Estimates of Proton and Electron Heating Rates Extended to the Near-Sun Environment

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ABSTRACT

A central problem of space plasma physics is how protons and electrons are heated in a turbulent, magnetized plasma. The differential heating of charged species due to dissipation of turbulent fluctuations plays a key role in solar wind evolution. Measurements from previous heliophysics missions have provided estimates of proton and electron heating rates beyond 0.27 au. Using Parker Solar Probe (PSP) data accumulated during the first ten encounters, we extend the evaluation of the individual rates of heat deposition for protons and electrons in to a distance of 0.063 au ($13.5\,R_\odot$), in the newly formed solar wind. The PSP data in the near-Sun environment show different behavior of the electron heat conduction flux from what was predicted from previous fits to Helios and Ulysses data. Consequently, the empirically derived proton and electron heating rates exhibit significantly different behavior than previous reports, with the proton heating becoming increasingly dominant over electron heating at decreasing heliocentric distances. We find that the protons receive about 80% of the total plasma heating at $\approx 13\,R_\odot$, slightly higher than the near-Earth values. This empirically derived heating partition between protons and electrons will help to constrain theoretical models of solar wind heating.

Keywords: magnetohydrodynamics — plasmas — solar wind — solar corona — turbulence — waves — dissipation

1. INTRODUCTION

The solar wind is a supersonic, magnetized plasma that flows into interplanetary space from the Sun. Observational evidence suggests continuous heat deposition into the solar wind plasma that begins in the corona and extends into the interplanetary space (Coleman 1968; Leer et al. 1982; Tu 1988; Grall et al. 1996; Verscharen et al. 2019). A leading candidate of this gradual heating is the dissipation of turbulent fluctuating energy that exists at large scales in the solar wind (Breech et al. 2009; Verdini et al. 2010). To better understand coronal and solar wind heating, solar wind acceleration, and the large-scale evolution of the solar wind plasma, we

need to know how energy is dissipated from turbulent fluctuations into different charged species.

The solar wind is a weakly collisional plasma, with the constituent charged species (e.g., protons, electrons, and heavy ions) often exhibiting significantly different temperatures, anisotropies, and even velocities (Marsch 2006). These deviations from thermal equilibrium are strongest in regions of low density and high temperatures where Coulomb collisions are infrequent (e.g., Neugebauer 1982; Kasper et al. 2008). Relative to the other regions of the heliosphere, the fast solar wind exhibits very low density and very high temperature, and consequently very infrequent Coulomb collisions. These properties make the fast wind an optimal 'plasma labo-

ratory' for studies of collisionless kinetic processes associated with turbulent dissipation.

Many previous works have used the measurement of plasma properties in the solar wind to derive the rates of energy dissipation from processes such as magnetohydrodynamic (MHD) turbulence (e.g., Tu 1988; Verma et al. 1995; Smith et al. 2001; MacBride et al. 2005; Livadiotis et al. 2020; Marino & Sorriso-Valvo 2023). Most of these studies, however, analyzed the energy budget of a single charged species and did not consider protons and electrons together (Hellinger et al. 2011; Stverak et al. 2015; Scudder 2015).

In an important antecedent to the present work, Cranmer et al. (2009) computed the individual estimates of proton and electron heating rates in the fast solar wind. This work used Helios and Ulysses data to estimate the heating rates from 0.3 au to about 5 au. A related investigation by Breech et al. (2009) showed that with the value of heating partition given by Cranmer et al. (2009), a MHD turbulent heating model can also be consistent with the empirical data. The present paper makes substantial extension of this approach by employing newly available data much closer to the sun.

NASA's Parker Solar Probe (PSP) (Fox et al. 2016; Raouafi et al. 2023) provides the first opportunity to extend these studies to the near-Sun environment, where the solar wind is 'young' in its evolution and the physical conditions are very different (DeForest et al. 2016; Chhiber et al. 2019; Bandyopadhyay & McComas 2021). Some PSP studies have estimated the turbulence heating rate near the Sun, but most of them have not treated the energetics of the protons and electrons together (Bandyopadhyay et al. 2020a; Sasikumar Raja et al. 2021; Abraham et al. 2022; Wu et al. 2023). Although the mass density and momentum of the solar wind plasma are dominated by protons, the electron internal energy budget constitutes approximately half of the total plasma internal energy and can be rather important in its dynamics. A quantitative estimate of the heating partition between the two charged species is useful not only for accurate solar wind modeling, but also for constraining energy dissipation mechanisms in the young solar wind and the solar corona (Adhikari et al. 2021). Therefore, a full treatment of solar wind plasma energetics should include both protons and electrons in the analysis but has not yet been reported close to the sun, as far as we are aware (however, see Shankarappa et al. 2023). Here, we use PSP data accumulated from the first 10 encounters alongside previous Helios and Ulysses data to estimate the individual rates of proton and electron heating from approximately 0.06 au ($13\,R_\odot$), out to 5 au.

2. IN-SITU DATA

We focus on proton and electron plasma properties for the high-speed solar wind. PSP measurements within the solar encounter phase are used for distances closer than 0.25 au. We use data from the first ten solar encounters of PSP. The SWEAP (Kasper et al. 2016) instrument suite provides measurements of proton temperature T_p and outflow speed u data. We utilized the moments data from Solar Probe Cup (SPC) (Case et al. 2020) and Solar Probe ANalyzers-Ion (Livi et al. 2022) (SPAN-I) to obtain proton temperature and velocity, whenever the distribution function was within the field-of-view (FOV) of either instrument (Kasper et al. 2019, 2021). No Maxwellian fits were used to derive the moments in this study. We have used SPC data for the first three encounters and SPAN-i data for the remaining seven encounters (Perez et al. 2021). The SWEAP measurements are further cleaned based on several criteria: we discard SPC data when the "general flag" variable is on; we check whether the peak of proton velocity distribution function (VDF) is within the FOV of SPAN-I, such as the solar wind flow angle is under an azimuthal angle of ~ 165 degrees in the instrument coordinate and the measured energy flux is peaked at least the second to the last azimuthal angle (e.g., Huang et al. 2023). Electron heat conduction flux $q_{\parallel,e}$ data were obtained from the Solar Probe ANalyzers-Electrons (SPAN-E) (Whittlesey et al. 2020) instrument of the SWEAP experiment, as described in Halekas et al. (2020, 2021). FIELDS (Bale et al. 2016) instrument suite measures magnetic and electric fields. Electron temperature T_e and electron density n_e data were evaluated from the quasi-thermal noise (QTN) spectrum provided by the electric field antennas (Pulupa et al. 2017; Moncuquet et al. 2020; Martinovic et al. 2022).

Helios and *Ulysses* temperature and electron heat conduction data were taken from Cranmer et al. (2009). We utilize the assumption of 5% helium abundance with $n_e = 1.1\,n_p$ to calculate n_p and n_e indirectly for the *Helios* and *Ulysses* proton density data and PSP electron density data, respectively.

We select the fast solar wind to be streams faster than 600 km s^{-1} for all three datasets of PSP, Helios, and Ulysses. This high cutoff helps to minimize contamination from the slow solar wind, which often exhibits different properties than the fast wind (Cranmer et al. 2009; Dasso et al. 2005; MacBride et al. 2008).

2.1. *Analytic Fits*

Figure 1 shows the radial dependence of the data along with the following analytic fits from the combined *PSP*, *Helios*, and *Ulysses* datasets:
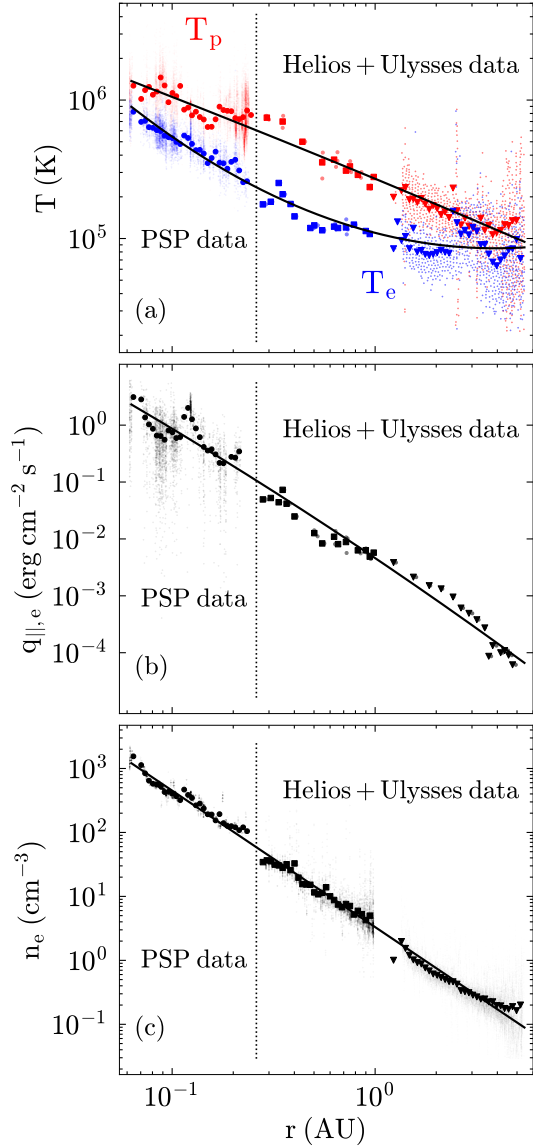
Figure 1. *In situ* measurements for the fast solar wind: (a) plasma temperature, (b) electron heat conduction flux, and (c) electron density. Binned *PSP* (dots), *Helios* (squares), and *Ulysses* (triangles) data are shown in all plots, with protons in red and electrons in blue. Whenever binning has been performed, we have plotted the original data points in smaller, transluscent symbols.

$$\ln\left(\frac{T_p}{10^5 \text{ K}}\right) = 0.9939 - 0.6073x - 0.0070x^2, \quad (1)$$

$$\ln\left(\frac{T_e}{10^5 \text{ K}}\right) = 0.0941 - 0.3765x + 0.1381x^2, \quad (2)$$

$$\ln\left(\frac{q_{||,e}}{q_0}\right) = -0.7752 - 2.4069x - 0.0574x^2, \quad (3)$$

$$n_e = 3.3120 \, r^{-2.1340}, \quad (4)$$

where $x = \ln(r/[1 \text{ au}])$ and $q_0 = 0.01$ erg cm^{-2} s^{-1}. These fits are roughly consistent with the heat flux constraint in the collisionless limit (Bale et al. 2013). We bin each individual dataset in the fitting process, thereby largely erasing the effect of non-uniformities in the number of data points. We notice that although the proton and electron temperature fits are rather close to the previous study by Cranmer et al. (2009), the radial fit for the electron parallel heat conduction flux differs in a significant way from Cranmer et al. (2009). With the Helios and Ulysses data, the electron heat conduction included data only for $r > 0.29$ au, resulting in a more concave shaped fit near the inner boundary of that region. This causes the local slopes of the $q_{||,e}$ fits to be shallower approaching Helios perihelion, thus biasing the fit towards a shallower slope in the inner heliosphere. The PSP electron heat flux data, however, continues to steeply increase at smaller radial distances, resulting in the very different fit seen in Fig. 1(b), compared to Cranmer et al. (2009). As we see presently, these new fits cause significantly different behavior in the derived proton and electron heating rates.

3. RESULTS: EMPIRICAL HEATING RATES

Next, we use the obtained fits in the internal energy equations to estimate the proton and electron heating rates. In employing the internal energy conservation equations, we neglect temperature anisotropies, which have been shown to affect the net heating only negligibly (Pilipp et al. 1990; Matteini et al. 2007; Vasquez et al. 2007) and tend to return to isotropy as a result of plasma instabilities (Kasper et al. 2002; Hellinger et al. 2006). Further, there is some indication that proton temperature anisotropy may become weak close to the Sun in the regions explored by PSP (Huang et al. 2020; Cranmer 2020). We have also neglected proton heat conduction which is generally considered small (Braginskii 1965; Sandbaek & Leer 1995), while the contribution from electron heat conduction is larger and retained.

Therefore, we may write the steady state proton and electron internal energy conservation equations (Arya & Freeman 1991; Cranmer et al. 2009) in the following form:

$$Q_p = \frac{3}{2}n_p u k_B \frac{\partial T_p}{\partial r} - u k_B T_p \frac{\partial n_p}{\partial r} + \frac{3}{2}n_p k_B \nu_{pe}(T_p - T_e)$$

$$Q_e = \frac{3}{2}n_e u k_B \frac{\partial T_e}{\partial r} - u k_B T_e \frac{\partial n_e}{\partial r} - \frac{3}{2}n_e k_B \nu_{ep}(T_p - T_e)$$

$$+ \frac{1}{r^2}\frac{\partial}{\partial r}(q_{||,e} r^2 \cos^2\Phi). \quad (5)$$

The left hand sides are the volumetric heating rates of protons Q_p and electrons Q_e, which can be determined
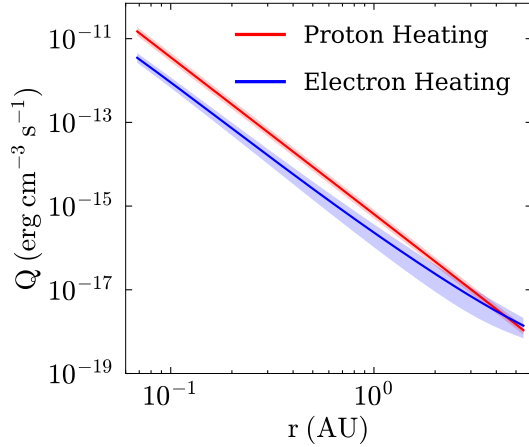
Figure 2. Empirically derived heating rates vs. heliocentric distance. Also shown are the error envelopes described in the text.

from these equations if reasonable measures of the terms on the right hand sides are obtained. Note that among these terms we have proton-electron collisions of ν_{pe} and ν_{ep}. We assume a constant outflow speed u of 700 km s^{-1}. The Parker spiral angle is Φ, given in its standard form as

$$\tan\Phi = \Omega\,r\sin\theta/u \qquad (6)$$

with a rotation frequency of $\Omega = 2.7$ x 10^{-6} rad s^{-1} and a colatitude of $\theta = 15°$. We utilize the proton-electron collision rate scaling relations given by Cranmer et al. (2009):

$$\nu_{pe} \approx 8.4 \times 10^{-9} \left(\frac{n_e}{2.5\ \mathrm{cm}^{-3}}\right)\left(\frac{T_e}{10^5\ \mathrm{K}}\right)^{-3/2}\ \mathrm{s}^{-1} \quad (7)$$

$$\nu_{ep} \approx 8.4 \times 10^{-9} \left(\frac{n_p}{2.5\ \mathrm{cm}^{-3}}\right)\left(\frac{T_p}{10^5\ \mathrm{K}}\right)^{-3/2}\ \mathrm{s}^{-1} \quad (8)$$

The resulting values of heating rates are relatively insensitive to the choice of u and θ in the inner heliosphere.

We numerically compute each derivative based on the fits in Equations 1, 2, 3, and 4 using the standard centered-difference approximation on a grid of 1000 points.

3.1. Results for Proton and Electron Heating

We solve Equations 5 for the proton and electron heating rates Q_p and Q_e over the range of heliocentric distances covered by the first ten solar encounters by PSP, Helios, and Ulysses data. These datasets cover heliocentric distances ranging from 0.063 au to 5.44 au. Fig. 2 shows the resulting heating rates.

To estimate the errors corresponding to each computed heating rate, we construct the upper and lower limit of the proton and electron heating rates by the standard deviation of each quantity from binning of the data. Then, for each quantity, the errors were propagated to the derived quantities. The relative uncertainties were calculated as nominal values across all radial distances. The obtained relative standard deviation values are $\delta_{T_p} = 0.09$, $\delta_{T_e} = 0.12$, $\delta_{q_{||,e}} = 0.39$, and $\delta_{n_e} = 0.15$. The uncertainty limits are shown by the translucent envelopes in Fig. 2. We find that the proton heating rate is well described by the following power-law fit, consistent with Cranmer et al. (2009), valid within 4% relative accuracy across all distances:

$$Q_p = 6.39\times10^{-16}\left(\frac{r}{1\ \mathrm{au}}\right)^{-3.76}\left(\frac{u}{700\ \mathrm{km\ s}^{-1}}\right)\mathrm{erg\ s}^{-1}\mathrm{cm}^{-3} \tag{9}$$

This scaling relation is also comparable to the rate predicted by Verma et al. (1995) for Alfvénic streams of $Q_p \propto r^{-3.3}$. An approximate fit was obtained for the electron heating rate with around 51% relative accuracy across all distances:

$$Q_e = 2.70\times10^{-16}\left(\frac{r}{1\ \mathrm{au}}\right)^{-3.27}\left(\frac{u}{700\ \mathrm{km\ s}^{-1}}\right)\mathrm{erg\ s}^{-1}\mathrm{cm}^{-3} \tag{10}$$

We can also calculate the total heating rate and compare with previous results. The following fit is valid to within 25% relative accuracy:

$$Q_{tot} = 9.25\times10^{-16}\left(\frac{r}{1\ \mathrm{au}}\right)^{-3.58}\left(\frac{u}{700\ \mathrm{km\ s}^{-1}}\right)\mathrm{erg\ s}^{-1}\mathrm{cm}^{-3} \tag{11}$$

approximated by a power law fit $Q \propto r^{-\delta}$ with δ slightly greater than 3.58. The total heating is shown in Fig. 3. For comparison the estimate from Cranmer et al. (2009) is plotted. Also, the heating rate values estimated using the MHD Yaglom law, taken from Bandyopadhyay et al. (2020a), are plotted.

It is interesting to note that this behavior is consistent with the scaling expected from a von Kármán decay (Matthaeus et al. 2016):

$$Q_p + Q_e \sim \rho\frac{Z^3}{\lambda}, \tag{12}$$

where ρ is the mass density, Z is the turbulent amplitude and λ is the correlation length.

This consistency can be readily demonstrated using even approximate canonical variations of the turbulence parameters. In the fast wind, usually $Z^2 \sim r^{-1}$ so $Z^3 \sim r^{-3/2}$. But $\lambda \sim r^{1/2}$ and density approximately $\rho \sim r^{-2}$. Therefore, $\rho Z^3/\lambda$ is expected to scale as r^{-4}, which is close to the present estimates. More refined estimates of radial variations can be found in the literature (e.g., Chhiber et al. 2021). The same scaling
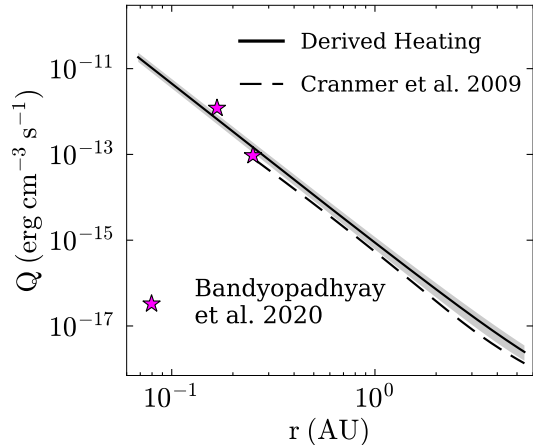
Figure 3. Total heating rates (proton plus electron) versus heliocentric distance. Error envelopes are described in text. The purple asterisks are the heating rate estimated using MHD cascade by Bandyopadhyay et al. (2020a).
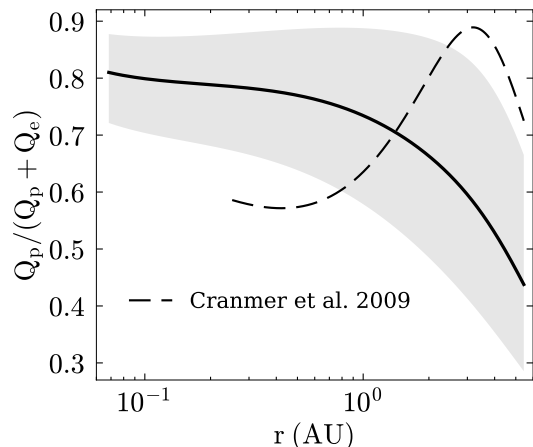

Figure 4. Proton heating to total heating ratio versus heliocentric distance. Uncertainty envelopes are described in text.

was also observed by using a multi-spacecraft study following the same solar wind plasma at two different distances (Sorriso-Valvo et al. 2023).

Perhaps the most interesting result of the paper is the estimation of heating fraction, plotted in Figure 4. The figure shows the ratio of the proton heating rate Q_p to the total heating rate $Q_p + Q_e$, as a function of radial distance. The translucent gray envelope represents the uncertainty bar, evaluated by propagating the uncertainties from temperature, heat flux, and density. We notice a significant departure in behavior from that reported in Cranmer et al. (2009). The difference is mainly due to the difference in the fits to the electron heat conduction, as discussed before.

4. CONCLUSIONS AND DISCUSSION

This paper has computed empirical estimates for the rates of proton and electron heating in the fast solar wind from the near-Sun environment, from about 0.06 au to approximately 5 au. The PSP mission makes it possible to study these characteristics in the near-Sun solar wind, for the first time. The proton and electron heating rates were estimated from mean radial fits in the three data sets (as indicated by the least-squares fits shown in Fig. 1 and given in equations 1-4), and they do not take into account the substantial spread that the data exhibits about the mean values. However, the results presented in this paper should give an estimation of the average heating fraction values for the radial distances covered.

A key aspect of this work has been the revised behavior of the electron heat conduction flux in the inner heliosphere, relative to the prior results by Cranmer et al. (2009). This change is revealed only by inclusion of the PSP measurements. The slope of $q_{||,e}$ is slightly steeper than r^{-2}, leading to outward conduction of heat and local electron heating. Notably the new fits to the electron heat conduction flux significantly revise the heating partition trend at smaller radial distances (see Cranmer & Schiff 2021). For example, we conclude that the protons receive about 70% of the total plasma heating near 1 au, and this fraction increases to approximately 80% at $< 15\,R_\odot$. At farther distances, near the orbit of Jupiter the proton heating fraction decreases to approximately 50%. Based on earlier analyses, modelers have frequently assumed that the protons receive about 60% of the dissipated energy over a wide range of distances. It is difficult to assess at present what impact this revision might have on results of global modeling (such as Usmanov et al. 2018; Adhikari et al. 2017), but it is possible that it will be significant.

Solar wind heating has been shown to occur near inhomogeneously near coherent structures, which may accelerate energetic particles (Osman et al. 2012; Bandyopadhyay et al. 2020b). Future works may explore how the heating rates of the different charged species change with the presence of energetic particles.

We recall that the heating rates Q are calculated here by evaluating other relevant terms in the energy equations. No form for Q was prescribed and no specific mechanism was assumed. If the heating is due to turbulence, however, one would expect that Q follows a von Kármán law. The present findings are indeed quite close to the scalings predicted using a von Kármán law, as explained previously. In this sense, the present results provide some justification for applicability of the use of the von Kármán MHD heating rate (Hossain et al.

1995; Wan et al. 2012; Bandyopadhyay et al. 2019) which is widely used in global solar wind MHD simulation codes (e.g., Usmanov et al. 2018). However, we note that this is a very simplistic picture. Several plasma parameters, such as cross helicity, guide-field strength, and plasma beta might affect the scaling of Eq. (12).

It is interesting to compare our estimates of the interplanetary proton and electron heating rates with those evaluated based on particular dissipation mechanisms. For example, a recent work by Shankarappa et al. (2023) estimates the proton and electron heating partition fraction using Landau damping. Although this work also suggests that protons are heated more than electrons, the proton heating fraction shows a slight decreasing trend at the inner heliosphere, close to the Sun. This is rather different from the behavior seen in Figure 4, which does not assume a particular dissipation mechanism. This contrast suggests that protons might be dominantly heated by other mechanisms although for electron dissipation, Landau damping might be the leading candidate (Chen et al. 2019; Afshari et al. 2021). Coronal observational data suggest that protons are preferentially heated over electrons in the coronal holes (Kohl et al. 2006; Wilhelm et al. 2007; Landi & Cranmer 2009; Kasper et al. 2017). This observation appears to be compatible with the trend we have found that the proton heating fraction is greater at lower altitudes.

An improved understanding of the different charged species in the solar wind and coronal plasma is an important ingredient in characterizing heliospheric properties and predicting space weather events (Shi et al. 2023). Thus, inclusion of accurate proton and electron heating rates in global solar wind and space weather models may be a crucial step in improving their performance and predictive accuracy. This paper makes a key advance in that direction.

APPENDIX

A. COMPARISON WITH PREVIOUS FITS

Here we show the comparison between the fits of the various data obtained in this paper with those from the previous study by Cranmer et al. (2009). Fig. 5 shows the earlier fits in dashed lines. Although there is some deviation between the fits in each variable, the most prominent difference between the old and new fits can be seen for parallel heat conduction flux.
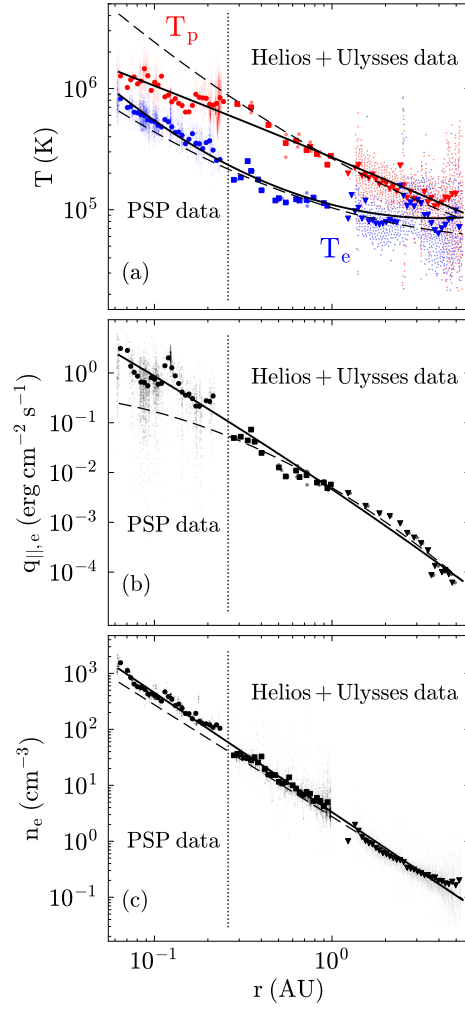
Figure 5. Our fits are shown in solid black lines, and the previous fits from Cranmer et al. (2009) are plotted in dashed black lines.

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