PLASMA FLOW AND SOLAR WIND ACCELERATION IN NON-RADIAL CORONAL MAGNETIC FIELDS

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In the vicinity of the Sun - especially above coronal holes - the magnetic field lines show strong non-radial divergence and considerable curvature (see e.g. Kopp and Holzer, 1976; Munro and Jackson, 1977; Ripken, 1977). In the following we study the influence of these characteristics on the expansion velocity of the solar wind.

1. BASIC CONCEPT OF THE SOLAR WIND FLOW IN A PRESCRIBED GEOMETRY

The steady state conservation equations for mass, momentum, energy and magnetic flux for an ideally conducting one-fluid plasma moving along a magnetic field line are given by the following equations (see e.g. Suess, 1979; Biernat et al., 1982):

$$nvA = F_1 \qquad (1)$$

$$mv \frac{dv}{ds} = - \frac{1}{n} \frac{d}{ds} (2nkT) - \frac{GmM}{r^2} \frac{dr}{ds} \qquad (2)$$

$$Anv \left[\frac{mv^2}{2} + \frac{\gamma}{\gamma-1} 2kT + Q - \frac{GmM}{r} \right] = F_2 \qquad (3)$$

$$AB = F_3 \qquad (4)$$

Here n is the number density of the protons, v the bulk velocity of the plasma, A the cross section of the flow tube; s the coordinate distance along the flow tube measured from the solar surface, T the temperature, r the radial distance from the solar centre and B the magnetic induction; Q is an energy addition function and γ the ratio of specific heats. F_1, F_2 and F_3 are constants of integration.

With the aid of (1) and (4) the Eq.(3) can be written as

$$\frac{1}{v} \frac{dv}{ds} \left[v^2 - \frac{c^2}{\gamma} \right] = \left[- \frac{GM}{r^2} \frac{dr}{ds} - \frac{1}{\gamma} \left(\frac{c^2}{B} \frac{dB}{ds} + \frac{dc^2}{ds} \right) \right] \qquad (5)$$

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where c is the adiabatic sound speed $c = (\gamma 2kT/m)^{1/2}$. We set $\rho = r/R$ and $\sigma = s/R$, where R is the solar radius. Now we construct ρ, $d\rho/d\sigma$, B, $dB/d\sigma$ as given analytic functions of σ and T as an analytic function of ρ. For this purpose we use a function of the form

$$f(x) = \frac{1}{2} \{a + b + (a - b) \sin\left[\pi \left(\frac{1}{2} \pm \frac{x - p}{q - p}\right)\right]\} \qquad (6)$$

which describes a sinusoidal increase (positive sign) or decrease (negative sign) of f from a to b within the interval $p \leq x \leq q$.

Fig. 1 shows three field lines of different curvature. Field line (I) is radial, i.e. $d\rho/d\sigma = 1$ over the whole range. The field lines (II) and (III) are obtained by a decrease of $d\rho/d\sigma$ ($d\rho/d\sigma = f(\sigma)$) from 1 at the solar surface $\sigma = 0$ to 0.766 and 0.5, respectively, at $\sigma = 1.5$. $d\rho/d\sigma$ is not changed up to $\sigma = 1.6$ and increases from there again according to (6) until the value 1 is reached at $\sigma = 3$.

The divergence of the flow tubes (Kopp and Holzer, 1976) is given by the magnetic field strength along the field line. B is assumed to decrease from 2Γ at the coronal base according to

$$B(\sigma) \sim (1 + \sigma)^{-f(\sigma)} \qquad (7)$$

By setting f = 2 over the whole range (case (A)) a divergence is obtained as suggested by the simple radial case, where $A \sim r^2$. In order to study the effect of a stronger flow tube divergence, we let $f(\sigma)$ increase between $\sigma = 0$ and $\sigma = 1.5$ and decrease between $\sigma = 1.6$ and $\sigma = 3$ according to Eq.(6). At $\sigma = 0$ we set f = 2. In the cases (B) and (C) we vary f up to 3 and 4, respectively. Within the interval $1.6 \leq \sigma \leq 3$ the value of f again decreases to 2.

We now determine the temperature as a function of the radial distanc from the Sun. We investigate two cases: (i) the isothermal case with $T = 2 \times 10^6$ K and (ii) the case with a temperature function fitted to observational data. At the coronal base we assume a low temperature (10^6 K) as might be expected for a coronal hole. From 1.5 up to 4 solar radii we take the values found by Withbroe et al. (1982) from EUV-obser-

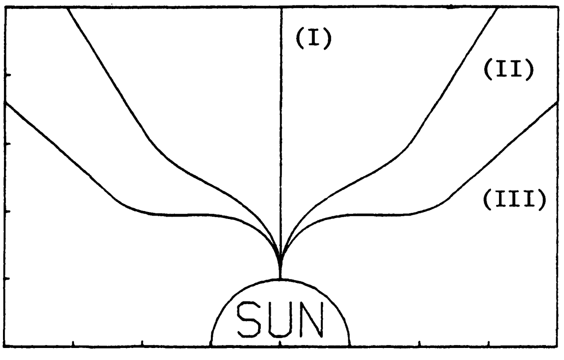

Fig. 1: Magnetic field lines of different curvature, along which the velocity profiles shown in Fig. 2 are calculated.

vations over a polar coronal hole. From 75 solar radii to 1 AU data of the HELIOS spacecraft as given by Cuperman et al. (1978) can be used. The exact values are given in Table 1.

Tab. 1: Temperature values as a function of the distance from the Sun

ρ	1.0	1.5	4.0	75.0	215.0 ($\hat{=}$ 1 AU)
T(K)	10^6	2.6×10^6	1.2×10^6	4.69×10^5	2.08×10^5

The increase of the temperature near the Sun is described by $T(\rho) = 10^6 \times (1 + 1.6 \sin \{\pi (\rho - 1)\})$. The temperature decrease beyond $\rho = 1.5$ is supposed to be

$$T(\rho) \sim \rho^{-f(\rho)} \qquad (8)$$

where $f(\rho)$ in each temperature interval of Table 1 is given by (6).

Finally F_1 and F_2 are determined from observations given by Feldman et al. (1976) for typical high speed streams. They find at 1 AU for the average particle flux density $\langle nv \rangle = 3.3 \times 10^8$ cm^{-2} s^{-1} and for the energy flux density $\langle E \rangle = 2.4$ erg cm^{-2} s^{-1}. The constants F_1 and F_2 are obtained by multiplying with the cross section A of the flow tube at 1 AU. The constant F_3 is obtained by using (4) at the solar surface.

Starting from the critical points (which are obtained by setting the two brackets in (5) equal to zero), Eq.(5) is integrated numerically.

2. RESULTS

For strong curvature and/or divergence multiple critical points occur (see also Kopp and Holzer, 1976). For all cases investigated here the solution which describes an expanding supersonic solar wind runs through the innermost critical point. Different velocity profiles are shown for the isothermal case in Figures 2a and 2aa and for the observed temperature in Figures 2b and 2bb. Figures 2a and 2b show a solar wind expansion along field lines with different curvature (I), (II) and (III) in the case (A). Figures 2aa and 2bb illustrate an expansion along the radial field line (I), but with different flux tube divergence (A), (B) and (C). A comparison of Figures 2a and 2b shows that an increase of the curvature leads either to a decrease or an increase of the asymptotic velocity, depending on the temperature profile. In the isothermal case a slight decrease occurs; in the case of the observed temperature a somewhat stronger increase of the final velocity v is found. From Figures 2aa and 2bb it is seen that increasing divergence in all cases increases the asymptotic velocity of the solar wind.

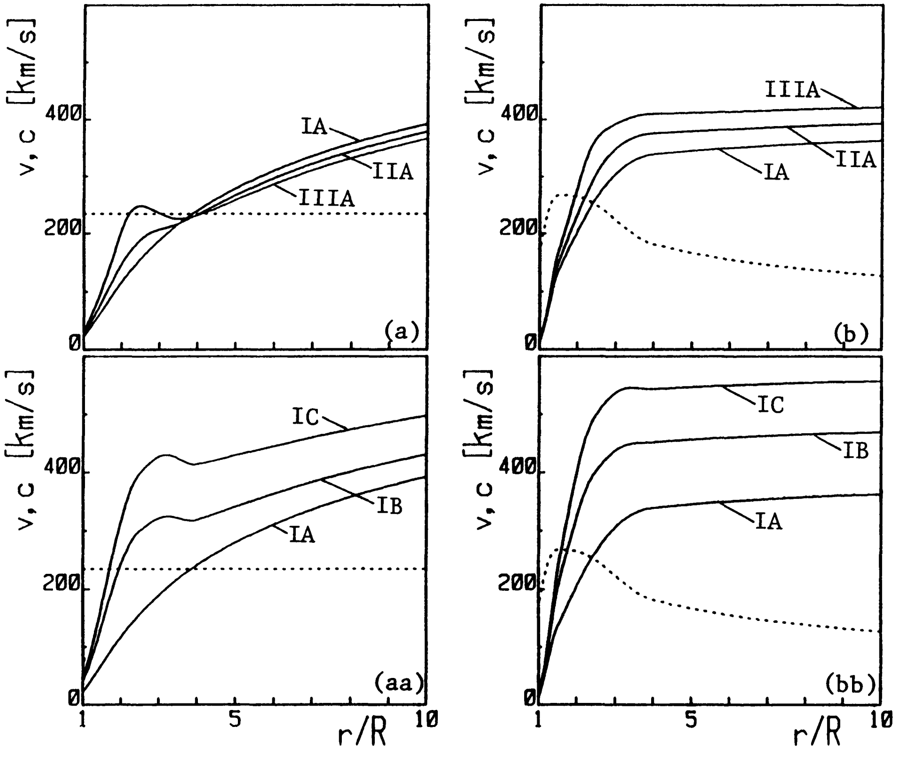

Fig. 2: Bulk velocity and adiabatic sound speed (dashed line) versus the distance from the solar centre in the isothermal case, (a) and (aa), and in the case of the observed temperature, (b) and (bb). IA denotes expansion along field line (I) with tube divergence (A), etc.

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DISCUSSION

ROXBURGH: The isothermal model equations can be integrated in closed form — and the solutions immediately obtained — for any area factor A(r) (cf. Rowse and Roxburgh: 1981, *Solar Phys.* **74**, p. 165).

CAMPOS: Have you plotted the variation of the various energy terms (radial and tangential kinetic energy, potential energy, etc.) along the magnetic field lines? I think this would illustrate why the asymptotic velocity increases with curvature for one temperature profile and decreases for another.

KÖMLE: We have not done this yet, but I think this is a good suggestion.

BENZ: What radial dependence of the temperature have you assumed for your second case?

KÖMLE: We assumed a low temperature (10^6 K) at the base of the corona, a temperature maximum of 2.6×10^6 K at 1.5 solar radii, and from there a decrease fitted to EUV measurements given by Withbroe et al. in a recent paper.

KUIN: The main difference between your work and previous models is the study of the influence of the curvature on the physical properties along a field line, while in previous work only the influence of the expansion has been considered. Can you point out what the separate effect of the curvature is?

KÖMLE: The effect of the curvature depends on the assumed temperature profile. In the isothermal case the asymptotic bulk velocity decreases as the curvature of the field line is increased. In the case of the more realistic temperature profile, increasing curvature leads to an increase of the asymptotic solar wind speed.