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How important are the alpha-proton relative drift and the electron heat flux for the proton heating of the solar wind in the inner heliosphere?

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Key Points:

- The energy in the alpha-proton drift can account for half of the proton heating
- The solar wind heat flux can also account for half of the proton heating
- Mechanisms are identified for the energy transfer to proton heating

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Abstract This report explores the feasibility of explaining the observed proton heating in the inner heliosphere (1) by tapping the field-aligned relative drift between alpha particles and protons in the solar wind plasma and (2) by tapping the strahl-electron heat flux from the Sun. The observed reduction of the alpha-proton drift kinetic energy from 0.3 to 1 AU and the observed reduction of electron heat flux from 0.3 to 1 AU are each about half of the energy needed to account for the observed heating of protons from 0.3 to 1 AU. A mechanism is identified to transfer the free energy of the alpha-proton relative drift into proton thermal energy: the alpha-proton magnetosonic instability. A mechanism is identified to transfer kinetic energy from the strahl-electron heat flux into proton thermal energy: weak double layers. At the current state of knowledge, the plausibility of heating the solar wind protons via the alpha-proton magnetosonic instability is high. The properties of the weak double layers that have been observed in the solar wind are not well known; more data analysis and plasma simulations are needed before the plausibility of heating the solar wind protons by the double-layer mechanism can be evaluated.

1. Introduction

In the inner heliosphere between 0.29 and 1 AU spacecraft measurements show that the protons of the fast solar wind are nonadibatically heated and that this proton heating is very weak in the nearly adiabatic slow solar wind [*Eyni and Steinitz*, 1978; *Freeman and Lopez*, 1985; *Hellinger et al.*, 2011]. For the fast solar wind there is an excess proton temperature at 1 AU of about 10 eV (see below).

For the energy source of the solar wind-proton heating, the large-scale velocity shears of the solar wind flow [*Coleman*, 1968; *Parker*, 1969] are a prime suspect. However, searches for evidence of solar wind proton heating at the sites of large-scale and small-scale velocity shears found no evidence of heating [*Borovsky and Denton*, 2010; *Borovsky and Steinberg*, 2013]. A second suspected energy source for this proton heating is long wavelength outward propagating Alfven waves [*Tu*, 1988; *Hollweg et al.*, 2013]. Often it is hypothesized that the large-scale-velocity-shear energy or long-wavelength-Alfven-wave energy is delivered to particle heating via a Kolmogorov-type turbulent cascade [*Tu and Marsch*, 1995; *Bruno and Carbone*, 2013].

A third possible energy source for the proton heating is the kinetic energy of the alpha-proton relative drift in the solar wind plasma, as has been suggested by *Safranknova et al*. [2013] (see also *Feldman* [1979] and *Schwartz et al.* [1981]). A fourth possible energy source for the proton heating is the electron heat flux from the Sun.

In this report the feasibility of (1) the alpha-proton relative drift and (2) the electron heat flux acting to heat protons in the fast solar wind is examined. The examination will find that the energy budgets of both the alpha-proton drift and the heat flux are sufficient for them to be important contributors to the increase in the proton temperature from 0.29 to 1 AU. Further, for both sources, we suggest that there are plasma-physical mechanisms available to transfer the energy into proton thermal energy.

This manuscript is organized as follows. In section 2 the heating of solar wind protons in the inner heliosphere by the alpha-proton relative drift in the solar wind plasma is explored. In section 3 the heating of the solar wind protons in the inner heliosphere by weak double layers interacting with the heat-flux electrons is explored. The estimates of sections 2 and 3 indicate that the alpha-proton drift and the weak double layers can each account for

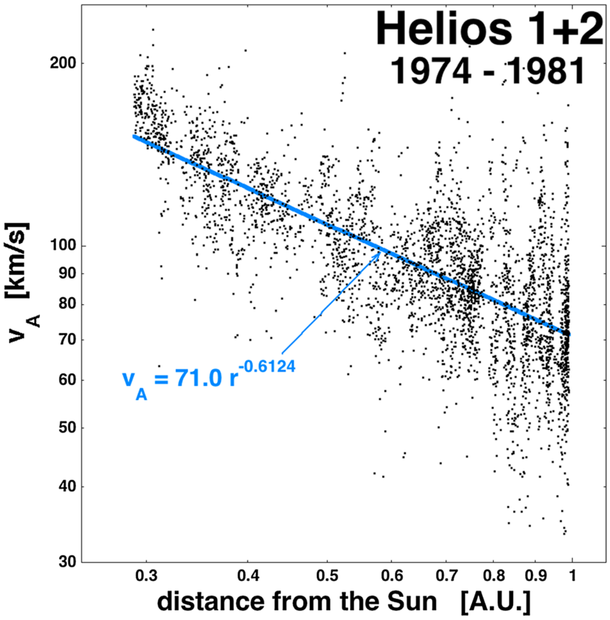

Figure 1. Hourly averaged measurements from the Helios 1 + 2 spacecraft are used to calculate the proton Alfven speed in the fast wind (600 km/s < v <750 km/s), plotted as the black points. The blue curve is a power law fit to the black points.

about half of the observed proton heating. The results are summarized in section 4, and a call for future research on weak double layers in the solar wind is made.

2. Proton Heating by the Free Energy in the Alpha-Proton Relative Drift

In the fast solar wind over the distance range of 0.3 to 1 AU an alpha-proton relative drift $v_{\alpha\text{-}p}$ is often seen, with a field-aligned drift velocity of the alpha particles relative to the protons of approximately v_A [*Marsch et al.*, 1982], where v_A is the proton Alfven velocity $v_A = B/(4\pi m_p n_p)^{1/2}$. The alpha-proton relative drift $v_{\alpha\text{-}p}$ in the slow solar wind is observed to be considerably less than v_A [*Hirshberg et al.*, 1974; *Asbridge et al.*, 1976; *Marsch et al.*, 1982].

For decades researchers have looked at alpha-proton-driven instabilities in the solar wind [e.g., *Revathy*, 1978; *Gary et al.*, 2000a, 2000b, 2006; *Lu et al.*, 2009], mostly with a focus on the heating of the alpha particles from the free energy of the relative drift [*Gary et al.*, 2000a, 2000b; *Gomberoff and Valdivia*, 2003; *Gomberoff*, 2006; *Li and Habbal*, 2000]. Here we argue that the alpha-proton drift-driven instability may also be important for the heating evolution of the solar wind protons.

Gary et al. [2000a, 2000b] studied the alpha-proton magnetosonic instability in the solar wind. The instability occurs when the alpha-proton drift speed $v_{\alpha\text{-}p}$ exceeds the proton Alfven speed v_A. Simulations [*Gary et al.*, 2000b] show that both protons and alpha particles are heated at the expense of the drift kinetic energy, with the alpha-to-proton temperature ratio remaining at $T_\alpha/T_p = 4$ as both the protons and the alpha-particles heat. The simulations of *Gao et al.* [2012] also showed that the protons are heated by this instability. Since the number density of the protons is much greater than the number density of the alphas, the protons obtain the vast majority of the heating energy in the alpha-proton magnetosonic instability.

One might think that the alpha-proton magnetosonic instability would also heat solar wind electrons. However, the Landau resonance for this instability is at $v_{||} \sim v_A$ in the proton rest frame. In the plasma rest frame a solar wind electron with $v_{||} \approx v_A$ has a kinetic energy $0.5 m_e v_{||}^2$ of ~0.01 eV: such electrons are highly collisional with the protons of the solar wind [*Borovsky and Gary*, 2011] (with collision times measured in seconds) and do not partake in collisionless mechanisms such as Landau damping.

Since the magnetosonic instability onsets when the relative drift speed between the alphas and the protons exceeds the proton Alfven speed, it is plausible that the instability could be initiated by a lowering of the Alfven speed.

In Figure 1 the proton Alfven speed in the solar wind plasma is plotted as a function of the distance from the Sun for fast-solar wind measurements in the Helios 1 + 2 data sets. Fast solar wind is here defined as 600 km/s $< v_{sw} <$ 750 km/s. In this speed range there is ejecta in addition to the fast coronal-hole plasma. To clean away some of the ejecta (which tend to have high Alfven speeds [*Lavraud and Borovsky*, 2008], low temperatures and specific entropies [*Gosling et al.*, 1987], and low densities [*Richardson et al.*, 2000]) as well as compressed wind (high density) and shocked plasma (high entropy [*Kennel*, 1988]), data are removed for (a) $n_p r^2 < 2\ \text{cm}^{-3}$, (b) $n_p r^2 > 9\ \text{cm}^{-3}$, (c) $v_A r^{0.584} < 30$ km/s, (d) $v_A r^{0.584} > 2000$ km/s, (e) $S_p < 2\ \text{eV cm}^2$, and (f) $S_p > 25\ \text{eV cm}^2$; here r is the distance from the Sun in AU and S_p is the proton specific entropy $S_p = T_p/n_p^{2/3}$. The statistical results of this section change very little if the fast-wind measurements from Helios 1 + 2 are not cleaned. As can be seen in Figure 1, the proton Alfven speed in the fast solar wind systematically decreases

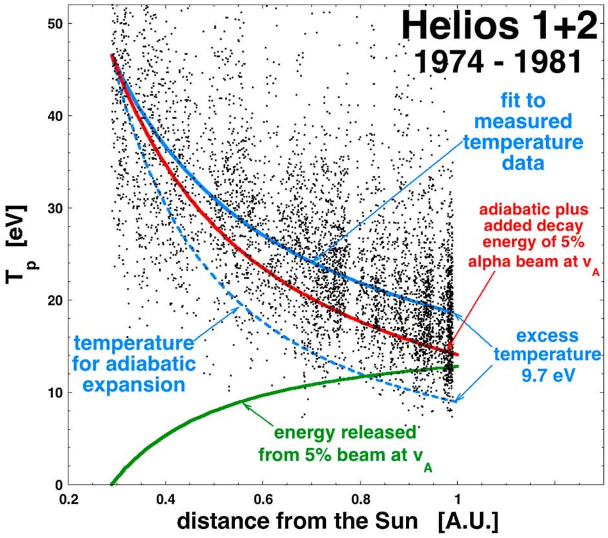

Figure 2. Hourly averaged measurements of the proton temperature from Helios 1 + 2 fast wind (600 km/s < v <750 km/s) are plotted in black. A power law fit to the black points is plotted as the solid blue curve. The dashed-blue curve is the expected proton temperature for adiabatic expansion without in situ proton heating. The green curve is the expected energy added to the protons by the decay of the alpha-proton relative drift. The red curve is the expected temperature of the solar wind protons with the energy of the green curve added.

with distance from the Sun. The alpha-proton drift velocity $v_{\alpha\text{-}p}$ is also observed to systematically decrease with distance from the Sun [*Marsch et al.*, 1982; *Neugebauer et al.*, 1996]. The blue curve in Figure 1 is a power law fit (least squares linear-regression fit in log-log space) to the black data points, resulting in the fit

$$v_A = 72\ \mathrm{km/s}\ r^{-0.6125} \tag{1}$$

valid for the fast solar wind from 0.29 to 1 AU.

If $v_{\alpha\text{-}p} \approx v_A$, then as the Alfven speed in a parcel of plasma decreases with time the amount of free energy in the alpha-proton drift decreases. This reduction in free energy can go into heating the protons and alpha particles. In the center-of-mass reference frame of the protons and the alphas, the total kinetic energy density of the proton and alpha drifts is $2m_p n_\alpha {v_A}^2[1 + 4(n_\alpha/n_p)]^{-1}$, where n_α/n_p is the alpha-to-proton density ratio. The free energy per proton in the drift is

$$E_{\text{free}} = 2m_p\left(n_\alpha/n_p\right){v_A}^2/\left[1 + 4\left(n_\alpha/n_p\right)\right]. \tag{2}$$

Expression (2) is the reservoir of free energy; as v_A decreases this reservoir decreases and the excess energy goes into heating. If the protons and the alpha particles are both heated such that their temperature ratio remains at $T_\alpha/T_p = 4$, then the fraction of the excess free energy that the protons can receive is

$$F_p = 1/\left[1 + 4\left(n_\alpha/n_p\right)\right]. \tag{3}$$

We will examine the amount of proton heating that can result from the decrease in the free energy of the beams as v_A decreases.

The energy budget of this alpha-proton streaming in the fast solar wind is examined in Figure 2. Here the Helios 1 + 2 measurements of the proton temperature of the fast wind are plotted as a function of the distance from the Sun. Each black point is a 1 h average of the proton temperature measured by the Helios plasma experiments [cf. *Rosenbauer et al.*, 1977]. A power law fit to the black points is plotted as the blue solid curve in Figure 2. An adiabatic temperature curve ($T \propto r^{-4/3}$) is plotted as the dashed blue curve that intersects the power law fit at 0.29 AU. If there were no in situ heating of the protons of the fast solar wind between 0.29 and 1 AU, the proton-temperature measurements would cluster along the blue dashed curve. They do not. Instead, at 1 AU there is an excess of about 9.7 eV of proton temperature above the adiabatic curve from 0.3 AU.

Assuming that all of the excess free energy of the alpha-proton drift (from expression (2)) goes into proton and alpha heating with a fraction F_p going into protons, as the Alfven speed of the solar wind decreases by an amount Δv_A (from v_A to $v_A - \Delta v_A$), the temperature of the solar wind protons will increase by an amount

$$k_B \Delta T_p = F_p 2m_p\left(n_\alpha/n_p\right)\left[{v_A}^2 - \left(v_A - \Delta v_A\right)^2\right)\right]/\left[1 + 4\left(n_\alpha/n_p\right)\right]. \tag{4}$$

Using the $T_\alpha/T_p = 4$ expression (3) for the fraction F_p of the excess free energy that goes into protons, expression (1) becomes

$$k_B \Delta T_p = 2\ m_p\left(n_\alpha/n_p\right)\left[{v_A}^2 - \left(v_A - \Delta v_A\right)^2\right)\right]/\left[1 + 4\left(n_\alpha/n_p\right)\right]^2. \tag{5}$$

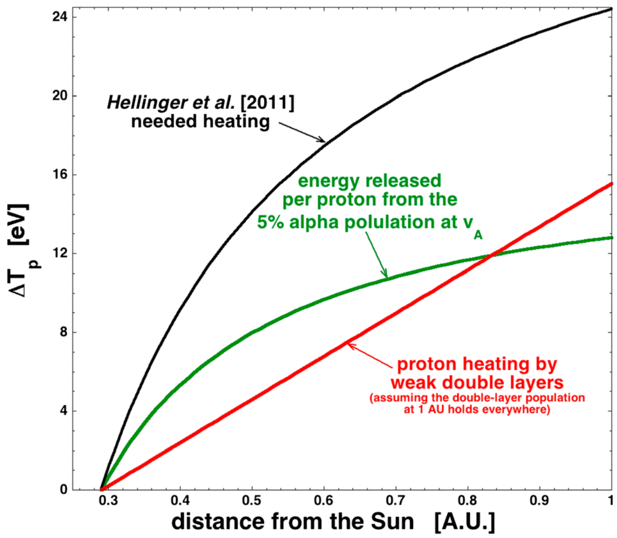

Figure 3. The black curve plots the heating needed to explain the nonadiabatic temperature of the solar wind protons as a function of distance from the Sun (from *Hellinger et al.* [2011]). The green curve is the estimated heat that the solar wind protons would obtain from the decay of the alpha-proton relative drift, transferred by the alpha-proton magnetosonic instability. The red curve is the estimated heating rate that the solar wind protons would receive owed to the propagation of weak double layers in the solar wind plasma.

In the fast wind of coronal-hole origin, the alpha-to-proton density ratio n_α/n_p is typically 4% to 5% [*Hirshberg et al.*, 1974; *Gosling et al.*, 1978; *Burton et al.*, 1999; *Borovsky and Denton*, 2010]. For v_A given by expression (1) and for $n_\alpha/n_p = 0.05$, expression (5) is numerically integrated from 0.29 to 1 AU to obtain the excess free energy released into protons as the alpha-proton relative drift decreases: this is plotted as the green curve in Figure 2.

As an aside, in Figure 3 this lost free energy of the alpha-proton relative drift is compared with the *Hellinger et al.* [2011] estimates of the amount of heat needed to explain the proton heating of the fast solar wind in the Helios data set. According to equation (10) of *Hellinger et al.* [2011] the fast-solar wind plasma needs to be heated at a rate of $Q = 2.4 \times 10^{-16}$ erg/s/cm^3 $r^{-3.8}$ to account for the radial evolution of the proton temperature. If the hourly averaged Helios 1 + 2 measurements of the proton number density are fit for the cleaned fast-solar wind collection used in Figures 1 and 2, $n_p = 3.23$ cm^{-3} $r^{-1.93}$ is obtained. Dividing $Q = 2.4 \times 10^{-16}$ erg/s/cm^3 $r^{-3.8}$ by $n_p = 3.23$ cm^{-3} $r^{-1.93}$ gives the heating rate per proton, which is then $Q/n_p = 7.5 \times 10^{-17}$ erg/s $r^{-1.9} = 4.7 \times 10^{-5}$ eV/s $r^{-1.9}$. For the fast wind moving at 650 km/s, this Q/n_p expression is time integrated from 0.29 to 1 AU to produce the black curve in Figure 3, which is the amount of heating in eV per proton needed to account for the increased proton temperature in the Helios data set above the adiabatic temperature curve, according to *Hellinger et al.* [2011]. The green curve of Figure 2, which is the free energy released per proton from the decay of the proton-alpha relative drift, is replotted as the green curve in Figure 3. As can be seen, the green curve given by the release of the free energy in the alpha-proton relative drift can account for about half of the heating needed.

As can be seen from the green curve in Figure 2, from 0.29 to 1 AU about 12.8 eV of thermal energy is added to each proton from the decay of the alpha-proton drift velocity. However, this green curve is not the temperature increase of the protons owing to the alpha-proton-drift heating: as each increment of temperature ΔT_p is added to the proton temperature, the protons adiabatically cool as they expand. Hence, the temperature ΔT_p added near 0.29 AU appears as an increase of much less than ΔT_p in the proton temperature at 1 AU. Incrementally adding ΔT_p to the proton temperature and evolving the proton distribution adiabatically as it expands out from the Sun result in the red curve of Figure 1, which is the expected proton temperature if the appropriate fraction of the excess free energy of the reduced alpha-proton drift energy goes into proton heating in the fast solar wind. The adding of the 12.8 eV of heat to the protons between 0.29 and 1 AU results in an increase in the proton temperature of 5.1 eV at 1 AU.

As can be seen in Figure 2, this 5.1 eV of increased proton temperature is about half on average of the 9.7 eV of excess temperature seen in the fast solar wind at 1 AU. Since the measured temperature of the fast solar wind in the 0.29 to 1 AU region varies considerably from instance to instance (cf. black points of Figure 2), one could imagine that sometimes the lost free energy of the alpha-proton relative drift can account for the excess proton temperature and sometimes it cannot.

3. Proton Heating by the Strahl Heat Flux Via Weak Double Layers

The strahl heat-flux energy budget may also contribute to proton heating in the inner heliosphere. The electron heat flux in the fast solar wind at 1 AU is 1–5 × 10^{-3} erg/cm^2 [*Salem et al.*, 2003a], and the excess

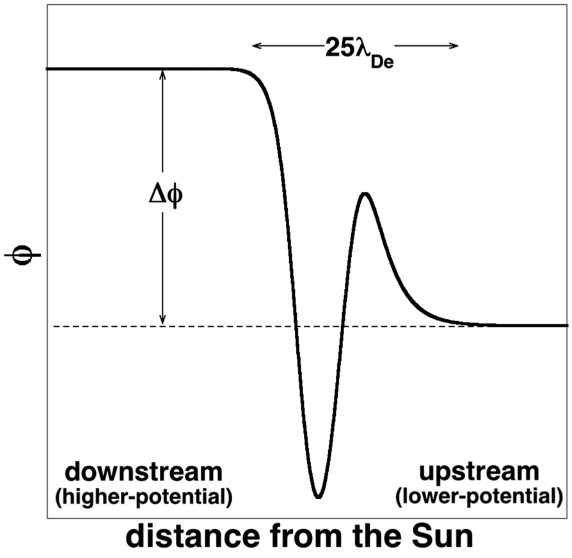

Figure 4. A sketch of a solar wind weak double layer (after Figure 1b of *Salem et al.* [2003b]). The Sun is to the left, and the Earth is to the right. The double layer propagates to the right in the reference frame of the solar wind plasma (hence, it moves outward at a speed slightly greater than the solar wind speed).

enthalpy flux of protons at 1 AU is $\sim 5 \times 10^{-3}$ erg/cm^2 (for $n_p \approx 5$ cm^{-3}, $v_{sw} \approx 650$ km/s, $\Delta T_p \approx 10$ eV, cf. Figure 2). Further, *Maksimovic et al.* [2005] (see also *Stverak et al.* [2009]) find that the electron strahl that carries the heat flux decays in intensity with distance from the Sun, with the strahl intensity at 0.3 AU being about twice the strahl intensity at 1 AU. Hence, the energy budget of the strahl electrons is not insignificant compared with the energy needed to heat the solar wind protons in the inner magnetosphere.

As a mechanism to transfer energy from the solar wind heat flux to the solar wind protons, plasma-wave instabilities that could couple the electron strahl to the solar wind protons have not been found [e.g., *Saito and Gary*, 2007; *Gary and Saito*, 2007; *Shevchenko and Galinsky*, 2010, 2012]. One connection between strahl electrons and the protons of the solar wind is through the lower-hybrid-wave resonances: a $v_{||}$ Landau resonance for the electrons and a cyclotron resonance for the protons [cf. *Lakhina*, 1979, 1985; *Marsch and Chang*, 1982, 1983; *Laming*, 2005] (see also *Markovskii and Hollweg* [2004]). However, to transfer a net energy from the strahl electrons to the protons the electron distribution function must have a positive $\partial f/\partial v_{||}$ (i.e., a beam, a bump-on-tail, or a two stream), which the strahl does not have. It has also been argued that lower-hybrid-type waves can be driven by electron anisotropy in the solar wind via an anomalous cyclotron resonance [*Krafft and Volokitin*, 2003; *Volokitin and Krafft*, 2004].

However, weak double layers are seen in the solar wind with antisunward-directed magnetic-field-aligned electric fields with double-layer potential drops of ~1 mV [*Mangeney et al.*, 1999; *Lacombe et al.*, 2002; *Salem et al.*, 2003b]. At 1 AU about 1 double layer per second convects past a spacecraft [*Lacombe et al.*, 2002; *Salem et al.*, 2003b], sufficient for the weak double layers to account for the interplanetary electric field of 400–1000 V between the Sun and the Earth [*Lemaire and Scherer*, 1971, 1973; *Pierrard*, 2012]. An example weak double layer is sketched in Figure 4. (For the actual time sequence of the electric field or the potential as seen on a spacecraft, see Figure 6 of *Mangeney et al.* [1999], Figure 1c of *Lacombe et al.* [2002], or Figure 1 of *Salem et al.* [2003b].) Outward-traveling strahl electrons each loose $\sim 1 \times 10^{-3}$ eV of kinetic energy as they cross each double layer. By energy conservation that lost strahl energy must go into the other particle populations interacting with the weak-double-layer structure.

The parameters and properties of the weak double layers observed in the solar wind are not well known. Using what is known, a number of estimate calculations relevant to solar wind proton heating are performed in the following paragraphs.

The propagation direction and propagation speeds of the weak double layers in the solar wind have not been measured, and there are no theoretical solutions or numerical simulations for weak double layers in a solar wind plasma composed of protons, core electrons, halo electrons, antisunward-drifting alpha particles, and shrahl electrons; however, we will assume that their propagation properties are similar to weak double layers observed in other plasmas. Weak double layers propagate at a speed on the order of the ion-acoustic speed C_s with respect to the plasma ions [*Das and Bujarbarua*, 1989]: from the measured antisunward direction of the electric field, the propagation direction should be antisunward in the rest frame of the solar wind protons. In the reference frame of the weak double layer, ions stream into the double layer from the lower-potential upstream plasma (from the right to the left in Figure 4) and are slowed across the double layer [*Bharuthram et al.*, 2008] increasing their thermal spread (like a shock). In the reference frame of the solar wind the bulk of the protons crossing the double layer receive a very slight antisunward acceleration and (see below) about a 1×10^{-3} eV increase in temperature.

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Vlasov phase-space arguments [cf. *Knorr and Goertz*, 1974; *Schamel*, 1982] indicate that the temperature of the proton population increases slightly as the weak double layer propagates through the solar wind plasma. This proton heating is easily calculated in the reference frame of the double layer. In the reference frame of the weak double layer the ions approach the structure with a mean velocity $v_o \approx C_s$ in the lower-potential upstream plasma: energy conservation upstream and downstream yields

$$0.5m_p(v_o + v_T)^2 = e\Delta\phi + 0.5m_p{v_{plus}}^2 \tag{6a}$$

$$0.5m_p(v_o - v_T)^2 = e\Delta\phi + 0.5m_p{v_{minus}}^2 \tag{6b}$$

where the top equation pertains to a proton approaching the double layer with an initial velocity $v_o + v_T$ in the reference frame of the double layer and the bottom equation pertains to a proton approaching the double layer with an initial velocity $v_o - v_T$, where v_T is the thermal speed of the protons in the upstream plasma, $\Delta\varphi$ is the potential step across the weak double layer, and v_{plus} and v_{minus} are velocities of the $v_o + v_T$ and $v_o - v_T$ protons in the higher-potential downstream plasma. A measure of the thermal spread of the protons in the upstream plasma is $v_T = [(v_o + v_T) - (v_o - v_T)]/2$; a measure of the thermal spread of the protons in the downstream plasma is $v_{Tnew} = (v_{plus} - v_{minus})/2$. To first order in small $\Delta\varphi$, expressions (6a) and (6b) are solved for v_{plus} and v_{minus} yielding

$$v_{plus} = (v_o + v_T) - e\Delta\phi/m_p(v_o + v_T) \tag{7a}$$

$$v_{minus} = (v_o - v_T) - e\Delta\phi/m_p(v_o - v_T). \tag{7b}$$

Subtracting expression (7b) from (7a) yields

$$v_{plus} - v_{minus} = 2\,v_T + \left(2e\Delta\phi/m_p\right)\ v_T/\left({v_o}^2 - {v_T}^2\right). \tag{8}$$

Taking [cf. *Chen*, 1974] $v_o = C_s = (k_BT_e + 3k_BT_p)^{1/2}/{m_p}^{1/2} \approx 2v_T$ for protons and $v_{Tnew} = (v_{plus} - v_{minus})/2$, expression (8) becomes

$$v_{Tnew} = v_T + e\Delta\phi/3m_pv_T. \tag{9}$$

Squaring expression (9) and keeping terms to first order in small $\Delta\varphi$ give

$${v_{Tnew}}^2 = {v_T}^2 + 2e\Delta\phi/3m_pv_T. \tag{10}$$

Taking $v_T = (k_BT_p/m_p)^{1/2}$ and $v_{Tnew} = (k_BT_{pnew}/m_p)^{1/2}$, expression (10) yields

$$T_{pnew} = T_p + 2e\Delta\phi/3k_B. \tag{11}$$

Hence, the temperature change $\Delta T_p = T_{pnew} - T_p$ of the protons in the fast solar wind after the passage of a single moving weak double layer is

$$\Delta T_p = 2e\Delta\phi/3k_B. \tag{12}$$

For a potential drop $\Delta\varphi \sim 1\times10^{-3}$ V, this is $\Delta T_p \sim 6.6\times10^{-4}$ eV of proton heating per double layer passage.

If weak double layers are swept across a solar wind spacecraft at a rate of about once per second [*Lacombe et al.*, 2002; *Salem et al.*, 2003b], in the fast wind they are on the order of 650 km apart. For $T_p \sim T_e \sim 20$ eV, the ion-acoustic speed is $C_s \approx 90$ km/s. In the plasma rest frame, a weak double layer propagating at a speed of 90 km/s propagates through 650 km of plasma in about 7 s. Thus, every 7 s on average the protons of the fast solar wind obtain a thermal increase of 6.6×10^{-4} eV owing to double layers propagating in the solar wind plasma. This corresponds to a proton heating rate $\partial T_p/\partial t$ of

$$\partial T_p/\partial t = 9.5\times10^{-5}\text{eV/s} = 0.34\ \text{eV/h}. \tag{13}$$

In the fast solar wind the advection time of the fast solar wind from 0.29 to 1 AU at 650 km/s is 45 h; if the population of weak double layers has the same properties everywhere in this region of the inner heliosphere, then the total heating amount of the protons from 0.29 to 1 AU is estimated to be $(\partial T_p/\partial t)$ (45 h) = 15 eV per proton. This estimate is somewhat greater than the ~12.8 eV per proton (green curve of Figure 2) of free energy released by the reduction of the alpha-proton relative drift. This integrated heating of the protons between 0.29 and 1 AU is plotted as the red curve in Figure 3, assuming that the properties of the population of weak double layers in the solar wind are the same everywhere from 0.29 to 1 AU.

As can be seen in Figure 4, the estimate of the proton heating from weak double layers in the solar wind is about half of the heating observed in the fast solar wind by Helios 1 + 2. As was the case for the alpha-proton drift in section 2, the energy transfer to the protons by the weak double layers may be important for the proton temperature evolution in the inner heliosphere.

If the weak double layers are about 650 km apart in the solar wind and each has a potential drop $\Delta\phi$ of 10^{-3} V, then the total potential drop from 0.3 to 1 AU is $(10^{-3}\ \mathrm{V})(1.05\times10^{8}\ \mathrm{km})/(650\ \mathrm{km}) = 161$ V. Hence, each strahl electron will lose ~161 eV of kinetic energy in travelling from 0.3 to 1 AU. If the strahl electron's kinetic energy $m_e v_{||}^2/2$ is $\mathcal{E}_0$ at 1 AU, its kinetic energy will be $\mathcal{E}_1 = \mathcal{E}_0 - 161$ eV at 1 AU. Likewise, if that same strahl electron had a velocity $v_{||0} = (2\mathcal{E}_0/m_e)^{1/2}$ at 0.3 AU it will have a velocity $v_{||1} = (2\ (\mathcal{E}_0 - 161\ \mathrm{eV})/m_e)^{1/2}$ at 1 AU. The outward energy flux of the strahl electrons at 0.3 AU is given by $\mathcal{F}_0 = n_{so}A_0v_{||0}\mathcal{E}_0$ where n_s is the number density of the shrahl electrons and A_0 is the surface area of the sphere with a radius of 0.3 AU. At 1 AU the energy flux will be $\mathcal{F}_1 = n_{s1}A1v_{||1}\mathcal{E}_1$. The ratio of the heat fluxes at 1 to 0.3 AU is

$$\mathcal{F}_1/\mathcal{F}_0 = n_{s1}A_1v_{||1}\mathcal{E}_1/n_{so}A_0v_{||0}\mathcal{E}_0. \tag{14}$$

Mass conservation yields $n_{s1}A_1v_{||1} = n_{so}A_0v_{||0}$, so the ratio of the energy fluxes becomes

$$\mathcal{F}_1/\mathcal{F}_0 = \mathcal{E}_1/\mathcal{E}_0 = (\mathcal{E}_0 - 161\mathrm{eV})/\mathcal{E}_0 = 1 - (161\ \mathrm{eV}/\mathcal{E}_0). \tag{15}$$

The kinetic energies of strahl electrons range from ~100 eV to ~1.4 keV [*Fitzenreiter et al.*, 1998; *Pagel et al.*, 2005; *de Koning et al.*, 2006], and the distribution functions of the strahls are steep [*Maksimovic et al.*, 2005], so the 161 V of potential owed to double layers could easily account for the observed factor-of-two decrease [*Maksimovic et al.*, 2005; *Stverak et al.*, 2009] in the electron heat flux from 0.3 to 1 AU.

It is observed that the protons of the solar wind have $T_\perp > T_{||}$ [cf. *Hu et al.*, 1997; *Li*, 1999], indicating that the protons are heated chiefly in the direction perpendicular to the local magnetic field. Weak double layers with electric fields parallel to the magnetic field would heat protons only in the field-aligned direction, increasing $T_{||}$ but not $T_\perp$. If the weak double layers are oriented obliquely to the magnetic field [*Reddy and Lakhina*, 1991] (where they still have field-aligned potential drops), the protons can be heated predominantly in the direction transverse to the magnetic field (cf. Figures 2 and 4 of *Borovsky* [1984]). However, there is no indication in the literature that the solar wind double layers are oblique.

The electrons of the solar wind will also interact with the weak double layer. Electrons moving sunward will receive a slight energy gain when crossing the weak double layer, and electrons moving antisunward will transfer kinetic energy to the double-layer structure as they cross it. Unlike the case for the protons, the details of the electron interactions with the double layer are insensitive to the motion of the double layer through the plasma. The ensemble of double layers in the solar wind are thought to comprise the interplanetary potential drop between the Sun and 1 AU [*Lacombe et al.*, 2002; *Salem et al.*, 2003b]; the behavior of solar wind electrons in this heliospheric potential has been modeled [cf. *Pierrard et al.*, 2001]. The modeling indicates that the radial evolution of the solar wind electron temperature depends on the radial profile of the heliospheric potential [cf. *Meyer-Vernet and Issautier*, 1998] and that a stronger strahl results in higher electron temperatures away from the Sun (cf. Figure 4 of *Maksimovic et al.* [1997], Figure 1 of *Pierrard et al.* [1999], or Figure 1 of *Pierrard* [2012]).

4. Summary and Call for Future Work

As the solar wind advects from 0.3 to 1 AU, there is an energy gain of the solar wind protons via a heating; simultaneously, there is an energy loss in the solar wind in the decay of the alpha-proton field-aligned relative drift and an energy loss in the reduction of the strahl-electron heat flux. Each of these two energy losses can account for approximately half of the thermal energy gain of the protons. Hence, both energy sources are potentially important for the thermal evolution of the solar wind in the inner heliosphere.

As a mechanism for the transfer into proton heating of energy from the decaying field-aligned alpha-proton relative drift in the solar wind plasma, the alpha-proton magnetosonic instability was considered. Prior simulations of this instability showed substantial proton heating at the expense of the alpha-proton drift kinetic energy. In fact the simulations showed that the majority of the alpha-proton drift energy goes into proton heating. Calculations of the energy budget of the decaying alpha-proton drift indicate that it can supply about half of the observed proton heating from 0.3 to 1 AU.

As a mechanism for the transfer of strahl-electron kinetic energy into proton heating, weak double layers were considered. Weak double layers are observed in the solar wind plasma, and some of their parameters are approximately known. Extrapolating to the knowledge about weak double layers in other plasmas, estimates of the heating rate of solar wind protons were made. It was estimated that the propagation of weak double layers through the solar wind plasma can result in about half of the observed proton heating from 0.3 to 1 AU and the net field-aligned potential drop of the double layers between 0.3 and 1 AU can reduce the strahl-electron heat flux by a factor of two. Based on those estimates, weak double layers seem plausible for transferring the kinetic energy of strahl electrons into proton heating. Estimated heating rates from double layers propagating through solar wind provide about half of the observed proton heating rate. However, unless the solar wind double layers are oriented oblique to the local magnetic field, proton heating by double layers is in the parallel direction.

It is concluded that it is plausible that these two energy sources can be substantially supplying the heating of the solar wind protons in the inner heliosphere. If the alpha-proton drift and the electron heat flux are not involved in the heating of the protons of the solar wind, then for completeness one has to account for where those lost energies go.

Weak double layers may be important for heating solar wind protons by providing a mechanism to transfer the kinetic energy of the strahl electrons into proton heating. To provide more-than-rudimentary knowledge about the parameters and properties of these solar wind double layers it is important to do further data analysis and to think about new instrumentation to better observe and diagnose these solar wind double layers. Particularly lacking is information about the double-layer population as a function of distance from the Sun. Computer simulations of weak double layers in the complex magnetized solar wind plasma (composed of protons, drifting alpha particles, core electrons, halo electrons, and field- aligned strahl electrons) are needed to discern the properties of weak double layers and to uncover the physics underlying the energy transfer between the different particle populations of the solar wind.

It appears that the heliospheric potential drop (interplanetary electric field) between the Sun and 1 AU may be composed of weak double layers [*Lacombe et al.*, 2002; *Salem et al.*, 2003b], and weak double layers propagate slowly in the reference frame of the moving plasma. Kinetic calculations of the evolution of the solar wind away from the Sun assume that the heliospheric potential structure is at rest with respect to the Sun [e.g., *Lemaire and Scherer*, 1973; *Meyer-Vernet and Issautier*, 1998; *Pierrard et al.*, 1999; *Pierrard*, 2012]; the evolution of the proton distribution is very different for a potential structure at rest with respect to the Sun rather than moving at a speed slightly faster than the local- solar wind speed. Hence, kinetic calculations of the global evolution of the solar wind need to be redone accounting for the double-layer nature of the heliospheric potential.

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