Extremely Cold Electrons in the January 1997 Magnetic Cloud

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Abstract. The 3D Plasma and Energetic Particle (3DP) instrument on the WIND spacecraft detected extremely cold solar wind electrons in the January 10-11, 1997 magnetic cloud, ~4 times lower temperature than any previously reported measurement. Detailed fits to the electron distributions show that the core electron temperature, T_{ec}, generally ranged from ~1 to 4.5 eV through the cloud, dropping to a low of ~0.7 eV in an unusually dense (n>~150 cm^{-3}) region in the trailing portion of the cloud. Due to the extremely low average electron temperature T_e and high density, the ions and electrons are collisionally coupled as confirmed by T_e=T_p, the first such observation in the solar wind. For most of the cloud the halo density is very low (n_{eh}<~0.1 cm^{-3}), implying magnetic disconnection from the Sun. Correlations in T_e and T_p are observed throughout the cloud and are particularly evident when n_{eh} is low. We suggest the diminished halo density has reduced a significant heat source to the core population, thus allowing the electrons to cool more thoroughly. Furthermore, we show that Coulomb collisions are a significant mechanism of energy transfer between the halo and core distributions under normal solar wind conditions.

Introduction

Magnetic clouds (MCs) are transitory solar wind phenomena characterized by strong magnetic fields (|**B**|>10 nT), depressed proton Beta (β_p) and a smooth rotation in the magnetic field direction indicative of a magnetic flux rope [*Lepping et al.*, 1990]. It has been well established that MCs are a subset of ejecta, the interplanetary manifestation of coronal mass ejections (CMEs). The January 10-11, 1997 MC was the first to be observed from “cradle to grave” [see *Burlaga et al*., 1998 and references within]. On Jan 6, an Earthward directed “halo” CME was observed by the LASCO coronagraph on SOHO, and H_α observations showed the disappearance of a filament on the solar disk. The type II radio emission emitted by the CME shock was then tracked from near the Sun to 1 AU. The in-situ measurements at 1 AU showed that the trailing portion of this MC has a cold (T_p < 1 eV), high density (n>~150 cm^{-3}) plug with a high He^{++}/H^{+} ratio and ion charge states corresponding to a low freeze-in temperature (1.4 - 4 x10^5 K), suggesting that this high density plug is filament material.

Electron measurements provide clues to a MC’s origin, its magnetic topology and structure, and its evolution as it travels to ~1 AU. The solar wind electron distribution typically consists of a cold bi-Maxwellian core with temperatures ~5-20 eV, and an outward streaming, suprathermal halo population with typically only ~5% of the core density and a characteristic temperature of ~30-100 eV [*Feldman et al*., 1975]. The core electrons are that part which is strongly influenced by collisions, while the halo electrons escape essentially collisionlessly from the corona and carry heat flux outward [*Scudder and Olbert*, 1979]. The presence of bidirectional halo electron streaming indicates that both ends of the magnetic field line connect back to the corona, and thus provides evidence for a CME [*Gosling et al*. 1987]. Likewise, heat flux dropouts (HFDs) suggest a disconnected field line, with neither end connecting back to the Sun [*McComas et al*.,1989]. Impulsively accelerated ~1-100 keV electrons that produce type III radio bursts have been used to deduce magnetic topology, fieldline length and magnetic connection to an active region for a MC. [*Larson et al*. 1997].

Here we present detailed fits to the electron measurements for the Jan. 1997 MC from the 3DP experiment on WIND [*Lin et al*., 1995], taking into account spacecraft potential and instrumental response to obtain accurate core and total electron temperatures (T_{ec} & T_e) through the entire MC, including the cold trailing portion (after ~1800 UT Jan 10) where previous studies were unable to determine T_e. We find that T_e for the leading portion of the MC is significantly lower (by as much as a factor of 5) than previously reported. Within the high density plug, T_{ec} drops to ~0.7 eV. We show that this low T_{ec} and high density result in the electrons and ions being collisionally coupled, confirmed by T_e=T_p within <5%. We also show that the halo population is providing a significant heat source to the core population, and that intervals of extremely cold core population results from a diminished halo density.

Observations

An illuminated spacecraft will emit photoelectrons and charge up to a potential, Φ_{sc}, such that the flux of escaping photoelectrons equals the flux of ambient electrons that hit the spacecraft (typically the ion flux can be ignored). As a result, electrons with energy E_∞ far from the spacecraft are measured with energy E_m=E_∞+$e\Phi_{sc}$ at the spacecraft. When Φ_{sc} rises above the detector’s low energy threshold, E_0, the distribution function, $f_\infty(E_\infty)$, can be sampled down to E_∞=0. When Φ_{sc}<E_0 and T_{ec} is low, a significant portion of the distribution may lie below E_0. It is essential to take into account this unmeasured portion when the temperature is low. We use a least squares fit to a model distribution, $f_\infty(E_\infty)$, which consists of two components: a cold core component modeled as a convecting bi-Maxwellian distribution, with different temperatures parallel, $T_{ec||}$, and perpendicular, $T_{ec\perp}$, to the magnetic field and a bulk flow velocity, v_{ec}, of the core parallel to the field relative to the solar wind ions; and a halo population modeled as a convecting kappa (κ) distribution, also with a bulk flow velocity, v_{eh}, parallel to the field.

Liouville’s Theorem relates the distribution function, f_m, measured at the spacecraft to f_∞ by $f_m(E_m,\theta_m,\varphi_m)$ = $f_\infty(E_\infty,\theta_\infty,\varphi_\infty)$ where E_m = E_∞ + $e\Phi_{sc}$. All electron observations were obtained using the 3DP EESA Low analyzer which is mounted on a boom away from the spacecraft with most angular sectors looking nearly radially away from the spacecraft. Thus, the angular deflections resulting from the spacecraft’s electric field are small and are neglected here, i.e. θ_m=θ_∞, φ_m=φ_∞. Finally, the model distribution is convolved with the detector response. A single EESA Low 3D distribution measurement (made in 1 spin period of 3 seconds) consists of counts in 88 angle bins $\times$ 15 energy steps for a total of 1320 data samples. The free parameters (Φ_{sc}, n_{ec}=core density, v_{ec}, $T_{ec||}$, $T_{ec\perp}$, n_{eh}=halo density, v_{eh}, T_{eh}=halo temperature, and k) are determined using standard least squares fitting techniques to obtain a best fit to the 1320 measured data points. For this study we assume quasi-neutrality and equate the total solar wind electron density (n_{ec}+n_{eh}) to the measured ion density, thus removing one free parameter. The core temperature is defined as T_{ec}=($T_{ec||}$+$2T_{ec\perp}$)/3 and the total (core+halo) electron temperature as $T_e = (n_{ec}T_{ec}+n_{eh}T_{eh})/(n_{eh}+n_{ec})$

Figure 1 shows 1-dimensional cuts of the electron distribution function in (A) the solar wind upstream, (B) the beginning portion of the MC and (C) an extremely cold period near the end of the

MC. In (B) and (C), the core temperature determination is based largely on measurements of the tail of the core distribution. The measured angular distribution of the electrons at a given energy provides a check of the fit which is independent of the energy dependence of the instrument's geometric factor, a quantity that is difficult to calibrate in the laboratory. For a convecting Maxwellian distribution in the solar wind, it is easy to show that the count rate for an energy step centered at velocity, v_i, will vary with the angle, ϕ, to solar wind direction as $Rate(\phi) \propto \exp((2v_iV_{sw}\cos\phi)/v_{ct}^2)$ where $v_{ct} = (2T_{ec}/m_e)^{1/2}$ is the core thermal speed. Figure 1DEF shows the good fits to the observed variation in phase space density as a function of spacecraft rotation angle for the same three time periods. Note, that in example (F) there is a ~100 to 1 ratio in flux between forward and backwards look directions.

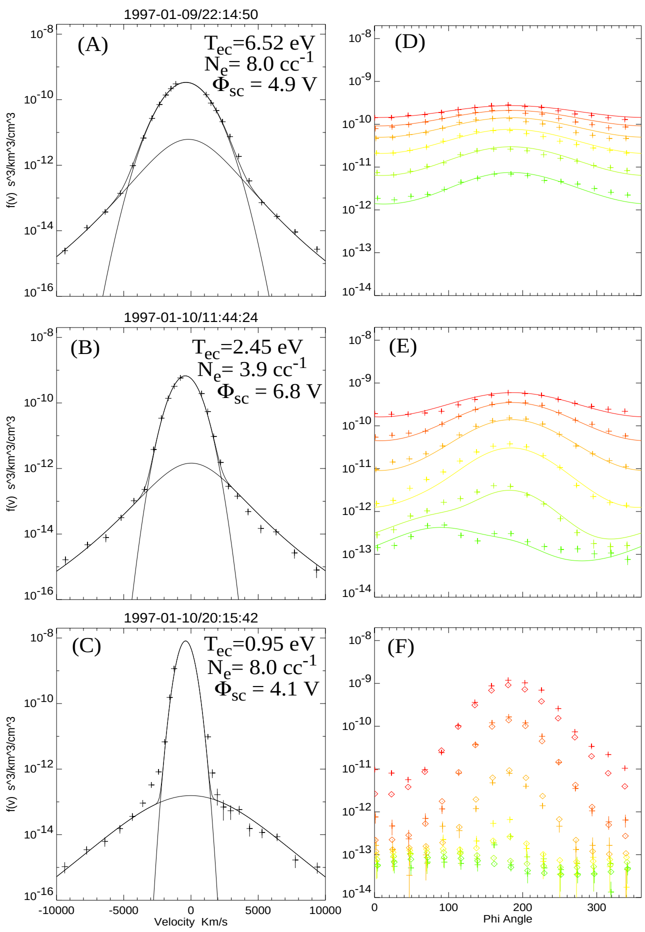

Figure 1. (A-C): Examples of 1-dimensional cuts through the electron distribution function along the GSE X-axis in the spacecraft velocity frame: (A) Undisturbed solar wind ahead of the cloud; (B) Beginning part of cloud; (C) Very cold region in trailing portion of cloud. (D-F): Phase space density vs. phi angle at 6 energy steps. (same times as A-C) Crosses are measurements. Solid lines (diamonds in F) show the model fits.

The WIND spacecraft encountered the magnetic cloud ~100 R_E upstream of Earth. Ion moments were determined using the Solar Wind Experiment (SWE) Faraday cup [*Ogilvie et al*., 1995]; the 3DP PESA Low ion analyzer (whose measurements generally agree well with SWE) was not used because it saturated during the very cold, dense region. Magnetic field measurements are obtained from the Magnetic Field Instrument (MFI) [*Lepping et al*., 1995].

Before the cloud, WIND was in the slow solar wind (V_{sw}~370 km/s) with density of 6 to 10 cm^{-3}, proton temperature (T_p) varying from ~2 to 5 eV, and a relatively constant T_{ec} of ~8 eV (Fig 2C, D, & F). An interplanetary shock occurs at 0052 UT Jan. 10, at which the density, V_{sw}, and T_p all increase. The cloud begins at 0450 UT [*Burlaga et al*. 1998] with an abrupt increase in |**B**| to ~15 nT, and sharp drops in both T_p and T_{ec} to ~2 eV, and in plasma beta to <0.1. |**B**| remains nearly constant and the direction rotates from south to north through the cloud (Fig 2A&B). The plasma density (Fig 2D) varies over a large range, from <1 cm^{-3} near the beginning to >150 cm^{-3} in the filament plug near the end.

The most notable feature of the electron population is the overall low core (and total) temperature throughout the cloud (Fig 2F); T_{ec} is ~2-4 eV up to 1810 UT Jan 10 (total T_e ~2.5-7 eV, compared to ~6-13 eV reported by *Osherovich et al., 1998*) and ~1-2 eV afterwards, but never rises above 4.5 eV. In typical solar wind outside of MCs, T_{ec} almost never drops below 5 eV at 1 AU. The abrupt jump in T_{ec} to ~7-8 eV at 0300 UT Jan 11 then confirms *Burlaga et al*.'s [1998] identification of the end of the MC.

The lowest electron temperatures, T_{ec} =~0.7 eV, are found within the high density (n= ~100-150 cm^{-3}) plug (0054 - 0200 UT, Jan 11). There the halo density (Fig 2D) is very low, 0.04-0.05 cm^{-3}, so T_{ec}=T_e. Furthermore, the proton temperature, T_p, measured by the SWE Faraday cup instrument, is observed to be equal to T_e to within < ~5%. The combination of the extremely high density and low T_e within this region leads to a thermal relaxation time between ions and electrons, τ_{relax}= 1/ν = 1/(3.2x10^{-9} λ n_e $T_e^{-3/2}$) [Book, 1998], of ~20 hours (Fig 2G), significantly less than the ~100 hour solar wind travel time to 1 A.U. Thus, the electron and ion populations have had time to equilibrate. The fact that T_p=T_e to within <5% here provides confidence that the measurements of both T_e and T_p are accurate to that level. Note that if the electrons obey an equation of state $T_e \propto n_e^{\gamma-1}$ with γ=5/3, then τ_{relax} remains constant as the solar wind expands. Just before and after the plug (~0030 to ~0300 UT), n drops below 100 cm^{-3} but τ_{relax} is still less than ~100 hours. As expected, T_e increases to slightly above T_p (up to ~15%).

Early in the MC, the alpha particle temperature T_α varies between two and ten times the proton temperature T_p, a range typical of the solar wind at 1AU. Around 2000 UT, T_α/T_p decreases to an unusually low and steady value near 1.5, where it remains for several hours. Here the width of the alpha particle distribution is so narrow as to be comparable to the size of the energy per charge step of the SWE ion detector, so T_α/T_p~1 falls within experimental uncertainty. A strong correlation between T_α/T_p (Fig 2K) and τ_{relax} (α-p) (Fig 2G) is apparent throughout. τ_{relax}(α-p)<100 hours for much longer than for τ_{relax}(e-p), extending beyond the prominence-related high density region. *Feldman et al*. [1974] suggested that Coulomb collisions limit T_α/T_p.

In the rest of this MC (and in all non-CME solar wind at 1 AU) the electrons and protons do not have time to equilibrate. Then if the halo electrons, which carry heat flux out from the Sun, deposit energy into the solar wind through Coulomb collisions, the core electrons will heat much more than the ions since electron-electron energy exchange is much faster than electron-ion. A general correlation is seen between T_{ec}-T_p (Fig. 2E) and halo density (Fig 2D) indicating the halo is a significant source of heating for the core electrons.

Heat flux dropouts (defined by *McComas et al*., 1989, as Q < 2×10^{-3} ergs/cm^2/s; dotted line in Fig 2H) extend over much of the MC. Because bidirectional electron distributions with nearly equal fluxes in both directions can also yield a nearly zero heat flux, a low halo density n_{eh} < 0.1 cm-3 (dotted line in Fig 2D) is a better indicator of heat input to the core, and of disconnection from the Sun. The second coldest region (~2000-2040 UT Jan 10), where T_{ec} drops to ~0.8 eV (T_e ~ 1 eV), is also where the halo density is lowest (n_{eh} ~0.04 cm^{-3}) and T_{ec}-T_p is only ~0.2 eV. The interval between the two coldest regions (2040 UT Jan 10 - 0054 UT Jan

11) show T_{ec}-T_p varying with n_{eh}. Through most of the MC the halo density n_{eh}<~0.1 cm^{-3} indicating magnetic disconnection from the Sun. T_{ec} then stays within ~1 eV of T_p, and often tracks the variation of T_p. The halo density is only at normal (~0.3-0.5 cm^{-3}) levels from 0824 to 0952 UT and from 1558 to 1816 UT on Jan 10; simultaneously T_{ec} is significantly (more than ~1 eV) above T_p.

Discussion

We have found that in this MC the electron temperature drops as low as T_e=0.7eV. This low temperature, combined with high density (n>150 cm^{-3}) within the filamentary plug results in collisional thermal equilibrium between electrons and ions even at 1

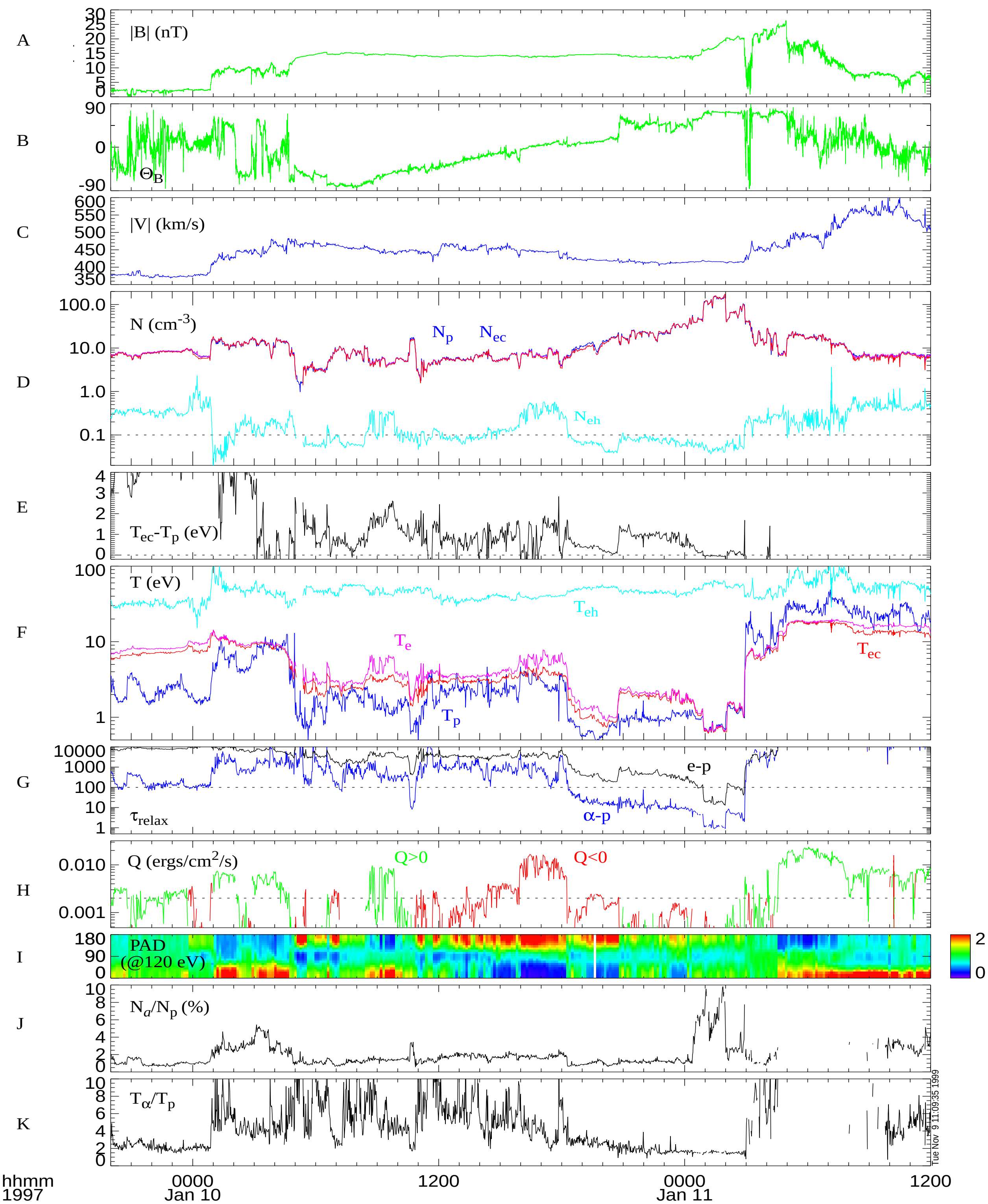

Figure 2. Summary plot of solar wind parameters: from top to bottom: Magnetic field strength (|**B**|), and angle out of ecliptic (Θ), velocity (V), density (N), core electron-proton temperature difference, temperature (T), collisional relaxation time (τ_{relax}), electron heat flux parallel to B (|**Q**|), normalized electron flux @ 121 eV vs. pitch angle (PAD), alpha to proton density ratio (N_α/N_p) and alpha to proton temperature ratio. The protons and electrons (core, halo and total) are color coded.

A.U. There is a general correlation between the halo density and T_{ec}-T_p, suggesting the halo population may be heating the core.

Previously reported measurements of total T_e (up to 1825 UT Jan 10) in this MC are much higher than reported here [*Burlaga et al.*, 1998; *Osherovich et al*., 1998]. Those temperatures were obtained from the SWE vector electron and ion spectrometer (VEIS) [*Ogilvie et al*., 1995] by computing the second moment of the electron distribution. When T_{ec} is low and $\Phi_{sc}<E_0$ a large portion of the core population may not be measured, then the contribution from the halo population becomes relatively larger, leading to erroneously high total electron temperatures. Thus measuring (or estimating) the lowest energy portion of the electron distribution and accounting for it in the analysis is essential, especially within MCs.

The value of T_e=0.7 eV is ~4 times lower than any previously reported electron temperature at 1 AU [*Montgomery et al.,* 1974; *Gosling et al.,* 1987.; *Newbury et al*., 1998], but this MC is neither unique nor the coldest; 6 out of 28 MCs observed by WIND between 1995 and 1997 have intervals with T_e<6 eV, and in one MC T_e reaches ~0.5 eV. All intervals where T_{ec} is less than 6 eV are within MCs or MC-like events.

Collisional coupling between electrons and ions requires both extremely high density (n>150 cm^{-3}) and extremely low electron temperature (T_e<1eV); this is the only case observed in the >4 years of WIND. The close agreement here between T_e and T_p, measured by two different instruments, provide strong evidence that these temperature determinations are accurate.

In the absence of external energy inputs an isotropic plasma obeys a polytrope law $T \propto n^{\gamma-1}$ with γ=5/3. Under a constant velocity, spherical expansion ($n \propto r^{-2}$) T should vary with distance r as: $T \sim r^{-4/3}$. If both electrons and ions obey polytropic laws, start at the same temperature, and have no external energy input, then T_e and T_p should be equal.

T_e and T_p, however are not well correlated under normal (non-MC) solar wind conditions and T_e is typically much higher than T_p, in the slow solar wind. The halo population typically contributes only ~30% to T_e, but it could be a significant source of heating for the core population over the 1 AU transit time. The rate of change of T_{ec} is controlled by two factors; cooling due to adiabatic expansion and heating due to collisional energy exchange from the halo population: $dT_{ec}/dr = [(dT_{ec}/dt)_{exp} + (dT_{ec}/dt)_{coll}]/V_{sw}$. The expansion term is obtained from the polytrope law: $T_{ec} \propto n^{\gamma-1}$, γ=5/3 and $n \propto r^{-2}$. Thus $(dT_{ec}/dt)_{exp} = -2(\gamma-1)V_{sw}T_{ec}/r$. The heating rate of the core population due to Coulomb collisions with a Maxwellian halo distribution can be estimated as: $(dT_{ec}/dt)_{coll} = k\ n_h \lambda (T_{eh}-T_{ec})/(T_{eh}+T_{ec})^{3/2}$ where $k = 6\mathrm{x}10^{-6}\ eV^{3/2}cm^3s^{-1}$ [*Book*, 1998] and the Coulomb logarithm λ~20. This differential equation was integrated assuming $n_{eh} \propto r^{-2}$, constant T_{eh}, and with initial condition $T_{ec}=T_{eh}$=50 eV at 10 solar radii. Assuming n_{eh}(1 AU)=0.5 cm^{-3}, this model predicts T_{ec}(1 AU) = 4.1 eV. However with n_{eh}(1 AU)=0.05 cm^{-3}, T_{ec}(1 AU) = 1.3 eV, and if n_{eh}=0 (polytropic behavior) then T_{ec}(1 AU)=0.85 eV. These estimates show that collisional heating of the core population by the halo is significant at 1 AU under typical solar wind conditions (i.e. n_{eh}~0.5 cm^{-3}) and thus wave particle interactions may not be needed [see *Newbury et al*., 1998]. The value of T_{ec}(1 AU) for this model is very insensitive to the value of T_{eh}.

Within this MC, due to the diminished halo population, the heating is much less significant. Charge state measurements indicate a freeze-in temperature of 1.4-4x10^5K (14-35 eV) within the cold, filamentary material [*Burlaga et al.* 1998], lower than the typical solar wind and much lower than ~2x10^6 K (~170 eV) typically observed in CME's, thus the initial temperature is also lower. Assuming $T_{ec}(10\ R_S) = T_{eh}$ = 20 eV and n_{eh}(1 AU) = 0.05 cm^{-3} one obtains T_{ec}(1 AU)=0.95 eV; slightly above the measured value. Note that energy loss to the collisionally coupled ions was not included in the model. Assuming no heating, (n_{eh}=0) adiabatic expansion predicts T_{ec}(1 AU)=0.35 eV. These calculations show the halo population can significantly heat the electron core population through collisional coupling.

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