries, where the field configuration shows closed features. Possible observations of very low plasma temperatures in the solar wind, not only at 1 AU but also nearer to the sun, performed succesively by Helios-1 and Helios-2, could eliminate temporal effects, and therefore could offer better observations for a further analysis of this phenomenon.

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