Heating of the Solar Wind Beyond 1 AU by Turbulent Dissipation

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Abstract

The deposition of energy into the solar wind is argued to result from the dissipation of low frequency magnetohydrodynamic turbulence via kinetic processes at spatial scales comparable to the ion gyro-radius. We present a theory for heating the solar wind that relies on fluid processes such as wind shear inside about 10 AU and the pickup of interstellar ions and the associated generation of waves and turbulence beyond the ionization cavity to serve as energy sources for the heating. We compare the predictions of this theory to the observed magnetic turbulence levels and solar wind temperature measured by Voyager 2 beyond 1 AU. The contribution to the heating of the solar wind provided by interstellar pickup ions is a key feature of this theory and is chiefly responsible for the excellent agreement between theory and observation that is seen beyond 10 AU.

1 Introduction:

Three principle sources exist for turbulence in the outer heliosphere. The first is shear associated with the interaction of fast and slow speed streams (Coleman 1968) and the second is compressional effects associated with both stream-stream interactions and shock waves. The third source, which occurs beyond the ionization cavity, is turbulence generated by the ionization of interstellar hydrogen. Both the shear and compressional source terms can be expressed as (Zank et al. 1996)

$$\dot{E}_{shear(comp)} = C_{shear(comp)} \frac{U}{r} Z^2, \tag{1}$$

where $Z^2 = \langle v^2 + b^2 \rangle$ is the energy density, U is the solar wind speed, and $C_{shear(comp)}$ is a prescribed constant.

The ionization of interstellar neutral H introduces an unstable ring-beam distribution of pickup ions into the solar wind. The pickup ions are assumed to scatter in pitch-angle by excited and ambient low-frequency waves while preserving their energy in the wave frame (Figure 1). If the pickup ion generated (unstable) parallel propagating modes dominate the fluctuation spectrum, then the pickup ions scatter onto partial shells centered on $\pm V_A$ (dotted and dashed circles in Figure 1) where V_A is the Alfvén speed, and asymptotically onto a "bispherical" shell distribution, whereas elastic scattering in the solar wind frame would yield a spherical distribution (solid curve). The difference in kinetic energy between the spherical and bispherical distributions is given to the waves and their free energy is $\sim V_A/U$ of the initial pickup ion number density (Williams & Zank 1994). The source term for pickup ion generated turbulence is (Williams & Zank 1994)

$$\dot{E}_{PI} = \frac{\mathrm{d}n_{PI}}{\mathrm{d}t} \frac{V_A U}{n_{SW}} = \frac{U V_A n_H^\infty}{n_{SW}^o \tau_{ion}^o} \exp\left[-\lambda_{PI}\theta / r \sin\theta\right], \tag{2}$$

where $n_{PI,SW}$ denote pickup ion and solar wind number densities respectively and the time derivative refers to a creation rate rather than a convective derivative. We express the pickup ion creation rate in terms of the cold gas interstellar neutral distribution approximation and n_H^∞ should be interpreted as the neutral number density at the termination shock.

This approximation is reasonable provided n_H^∞ is chosen properly. Finally, τ_{ion}^0 is the neutral ionization time at 1 AU, λ_{PI} the ionization cavity length scale, and θ the angle between the observation point and the upstream direction.

Heating by pre-existing fluctuations (Schwartz, Feldman and Gary 1981) is insignificant in comparison with the energy that spectral transport can deliver from the large-scale fluctuations. The large-scale wind shear and magnetic waves generated by the scattering of suprathermal pickup ions constitute a large energy source available to the dissipation process. The nonlinear processes inherent in the turbulent evolution of the fluid transport the low-frequency energy to smaller spatial scales where resonant and nonresonant processes can dissipate the energy, thereby heating the background ions. The details of the dissipation process are not important to this model (see Leamon et al. 1998 for a discussion of IMF dissipation processes).

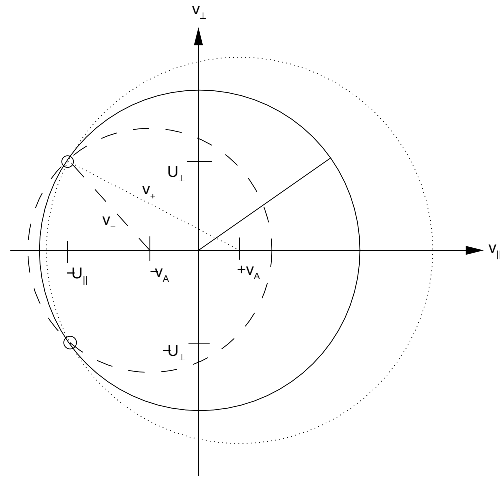

Figure 1: The bispherical distribution is composed of the dotted circle for $v_\parallel < -U_\parallel$ and the dashed circle for $v_\parallel > -U_\parallel$ where $\parallel$ / $\perp$ indicates parallel/perpendicular to the IMF and v the particle velocity.

2 Transport Theory:

To develop a tractable model for the radial evolution of MHD-scale solar wind turbulence, we view the fluctuations *locally* as nearly incompressible (Zank & Matthaeus 1992), strongly nonlinear and homogeneous (Tu et al. 1984; Zhou & Matthaeus 1990). MHD turbulence transport equations were derived using an assumption of scale separation ($\lambda/r \ll 1$), thereby generalizing WKB theory and leading to evolution equations for various correlation functions involving the Elsässer variables $\mathbf{z}_\pm = \mathbf{v} \pm \mathbf{b}$, where $\mathbf{v}$ is the turbulent plasma velocity and $\mathbf{b}$ the fluctuating component of the magnetic field in Alfvén units.

A simplified theory, analogous to the Taylor–von Kármán hydrodynamic approach (Taylor 1935; von Kármán & Howarth 1938) can be derived for the evolution of "energy-containing eddies" in a turbulent MHD medium. For low $\langle \mathbf{v} \cdot \mathbf{b} \rangle$ correlation the theory takes the form:

$$\frac{dZ^2}{dr} = -\frac{A'}{r}Z^2 - \frac{\alpha}{U}\frac{Z^3}{\lambda} + \frac{\dot{E}_{PI}}{U}, \tag{3}$$

$$\frac{d\lambda}{dr} = -\frac{C'}{r}\lambda + \frac{\beta}{U}Z - \frac{\beta}{U}\frac{\lambda}{Z^2}\dot{E}_{PI}, \tag{4}$$

$$\frac{dT}{dr} = -\frac{4}{3}\frac{T}{r} + \frac{2}{3}\frac{m_p}{k_B}\frac{\alpha}{U}\frac{Z^3}{\lambda}, \tag{5}$$

where T is the thermal ion temperature, $U = 400$ km/s is the solar wind speed and r is the heliocentric distance. The remaining parameters: A', C', α and β, are heavily constrained by rotational symmetry, local MHD decay phenomenology, and solar wind conditions. λ may be associated with a correlation scale transverse to the mean field (Batchelor 1970) given by $\int_0^\infty R(r', 0, 0)\, \mathrm{d}r' \equiv L = \lambda Z^2$ where R is the 2-point autocorrelation function for magnetic fluctuations. An alternate e-folding definition for λ is that separation distance where $R(\lambda^e) = R(0)/e$. Details of the derivation are available in Matthaeus et al. (1999).

It is important to note the key difference between this theory, which allows for spectral transport of energy associated with large-scale fluctuations to small scales where dissipation is more efficient, and non-turbulent models such as WKB theory. If spectral transport of energy is not

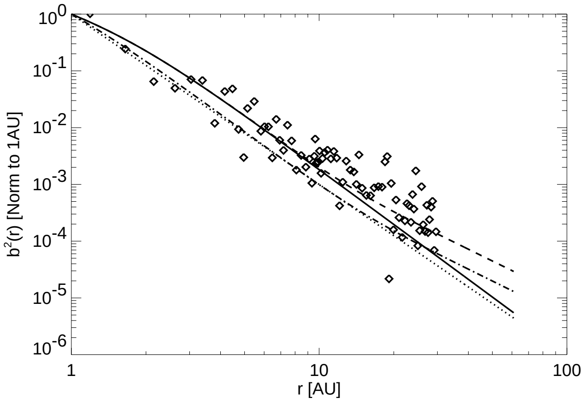

Figure 2: Measured energy of the IMF fluctuations (diamonds); WKB predition (dotted); transport for wind shear alone (solid) with $Z^2 = 250$ and $T_0 = 7 \times 10^4$; wind shear with pickup ions (dot-dash); and for same with $Z^2 = 650$ and $T_0 = 4 \times 10^4$ (dashed).

permitted, then the only energy which is available to heat the particles within the ionization cavity is whatever is available in the small-scale component of the static spectrum. Since the spectrum falls as a powerlaw form with wavenumber k this represents only a minor fraction of the total fluctuation energy which cannot be replenished as dissipation depletes the spectrum. The sweeping of the cyclotron resonance to smaller wavenumbers as the fluid element is convected to greater heliocentric distance allows dissipation to slowly absorb only residual energy from the large-k end of the spectrum (Schwartz, Feldman & Gary 1981). Spectral transfer of the large-scale energy to the dissipation regime by MHD turbulence permits a much greater dissipation rate and makes available the relatively large reservoir of energy associated with the large-scale fluctuations.

3 Observations:

Voyager 2 provides an ideal comparison to the theory as the spacecraft moves to heliocentric distances > 60 AU, but stays at low latitudes out to 40 AU and climbs to higher latitudes only slowly after that point. The observations presented here were obtained from launch in 1977 through 1998. Spacecraft noise and the low IMF intensity forces us to only consider IMF measurements made prior to 1990.

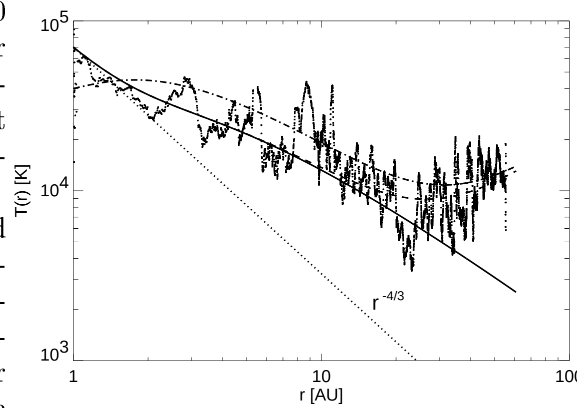

Figure 3: The measured thermal proton temperature as compared with adiabatic expansion (dotted curve) and the same three parameterizations of the transport model.

The magnetic power measurements are derived from 10-hour means and variances of the N component (in heliocentric RTN coordinates). One-hour resolution magnetic field data was used. The N component is free of the IMF reversals associated with sector structure (heliospheric current sheet crossings) which would provide a false power contribution to estimates of the fluctuations and are difficult to remove effectively. The resulting radial variation is averaged over 50 consecutive estimates to smooth the local variability in the IMF power. Possible time dependence in the solar source for IMF energy and thermal ion temperatures is removed using 1 AU observations by the Omnitape dataset for the corresponding interval, taking into account the appropriate time lag for convection. The thermal ion temperature was smoothed by the instrument team. A 1 AU normalization of the temperature data was performed (not shown) and confirms these conclusions.

Wind Shear: We assume that the turbulence is driven entirely by shear with $C_{sh} = \hat{C}_{sh} = 2$. Figure 2 shows the observed magnetic fluctuation energy normalized by 1 AU observations. Figure 3 shows the ion temperature as measured by the Voyager 2 spacecraft. Theoretical predictions from shear driving alone are represented by solid lines in both panels. The shear-driven turbulence model gives a good prediction for the radial dependence of the magnetic energy level to ~ 10 AU, but at greater distances the observed energy appears to consistently exceed the predicted level. The solar wind ion temperature exhibits greater variation than the magnetic energy; but here, too, the theory and observations agree well out to ~ 10 AU. Beyond this distance, both the observed magnetic energy and ion temperatures consistently exceed the predicted levels. There is insufficient energy in the wind shear source to continue heating the solar wind beyond ~ 10 AU.

Pickup Ions: We can remedy the shortfall by including energy input due to wave excitation by pickup ions (Williams, Zank & Matthaeus 1995), a process that becomes important in the outer heliosphere. The pickup energy input scales as $\dot{E}_{PI} \sim f_D v_A U n_H/\tau$, where n_H is the density of interstellar neutrals, τ is their ionization time and $f_D = 0.04$. The theoretical results continue to include the shear source, but beyond ~ 10 AU this term is weakened and largely ineffective. The theoretical predictions with pickup ion driving are represented in the same figures by dashed lines. From 1 to ~ 10 AU there is little difference from the first case. However, for $r \geq 10$ AU there are notable effects associated with pickup ions. The predicted turbulence level is slightly higher (Fig. 2), and in somewhat improved accord with the data. On the other hand the temperature prediction from the theoretical model with pickup ions accounts for the Voyager proton temperatures very well (Fig. 3). There is a clear rise in the ion temperature beyond ~ 30 AU that is accounted for by the pickup ion source.

4 Summary:

A model has been presented which accurately describes the heating of the solar wind ions by the turbulent evolution of the plasma. A key feature of this model is the requirement for the newborn pickup ions of interstellar origin to provide energy to heat the plasma beyond ~ 20 AU. This energy source represents a small (4%) fraction of the total energy of the pickup ion population, but is consistent with the energy available for wave generation as the newborn ion scatters onto the bisphere according to familiar physical processes. As a demonstration of the central role of the newborn pickup ions in heating the solar wind, we note that the solar wind ions are observed to increase in temperature as the spacecraft moves out. The apparent heating has been compared with solar wind velocities in an effort to resolve possible high-latitude effects and it is the opinion of these authors that the spacecraft has not yet sampled a sufficient fraction of the high-latitude wind to account for the apparent heating through latitudinal effects and the mixing of the high-speed and low-speed solar wind. These arguements will be presented elsewhere as space allows.

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