SOME PHYSICAL IMPLICATIONS OF RECENT SOLAR WIND MEASUREMENTS

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ABSTRACT The physical implications of the existence at about 1 AU of a quiet solar wind particle flux about 90 percent larger than that suggested in the past [*Hundhausen et al.,* 1970] is investigated within the framework of the two-fluid solar wind model equations.

During the spherically symmetric radial expansion of the quiet solar wind the particle flux is a conserved quantity; therefore, one expects the new piece of observational information to affect strongly the predicted gross features of the solar wind.

It is found that a "pure collisional" two-fluid model provides good particle density and streaming velocity at 1 AU, but predicts too large an electron temperature and too small a proton temperature.

When noncollisional contributions to the transport coefficients are incorporated in the model equations, a complete and satisfactory agreement with the available observations between about $12 R_\odot$ and 1 AU is obtained. Between $1 R_\odot$ and about $12 R_\odot$, particle densities lower than indicated by observations are found.

Upper limits to the effective coupling between electrons and protons, as well as to the effective proton thermal conductivity, and both upper and lower limits to the effective electron thermal conductivity in the quiet solar wind, required to provide agreement with observations, are given.

INTRODUCTION

Recently, a statistical description of the solar wind properties observed at 1 AU has been given by *Hundhausen et al.* [1970]. Unlike earlier reports, which covered relatively short time periods, this last analysis is based on the Vela 3 positive-ion data accumulated during a rather long period, extending from July 1965 to Jun 1967. Among the data covering this time period, of special interest are those referring to the "quiet conditions"–to periods during which the solar wind is steady. In this last case, it is possible to compare with theoretical fluid models based on the assumption of a steady flow from a spherically symmetric corona. This, in turn, could help to understand better the basic processes existing in the solar wind.

Thus, Hundhausen and his collaborators selected from the existing data only those referring to time periods when the flow speed lay between 300 and 350 km sec^{-1} as being characteristic of the "quiet" or steady solar wind. Their results indicate a rather good agreement between the average proton temperature and the previously found values, namely $T_{p,E} = (4.4 \pm 1.8) \times 10^4$ °K, ±1.8 being the standard deviation. The subscript E here represents a distance 1 AU away from the sun. However, the average proton density n_E is now found to be 8.7 ± 4.6 cm^{-3}, which is more than 70 percent larger than the one suggested in the past. Consequently, the proton flux $n_p v_p$ at 1 AU is found to be $(3 \pm 1.5) \times 10^8$ cm^{-2} sec^{-1}, which is to be compared with the value 1.6×10^8 cm^{-2} sec^{-1} indicated by *Hundhausen* [1968].

Now, it is well known that the particle flow $J = nvr^2$ (r being the radial distance) is a conserved quantity during the spherically symmetric radial expansion of the solar

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wind. In fact, its actual constant value represents a constraint which any solution of a fluid (or multifluid) model equation should obey. Since in the past, a value $J_E/r_E^2 = 1.625\times10^8$ cm^{-2} sec^{-1} has been used in solving two-fluid model equations with allowance for noncollisional contributions to the coupling between the electrons and the protons and to the thermal conductivities [*Cuperman and Harten,* 1970, 1971], it was of interest to investigate how the previously found results change with the use of the new, much more reliable observational data now available.

Thus, we solved the two-fluid model equations for the spherically symmetric quiet solar wind by the same integration method as described in *Cuperman and Harten* [1970, 1971] but using the constraint that the proton particle flux $J = nvr^2$ be everywhere equal to that observed at 1 AU–namely, $J = J_E = (nvr^2)_E$–and we took $(nv)_E = 3\times10^8$ cm^{-2} sec^{-1} instead of 1.6×10^8 cm^{-2}sec^{-1}, as in *Cuperman and Harten* [1970, 1971].

First, we solved the equations by using "pure collisional" coupling between electrons and protons as well as thermal conductivities. Next, we allowed for noncollisional contributions to those quantities, and determined their effective values by requiring the predicted gross features for the solar wind at 1 AU to fit the observations of *Hundhausen et al.* [1970].

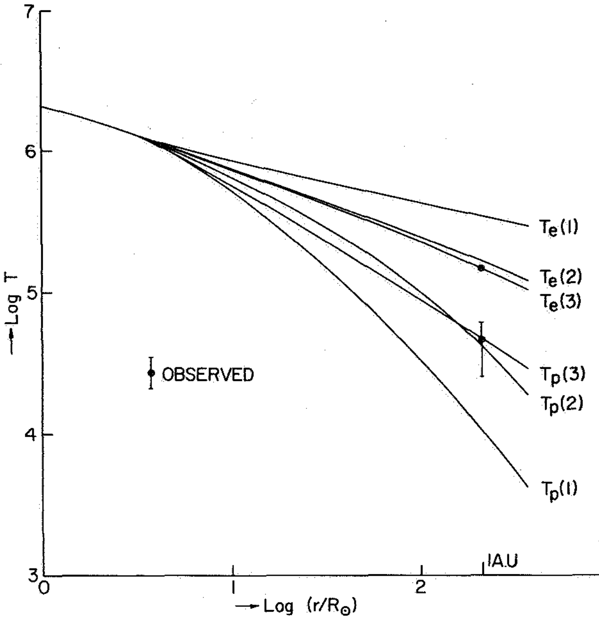

Figure 1. *Electron and proton temperature profiles obtained by solving the two-fluid equations with the constraint* $(nv)_E = 3\times10^8$ *cm*$^{-2}$ *sec*$^{-1}$*. The symbols* 1, *2, and 3 represent the corresponding cases in table 1.*

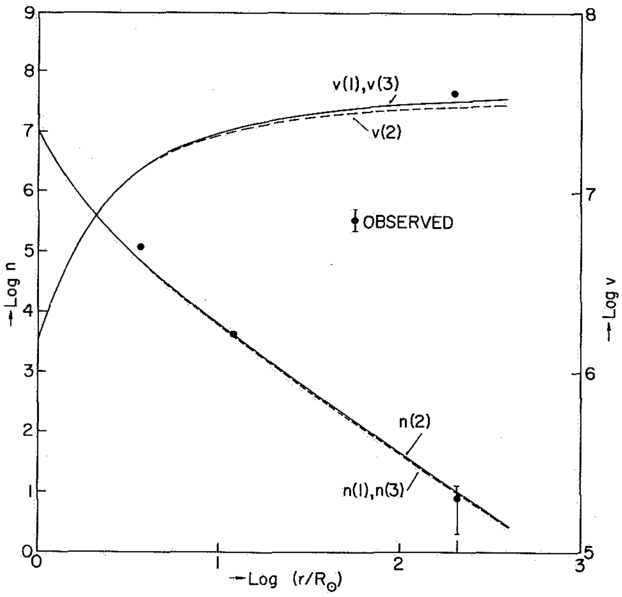

Figure 2. *Particle density and radial streaming velocity obtained by solving the two-fluid equations under the same conditions specified in figure 1.*

RESULTS

The solutions of the integration of the two-fluid model equations for the quiet solar wind (with the constraint $J_E/r_E^2 \equiv (nv)_E = 3\times10^8$ cm^{-2} sec^{-1}) obtained are given in table 1 and figures 1 and 2. For convenience, the values obtained in *Cuperman and Harten* [1970, 1971], using the constraint $J_E/r_E^2 = 1.625\times10^8$ cm^{-2} sec^{-1} ($n_E = 5$ cm^{-3}, $v_E = 325$ km sec^{-1}), are given in parentheses.

Case 1 represents the solution of the model equations with "pure collisional" energy exchange rate between electrons and protons ν as well as pure collisional electron and proton thermal conductivities K_e and K_p, respectively. As seen, while the agreement of the calculated particle density and the streaming velocity with the observed values are very good, the other gross features predicted for the solar wind at 1 AU are completely unsatisfactory. The predicted electron temperature is about 2.2 times larger, proton temperature about 4 times lower, and electron thermal flux about 25 times higher than the observed values, respectively. It should be noted that the disagreement of the last three quantities with the observations is even worse than in the pure collisional case with $J_E/r_E^2 = 1.625\times10^8$ cm^{-2} sec^{-1}, obtained in *Cuperman and Harten* [1970]. In addition, the values obtained for the particle density at the base of the corona are smaller than those obtained in *Cuperman and Harten* [1970] and the observed values. Actually, the predicted particle

Table 1. *Solutions of the two-fluid equations for the quiet solar wind*

Case	$\frac{\nu_{mod}}{\nu}$	$\frac{K_{e,mod}}{K_e}$	$\frac{K_{p,mod}}{K_p}$	nvr^2, $10^8\,cm^{-2}\,sec^{-1}$	$\frac{r_c}{R_\odot}$	$r = 1R_\odot$		$r = r_c$	$r = 12R_\odot$	1 AU					
						n, $10^8\,cm^{-3}$	$T_e = T_p$, $10^6\,°K$	$\frac{n}{n_{obs}}$	$\frac{n}{n_{obs}}$	n, cm^{-3}	v, km/sec	T_e, $10^5\,°K$	T_p, $10^5\,°K$	$-K_{e,mod}\frac{dT_e}{dr}$ $10^{-2}\,erg\,cm^{-2}\,sec^{-1}$	$-K_{p,mod}\frac{dT_p}{dr}$
1	1 (1)	1 (1)	1 (1)	3 (1.625)	3.832 (5.437)	0.1 (0.24)	2.08 (1.66)	0.5 (0.5)	~1 (~0.7)	9.46 (6.00)	325 (271)	3.40 (2.64)	0.10 (0.16)	24.8 (11.61)	2.7×10^{-3} (0.27×10^{-3})
2	30 (30)	0.25 (0.25)	1 (1)	3 (1.625)	3.813 (5.411)	0.1 (0.23)	2.08 (1.67)	0.5 (0.5)	~1 (~0.7)	10.20 (6.33)	302 (256)	1.60 (1.60)	0.45 (0.43)	0.84 (0.75)	1.43×10^{-3} (1.30×10^{-3})
3	1 (1)	0.18 (0.20)	2.3 (2)	3 (1.625)	3.838 (5.443)	0.1 (0.24)	2.08 (1.66)	0.5 (0.5)	~1 (~0.7)	9.66 (6.00)	318 (270)	1.47 (1.59)	0.41 (0.43)	0.51 (0.60)	4.84×10^{-3} (3.76×10^{-3})
Obser.*	– –	– –	– –	3 (1.625)		~2.3 ~2.3	~1.2–2 ~1.2–2		1 1	8.7±4.6 (5)	~350 (325)	~1.5 (~1.5)	4.4±1.8 (4)	<1 (<1)	– –

**The observations at 1 AU are taken from Hundhausen et al. [1970]; the values in parentheses are from Hundhausen [1968]. The observations at $1R_\odot$ are taken from Billings [1966] and those for $1 < r/R_\odot < 215$ are from Newkirk [1967].*

density equals the observed density at about $12 R_\odot$. Thus, we were able to obtain solutions matching the available observations between about $12 R_\odot$ and 1 AU. As for the agreement between 1 and $12 R_\odot$, almost unaffected by the modifications to be discussed in the following, we assumed that some more basic physical processes not included in the model equations are required to describe the correct situation prevailing in that region. This point has been strongly emphasized in the literature [*Parker,* 1969; *Hundhausen,* 1968], and has also been the object of a discussion in *Cuperman and Harten* [1970].

As already discussed in *Cuperman and Harten* [1970, 1971], modification of the transport coefficients in the two-fluid equations could provide satisfactory solutions for *all* of the characteristics of the solar wind at 1 AU. After systematically investigating the effect of modified (essentially noncollisional) transport coefficients in the two-fluid model equations, we found that the agreement with the observations at 1 AU may be achieved in two ways:

1. By using an "enhanced" energy exchange rate between electrons and protons ν_{mod} about 30 times larger than the collisional one (which raises the proton temperature to the observed value but leaves the electron temperature and heat flow almost unchanged) in conjunction with an electron thermal conductivity $K_{e,mod}$ 4 times lower than the collisional one lowering both electron temperature and heat flow to the observed values without further changing the agreement of the proton temperature with the observations (case 2 in table 1).
2. By using an "enhanced" proton thermal conductivity $K_{p,mod}$ about 2.3 times larger than the collisional one (which, like the enhanced energy exchange rate in case 2, raises the proton temperature at 1 AU to the observed value, without affecting the electron temperature and heat flow) in conjunction with an electron thermal conductivity about 5.5 times lower than the collisional one (which as in case 2, lowers both the electron temperature and the heat flow to the observed values) (case 3 in table 1).

Presumably, the actual situation is intermediate between those corresponding to cases 2 and 3. This indicates the existence of an effective energy exchange rate $\nu \leq \nu_{mod} \leq 30\nu$, an effective proton thermal conductivity $K_p \leq K_{p,mod} \leq 2.3\, K_p$, and an effective electron thermal conductivity $K_e/5.5 \leq K_{e,mod} \leq K_e/4$.

Little difference is obtained by comparison of these limit values (namely, 30, 2.3, 4, and 5.5), which are based on a particle flow at 1 AU of 3×10^8 cm^{-2} sec^{-1}, with the corresponding ones obtained in *Cuperman and Harten* [1971] (namely, 30, 2, 4, and 5), which were based on a particle flow at 1 AU of 1.625×10^8 cm^{-2} sec^{-1}.

Thus, the calculations in this work based on the new, and more reliable, statistical value of 3×10^8 cm^{-2} sec^{-1} for the particle flow at 1 AU give satisfactory solutions for n, v, T_e, and T_p between $12 R_\odot$ and 1 AU, and for $(K_e dT_e/dr)_E$, for which observations are available. Between $1R_\odot$ and $12R_\odot$ a disagreement with the present observational data exists, which is thought to be due to the absence, in the model equations, of terms describing some additional physical processes present in that region.

ACKNOWLEDGMENT

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REFERENCES

Billings, D. E.: *A Guide to Solar Corona,* Academic Press, New York, 1966.

Cuperman, S.; and Harten, A.: *Astrophys. J.,* Vol. 162, 1970, p. 315.

Cuperman, S.; and Harten, A.: *Astrophys. J.,* Vol. 163, 1971, p. 383.

Hundhausen, A. J.: *Space Sci. Rev.,* Vol. 8, 1968, p. 666.

Hundhausen, A. J.; Bame, S. J.; Asbridge, J. R.; and Sydoriak, S. J.: Solar Wind Properties: Vela 3 Observations from July 1965 to June 1967, University of California, Los Alamos Sci. Laboratory, 1970.

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

Parker, E. N.: *Space Sci. Rev.,* Vol. 9, 1969, p. 325.