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Constraints on solar wind acceleration mechanisms from Ulysses plasma observations: The first polar pass

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Abstract. The mass flux density and velocity of the solar wind at polar latitudes can provide strong constraints on solar wind acceleration mechanisms. We use plasma observations from the first polar passage of the Ulysses spacecraft to investigate this question. We find that the mass flux density and velocity are too high to reconcile with acceleration of the solar wind by classical thermal conduction alone. Therefore acceleration of the high-speed wind must involve extended deposition of energy by some other mechanism, either as heat or as a direct effective pressure, due possibly to waves and/or turbulence, or completely non-classical heat transport.

Introduction

The mechanism or mechanisms of solar wind acceleration remain one of the fundamental unsolved problems of space physics (e.g., *Barnes* [1992]). The solar wind originates in the solar corona, a complicated system consisting of two qualitatively different kinds of regions, dense regions confined by closed magnetic field configurations, and more rarefied regions on open field lines. Coronal holes are extensive regions of very low density, containing magnetic field of a single polarity. By the mid-1970s it had become clear that high speed solar wind primarily originates in coronal holes (cf. the book edited by *Zirker* [1977], especially the article of *Hundhausen* [1977]).

From that time a widely accepted model of the global morphology of solar wind and its magnetic field has emerged. Near the ecliptic plane the average solar wind speed is usually of order 400 km/s. In the inner heliosphere the speed often varies by several hundred km/s or more; in the outer heliosphere the fluctuations tend to be much smaller, but the average remains about the same [e.g., *Gazis et al.*, 1989; *Mihalov et al.*, 1990; *Barnes*, 1990]. However, near solar minimum, when the interplanetary current sheet becomes flattened and near-equatorial [e.g., *Levy*, 1976; *Hundhausen*, 1977; *Smith et al.*, 1978], in situ observations show a strong latitudinal gradient in velocity, increasing to higher latitudes [*Gazis et al.*, 1989; *Mihalov et al.*, 1990; *Barnes*, 1990]. The observations provide confirmation for the familiar model in which the speed increases with distance (or with "heliomagnetic latitude") from the current sheet. This current sheet becomes aligned with the solar equatorial plane as sunspot minimum approaches, but deviates rapidly from that orientation after minimum. More recently, high-latitude Ulysses observations have confirmed this general picture [*McComas et al.*, 1995; *Phillips et al.*, 1995]. During the south polar pass of 1994 the speed of the solar wind flowing from the south polar coronal hole is consistently in the range 700~800 km/s.

Nearly twenty years ago the study by *Munro and Jackson* [1977] (MJ) of a single, well-developed, long-lived polar coronal hole seemed to settle the issue of whether thermal conduction could be the sole energy supply to the solar wind. From SKYLAB white-light coronagraph observations they deduced the density structure of the hole, and its geometrical variation with altitude. Then, assuming that far from the Sun the polar mass flux density would be the same as the average observed at the same heliocentric distance in the ecliptic plane, they used mass conservation to deduce a velocity profile for wind expansion within the hole. Consideration of the momentum equation then led them to conclude that in order to drive the flow, more energy was required than classical thermal conduction could supply.

More recently, however, these conclusions were questioned. Observations of solar Lyman α have been interpreted as indicating that the polar mass flux density is lower than the equatorial average [*Kumar and Broadfoot*, 1979; *Lallement et al.*, 1985]. This led *Lallement et al.* [1986, subsequently referred to as LHM] to revisit the MJ model, using varying assumptions about the polar mass flux density, and the density profile within the hole. It turns out that the results are quite sensitive to the polar mass flux density. According to their analysis, the observations could be consistent with either of two extreme hypotheses: (1) classical thermal conduction is adequate to drive the flow, or (2) the Munro-Jackson conclusion, i.e., that substantial additional energy and/or momentum deposition is required. Clearly, unambiguous determination of the solar wind mass flux density at polar heliographic latitudes is essential to the resolution of this dilemma. In the present paper we apply Ulysses plasma analyzer data [instrument described by *Bame et al.*, 1992] from the first polar passage (late 1993 through the end of 1994) to this problem.

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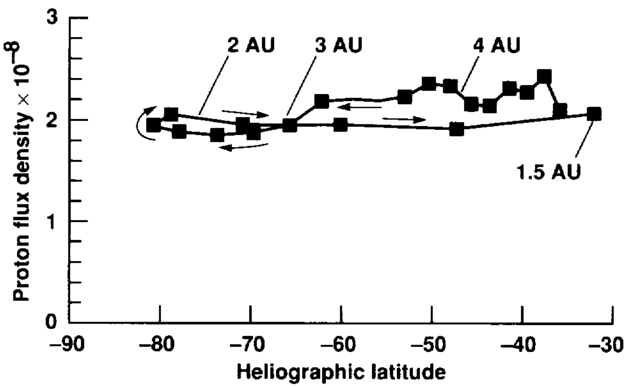

Figure 1. Median values of the proton flux density (normalized to 1 AU), for each solar rotation from late 1993 to the beginning of 1995, given as a function of heliographic latitude.

Observations of the Polar Mass Flux Density

Figure 1 shows median values of the proton flux density (normalized to 1 AU), for each solar rotation from late 1993 to the beginning of 1995, given as a function of heliographic latitude. The observation period covers the entire south polar pass of Ulysses, from the time the spacecraft emerged into continuous fast solar wind until the time it first reencountered slow wind, corresponding to latitudes ranging from just above 30 degrees to ~80 degrees south. The median values of the measured flux density F_p vary from 1.8 to 2.4×10^8 protons cm^{-2} s^{-1} during this period. However, the higher values of this range come from the earlier part of the sampling period, when the measured flux showed relatively large variations. This fact suggests that the higher medians are associated with temporal variations, and that the best values for the quiet-time south polar proton flux density are in the range F_p = 1.9-2.2×10^8 protons cm^{-2} s^{-1}.

Before relating these measurements to the LHM analysis, two further points should be raised. The first is that He^{++} comprises about 15-20% (by mass) of the solar wind outflow. Figure 2 shows the medians (binned by solar rotation) of the ratio F_α/F_p, where F_α is the He^{++} *particle* flux density, versus time for the south polar passage. This quantity is nearly constant, fluctuating from 0.04 to 0.045. The formal LHM analysis treated a pure hydrogen plasma, which would require a proton flux density of 2.2-2.6×10^8 protons cm^{-2} s^{-1} to match the observed polar mass outflow. The other salient point is that the LHM study made use of a range of coronal electron density profiles inferred for a polar hole observed in 1973. It is very plausible that this profile is typical of the polar coronal near solar minimum, although this has not been established in detail, and in particular has not yet been established for the south polar coronal hole at the time of the Ulysses polar passage. However, the published LHM results (cf. Figs. 3 and 4 of that paper) indicate that their conclusions are considerably more sensitive to variations in the mass flux density than to variations in the coronal density profile.

Constraints on Solar Wind Acceleration Processes

Keeping the above statements in mind, it is reasonable to inquire what the particle flux densities observed at Ulysses imply for solar wind acceleration in the context of the LHM model. These flux densities are lower than those observed at lower latitudes, but definitely higher than the value 1.6×10^8 cm^{-2} s^{-1} for the polar flux density inferred from Lyman α observations by *Lallement et al.* [1985].

The parametric study of LHM focused on what they considered the possible extremes of (normalized) flux density, 1×10^8 cm^{-2} s^{-1} and 3×10^8 cm^{-2} s^{-1}. From Ulysses observations we may say conservatively that the appropriate flux density to use in relationship to the LHM models is $F_p > 2\times10^8$ cm^{-2} s^{-1}. Their analysis, essentially an extension of the MJ study, begins with deducing a solar wind speed profile from mass conservation, using assumed radial density profiles and profiles of coronal-hole area. Next, assuming no force other than gravity, the momentum equation is used to deduce a radial profile of pressure, and thence temperature. In many such models the inferred model temperature increases outward for several solar radii. If the real temperature behaves in this way, it is clear that extended heating must occur. Alternatively, acceleration by some additional mechanism such as Alfvénic turbulence could be acting. In either case, a positive gradient in the model temperature is strong evidence that classical heat conduction by itself is not sufficient to accelerate the solar wind at polar latitudes.

Figures 3-4 of the LHM paper show model-temperature profiles obtained under various assumptions. Clearly for high flux density (3×10^8 cm^{-2} s^{-1}) a positive temperature gradient is found for all assumptions about the coronal density profile. The opposite conclusion applies to low flux density (1×10^8 cm^{-2} s^{-1}) , i.e., the temperature gradient is fairly flat or negative for all assumptions about the coronal density profile. LHM give one model for an intermediate flux density (2×10^8 cm^{-2} s^{-1}), which shows a strong positive model-temperature gradient. Therefore the Ulysses result that the appropriate value of flux density for such models is well above 2×10^8 cm^{-2} s^{-1} strongly favors the conclusion that classical thermal conduction is inadequate to drive the solar wind and that an extended (at least over several solar radii) nonthermal energy flux is required.

Quite independently of the LHM models, purely energetic arguments favor extended energy addition to the wind. Conservatively speaking, Ulysses observations show that in the polar regions the solar wind velocity is greater than 750 km/s, and the mass flux density is greater than 3.7×10^{-16} gm cm^{-2} s^{-1} so that the energy flux density (normalized to 1 AU) is greater than 1.0 erg cm^{-2} s^{-1}. Extrapolated back to the Sun, the total energy flux would then be > 4.6×10^4 Φ_A erg cm^{-2} s^{-1}, where Φ_A is the area expansion factor, i.e., the factor by which

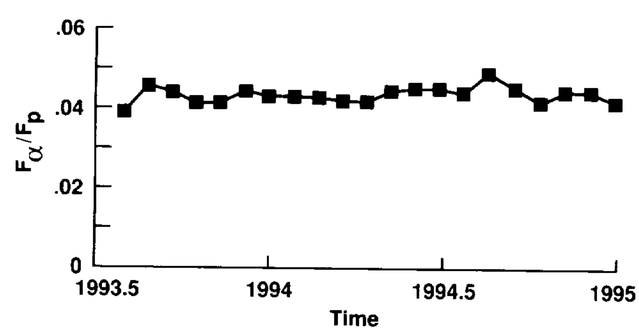

Figure 2. Median values of the ratio of the He^{++} particle flux density F_α to proton flux density F_p, for each solar rotation for the same period as in Figure 1.

the expansion of the flow tube exceeds that predicted for an r^{-2} expansion. Φ_A is not known precisely, but values of ~3 to 6 are estimated for high-speed flows from coronal holes near the ecliptic [*Hundhausen,* 1977]. Therefore at the Sun the total energy flux density F_T is greater than 1.4 to 2.8×10^5 erg cm^{-2} s^{-1}. At least this much energy (actually somewhat more, to account for gravitational potential energy) must be provided to the flow by whatever mechanism drives the wind. The energy flux density due to classical conduction is $F_C \leq 1.3\times10^4\, q(T,r)$ where $q(T,r)=(T/10^6)^{7/2}\, |d \ln T/ d \ln r|$ (cgs units, T in Kelvin). So a conservative upper limit to the ratio of thermal conduction total energy flux density is $F_C/F_T \lesssim 0.05\text{-}0.1\, q(T,r)$. Therefore if classical thermal conduction flux is to be comparable to the total energy flux the coronal electron temperature must be $T \gtrsim 1.9\text{-}2.4 \times 10^6\, |d \ln T/ d \ln r|^{-2/7}$; the logarithmic term is typically somewhat less than unity for models in which thermal conduction dominates the energetics. Therefore an electron temperature of at least 2×10^6 K would be required for the classical conduction flux density to be comparable to the total energy flux density; such a high temperature is unlikely in a coronal hole [e.g, *Hundhausen,* 1977; *Geiss et al.,* 1995].

Conclusions

The mass flux density and velocity of the solar wind observed by Ulysses during its south polar passage are too high to reconcile with acceleration of the solar wind by classical thermal conduction alone. Therefore acceleration of the high-speed wind must involve extended deposition of energy by some other mechanism, either as heat or as a direct effective pressure, due possibly to waves and/or turbulence, or completely non-classical heat transport [e.g., *Scudder and Olbert,* 1983; *Shoub,* 1988].

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