Solar Wind $\sim$0.15–1.5 keV Electrons around Corotating Interaction Regions at 1 au

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Abstract

Here we present a statistical study of the $\sim$0.15–1.5 keV suprathermal electrons observed in uncompressed/compressed slow and fast solar wind around 59 corotating interaction regions (CIRs) with good measurements by Wind 3DP from 1995 through 1997. For each of these CIRs, we fit the strahl and halo energy spectra at $\sim$0.15–1.5 keV to a Kappa function with a Kappa index $\kappa$ and kinetic temperature $T_{\text{eff}}$. We find that the $\sim$0.15–1.5 keV strahl electrons behave similarly in both slow and fast wind: the strahl number density $n_s$ positively correlates with the solar wind electron temperature $T_e$ and interplanetary magnetic field magnitude $|B|$, while the strahl pitch angle width $\theta_s$ decreases with the solar wind speed $V_{\text{sw}}$. These suggest that the strahl electrons are generated by a similar/same process at the Sun in both slow and fast wind that produces these correlations, and the scattering efficiency of strahl in the interplanetary medium (IPM) decreases with $V_{\text{sw}}$. The $\sim$0.15–1.5 keV halo electrons also behave similarly in both slow and fast wind: the halo parameter positively correlates with the corresponding strahl parameter, and the halo number density $n_h$ positively correlates only with $T_e$. These indicate that the halo formation process in the IPM retains most of the strahl properties, but it erases the relationship between $n_h$ and $|B|$. In addition, $\kappa$ in compressed wind distributes similarly to that in uncompressed wind, for both the strahl and halo. It shows that CIRs at 1 au are not a significant/effective acceleration source for the strahl and halo.

Unified Astronomy Thesaurus concepts: Solar wind (1534); Solar particle emission (1517); Corotating streams (314)

1. Introduction

The solar wind electrons near 1 au consist of a thermal core population at energies below $\sim$80 eV, suprathermal halo/strahl populations at $\sim$0.1–1.5 keV and a suprathermal superhalo population at energies above $\sim$2 keV (e.g., Feldman et al. 1975; Pilipp et al. 1987; Wang et al. 2012). The strahl population beams antisunward along the interplanetary magnetic field (IMF), and the halo population occurs roughly isotropic in all directions. Both the strahl and halo electron distributions/spectra can be described by the Kappa distribution (Maksimovic et al. 1997; Štverák et al. 2009). The strahl/halo generation processes are still not well known.

Previous studies (e.g., Montgomery et al. 1968; Feldman et al. 1975; Rosenbauer et al. 1977; Pilipp et al. 1987; Pierrett et al. 2001; Salem et al. 2007) suggested that the highly anisotropic strahl population can result from the escape of thermal electrons from the hot ($\sim$10$^6$ K) solar corona that carries heat flux outward, while the roughly isotropic halo population could be caused by scattering of the strahl in the interplanetary medium (IPM). Using the suprathermal electron measurements by Wind during quiet times at 1 au, recently, Yang et al. (2020) reported that the strahl electrons originating from the hot helmet streamers/active regions tend to have a smaller Kappa index and a larger number density compared to those from the cold quiet Sun/coronal holes. Furthermore, the observed strahl Kappa index at $\sim$0.1–1.5 keV is roughly anticorrelated with the observed O$^+$/O$^+$ ratio (indicative of the coronal electron temperature). These observations support the scenario that the strahl electrons originate from escaping thermal electrons from the corona. On the other hand, Tao et al. (2016) reported that both the quiet-time $\sim$0.1–1.5 keV strahl and halo electrons exhibit a strong positive correlation between the fitted Kappa index and kinetic temperature. They proposed that such a positive correlation is likely formed in the generation process of strahl electrons at the Sun, and the formation process of halo electrons in the IPM retains this characteristic of strahl electrons.

Combining the measurements from multiple spacecraft, Maksimovic et al. (2005) and Štverák et al. (2009) reported that the relative halo (strahl) number density to the total electron density increases (decreases) with the heliocentric distance, while the relative core density remains roughly constant. In addition, the strahl angular width appears to increase with the heliocentric distance in fast solar wind (Hammond et al. 1996), significantly wider than the adiabatic magnetic focusing effect. Štverák et al. (2009) also found that, in both slow and fast wind, the fitted Kappa index of the strahl and halo populations roughly decreases with the heliocentric distance. Using the Parker Solar Probe (PSP) electron observations, Halekas et al. (2020) found that both the strahl and halo fractional density (with respect to the core density) have some trends with the solar wind electron plasma $\beta_e$ and/or collisional age within 0.25 au. Jagarlamudi et al. (2021) also
Figure 1. Summary plot of the 1997 January 25–26 CIR. (a) The PAD spectrogram of the 370 eV electrons, normalized by the PA-averaged flux of each time bin. Isotropic distributions show the normalized values around 1 (green and blue), while beam distributions have larger values (red) in the beaming direction. (b) The 5 minute average omnidirectional flux vs. time for the ∼0.15–1.5 keV electrons measured by EESA-L and EESA-H. (c)–(d) The IMF magnitude and azimuthal angle. (e)–(g) The solar wind proton density \( n_p \), proton temperature \( T_p \) and bulk velocity \( V_{sw} \). (h) The solar wind total pressure \( P_t \) (the sum of magnetic pressure and particle (proton, alpha and electron) thermal pressure). The vertical red dashed lines indicate the start time, SI, and end time of this CIR, respectively, from left to right. The intervals of R1 and R4 are bounded by vertical dark blue dashed lines; the interval of R2 (R3) is bounded by the left (right) vertical light blue dashed line and middle vertical red dashed line. For this CIR, the peak of total pressure appears shortly after the SI.
showed that the strahl population becomes broader during the presence of large amplitude whistler waves. These observations of strahl and halo radial evolution agree with the scenario of scattering of the strahl into the halo in the IPM. Possible particle interactions, among which the more generally accepted is scattering by whistler waves (Vocks et al. 2006; Gary & Saito 2007; Saito & Gary 2007; Kajdič et al. 2016; Verscharen et al. 2019; Cattell et al. 2020).

Moreover, the strahl and halo electrons could experience some acceleration throughout the IPM. Yang et al. (2019) and Liu et al. (2020) showed that the solar wind suprathermal electrons can be accelerated by coronal mass ejection-driven shocks and by the terrestrial bow shock at 1 au. Simnett et al. (1995) reported energetic electrons due to the acceleration by corotating interaction regions (CIRs), especially at their reverse shocks, observed by Ulysses beyond 3.8 au. However, the properties of solar wind suprathermal electrons around CIRs at 1 au have not been systematically investigated yet.

In this paper, we comprehensively examine the energy spectrum and pitch angle distribution (PAD) of ∼0.15–1.5 keV strahl/halo electrons around 59 CIRs, measured by the Wind 3D Plasma and Energetic Particle (3DP) instrument at 1 au from 1995 to 1997 (across the minimum between solar cycle 22 and 23). The observed properties of these suprathermal electrons provide new clues on the formation of strahl and halo electrons.

2. Observations

The Wind spacecraft was launched on 1994 November 1 into highly elliptical Earth orbits, followed by halo orbits around the Lagrange 1 point since 2004 May (Wang 2009). In the onboard 3DP instrument (Lin et al. 1995), electron electrostatic analyzers (low sensitivity EESA-L and high sensitivity EESA-H) provide the full three-dimensional measurements of ∼3 eV–30 keV electrons with an energy channel resolution of ΔE/E ≈ 0.2 and an angular resolution of 22.5° × 22.5°. The 4π steradian electron angular distribution data are sorted into eight pitch angle (PA) bins with a 22.5° PA resolution, with some overlap between adjacent bins (Wang et al. 2011), according to the IMF direction measured by the Magnetic Field Investigation (Lepping et al. 1995). In this paper, the solar wind proton density n_p, proton temperature T_p, and velocity V_sw are calculated from the proton thermal distributions measured by the 3DP instrument, while the solar wind electron temperature T_e is measured by the Solar Wind Experiment (Ogilvie et al. 1995). In addition, the EESA measurements dominated by the instrumental background and/or penetrating particles have been excluded in this study.

Here we focus on the CIR observations near the solar minimum when the CIR structures are usually stable and evident. Among the 86 CIRs observed by Wind from 1995 through 1997 at 1 au (Jian et al. 2006), we select 59 CIRs with the electron omnidirectional flux at ∼0.15–1.5 keV in the spacecraft frame that is ten times larger than the prediction of thermal electron Maxwellian distribution (determined by the solar wind density and T_e), in order to investigate the properties of solar wind suprathermal electrons around the CIRs. For each of these 59 CIRs, we identify the stream interface (SI) by the essentially simultaneous presence of an abrupt decrease in n_p and sudden increases in both V_sw and T_e, while we utilize the CIR start time and end time selected by Jian et al. (2006).

![Figure 2. The PAD properties of the strahl and halo electrons observed during the R1, R2, R3, and R4 intervals for the 1997 January 25–26 CIR. (a)–(d) The normalized average electron differential flux A_i vs. PA for the 370 eV electrons. The black open circles denote the electron measurements with A_i < 1.2, caused by the roughly isotropic halo. The red open circles denote the outward-traveling electron measurements with A_i > 1.2, caused by the strahl superimposed on the halo. The dark blue open circles indicate the inward-traveling electron measurements with A_i > 1.2. The horizontal black dashed lines indicate the calculated average flux of halo electrons J_h. The red solid circles represent the strahl electron fluxes after subtracting J_h. The red double-ended arrows and the vertical red dashed lines indicate the strahl PA width θ_s at half-maximum. The horizontal error bars represent the bandwidth of PA bin, while the vertical error bars represent the (very small) statistical errors in flux. (e) θ_s vs. electron energy for R1 (purple), R2 (green), R3 (brown) and R4 (light blue).](image)

Afterwards, we define a 3 hr interval (ending about 3 hr earlier than the CIR start time) in the uncompressed slow wind, named as “Region 1” (R1), a 3 hr interval (ending right before the SI) in the compressed slow wind, named as “Region 2” (R2), a 3 hr interval (starting right after the SI) in the compressed fast wind, named as “Region 3” (R3), and a 3 hr interval (starting about 3 hr later than the CIR end time) in the uncompressed fast wind, named as “Region 4” (R4), to obtain the average measurements of strahl and halo electrons in the uncompressed and compressed solar wind around the CIR. For some CIRs with a <3 hr duration between the CIR start time (end time) and the SI, the R2 (R3) interval is taken as the time duration between the CIR start time (end time) and the SI. Among these 59 CIRs, eight have a forward shock, four have a reverse shock, and none have a pair of forward/reverse shocks observed at 1 au.
Figure 1 shows the Wind measurements around a CIR on January 25–26, with the CIR start time at 1830 UT on January 25 (left vertical red dashed line), SI at 0906 UT on January 26 (middle vertical red dashed line), and CIR end time at 1730 UT (right vertical red dashed line). Around this CIR, the IMF is generally pointing sunward and thus, the strahl electrons at ∼0.15–1.5 keV are beaming antisunward along the 180° PA. The occasional presence of sunward-beaming electrons with an intensity much smaller than that of antisunward-traveling strahl electrons is probably due to reflection of strahl electrons beyond the spacecraft. For this CIR with no shocks formed at 1 au, we select four intervals, R1 during 1230 UT–1530 UT on January 25, R2 during 0609 UT–0906 UT on January 26, R3 during 0906 UT–1206 UT on January 26, and R4 during 2030 UT–2330 UT on January 26, to obtain the average measurements that represent, respectively, the uncompressed slow wind with a $V_{sw}$ of ∼350 km s$^{-1}$, the compressed slow wind, the compressed fast wind, and the uncompressed fast wind with a $V_{sw}$ of ∼600 km s$^{-1}$. The average density compression ratio is 1.7 between R2 and R1 and 4.2 between R3 and R4.

Figure 3. The differential flux energy spectra of the ∼0.15–1.5 keV strahl (red) and halo (black) electrons, averaged during the R1, R2, R3, and R4 intervals for the 1997 January 25–26 CIR. The red and black solid lines represent the Kappa distribution fit, respectively, to the strahl and halo spectra. Note that the conversion from the spacecraft frame to solar wind frame would almost not change the fitted parameters of strahl and halo spectra at ∼0.15–1.5 keV, as suggested by simulations.

At ∼0.15–1.5 keV, we separate the roughly isotropic halo population and the antisunward-beaming strahl population according to their different behaviors in PADS. For each energy channel, we calculate the normalized electron differential flux, $J_i = j_i / j_{\text{min}}$, where $j_i(E)$ is the electron differential flux for the $i$th PA bin and $j_{\text{min}}(E)$ is the minimum electron flux among the eight PA bins. We define that (1) the electron measurements in PA bins with $A_i < 1.2$ are caused by the roughly isotropic halo, and the average halo electron differential flux is calculated as

$$J_h(E) = \frac{\sum_{A_i < 1.2} j_i \times \Omega_i}{\sum_{A_i < 1.2} \Omega_i},$$

where $\Omega_i$ is the solid angle for the $i$th PA bin.
where $\Omega_i$ is the solid angle of the $i$th PA bin; (2) the antisunward-traveling electron measurements in PA bins with $A_i > 1.2$ are caused by the strahl electrons superimposed on the halo, and the strahl electron differential flux in each of these antisunward PA bins is calculated after subtracting the average halo electron flux $J_{h,i}$ from $J_i$, in (g) the dashed lines represent a 1:1 ratio. For $\kappa_s$, $T_{\text{eff}}$, $\kappa_h$ and $T_{\text{eff}}$, the error bars represent the fitting errors. For $\Theta_s$, the error bars represent the uncertainties estimated from the bandwidth of PA bin.

For the strahl electrons (see Figure 2, for example), we obtain the pitch angle width at half maximum, $\theta_s$, from the linear interpolation between two bins bracketing the half-value of maximum flux (suggested by Wang et al. 2011), and calculate the average strahl electron flux over PA bins as

$$J_s(E) = \frac{\sum_{A_i > 1.2} J_{h,i} \times \Omega_i}{\sum_{A_i > 1.2} \Omega_i}. \quad (2)$$

Figure 2(e) shows that the observed $\theta_s$ in R1–R3 has random and small variations with the electron energy, while $\theta_s$ in R4 varies insignificantly with the electron energy at $\sim$0.15–0.6 keV and roughly increases with the electron energy at $\sim$0.6–1.5 keV. In this paper, we use the average of $\theta_s$ over energies of $\sim$0.15–1.5 keV, $\Theta_s$, to characterize the PA width of strahl electrons, since the observed $\theta_s$ mostly shows no obvious energy dependence.

For all the 59 CIRs, the observed average differential flux of both the strahl and halo electrons in the uncompressed/compressed slow and fast wind generally fits well to a Kappa

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**Figure 4.** Scatter diagrams of the strahl and halo parameters in R1 (purple) and R4 (light blue) for the 59 CIRs. (a)-(c): $\kappa_s$ vs. $T_{\text{eff}}$, $n_s$ and $\theta_s$; (d): $n_s$ vs. $\Theta_s$. (e)-(f): $\kappa_h$ vs. $T_{\text{eff}}$ and $n_h$. (g): $\kappa_s$ vs. $\kappa_h$, (h): $T_{\text{eff}}$ vs. $T_{\text{eff}}$. (i) $n_s$ vs. $n_h$. In (g)-(i), the dashed lines represent a 1:1 ratio. For $\kappa_s$, $T_{\text{eff}}$, $\kappa_h$ and $T_{\text{eff}}$, the error bars represent the fitting errors. For $\Theta_s$, the error bars represent the uncertainties estimated from the bandwidth of PA bin.
Figure 5. Scatter diagrams of the strahl parameters vs. solar wind parameters in R1 (purple) and R4 (light blue). (a)–(e): $n_s$ vs. the solar wind electron temperature $T_e$, IMF magnitude $|B|$, speed $V_{sw}$, proton temperature $T_p$, and proton density $n_p$. (f)–(j): The $n_s/n_p$ ratio vs. $T_e$, $|B|$, $V_{sw}$, $T_p$, and $n_p$. (k)–(o): $\Theta_s$ vs. $T_e$, $|B|$, $V_{sw}$, $T_p$, and $n_p$. For $\Theta_s$, the error bars represent the uncertainties estimated from the bandwidth of PA bin. For $n_s$, the error bars represent the fitting errors.

Figure 6. Scatter diagrams of the solar wind parameters in R1 (purple) and R4 (light blue). (a)–(d): The solar wind electron temperature $T_e$ vs. IMF magnitude $|B|$, solar wind proton temperature $T_p$, solar wind speed $V_{sw}$, and solar wind proton density $n_p$. (e) $V_{sw}$ vs. $n_p$. (f)–(h): $|B|$ vs. $T_e$, $V_{sw}$, and $n_p$. (i)–(j): $T_p$ vs. $V_{sw}$ and $n_p$. (k)–(o): $T_p$ vs. $V_{sw}$, $T_e$, and $n_p$. For $T_p$, the error bars represent the uncertainties estimated from the bandwidth of PA bin. For $T_p$, the error bars represent the fitting errors.
distribution function of energy (see Figure 3):
\[
\hat{j}(E; n_0, \kappa, T_{\text{eff}}) = \frac{E n_0}{\pi m_e^{1/2} (2\kappa - 3) k_B T_{\text{eff}}^{3/2}} \times \frac{\Gamma(\kappa + 1)}{\Gamma(\kappa - \frac{1}{2}) \Gamma(3/2)} \times \left(1 + \frac{2E}{(2\kappa - 3) k_B T_{\text{eff}}} \right)^{-(\kappa+1)},
\]
where \(m_e\) is the electron mass, \(\kappa > 3/2\) is the Kappa index, \(n_0\) is the number density over the energy range from 0 to infinity, and \(T_{\text{eff}}\) is the kinetic temperature defined in the Tsallis statistical (e.g., Livadiotis & McComas 2010; Pierrard & Lazar 2010; Tao et al. 2016). Furthermore, the strahl (halo) number density at \(\sim 0.15\)–1.5 keV, \(n_s (n_h)\), is estimated by integrating the fitted Kappa distribution \(\hat{j}\) from 0.15 to 1.5 keV:
\[
n = \int_{0.15 \text{keV}}^{1.5 \text{keV}} \frac{\hat{j} \times \hat{\Omega}}{v} dE,
\]
where \(v\) is the electron velocity, and for \(E\) within the bandwidth of \(j\)th energy channel, the total solid angle \(\hat{\Omega}\) is \(4\pi\) for the nearly isotropic halo and is the sum of solid angle in antisunward PA bins with \(A_\beta > 1.2\), \(\hat{\Omega} = \sum_{A_\beta > 1.2} \Omega_i\), for the strahl. Figure 3 plots the electron energy spectra of strahl (red) and halo (black) electrons, as well as their integrated number densities, at \(\sim 0.15\)–1.5 keV in the R1, R2, R3, and R4 intervals for the 1997 January 25–26 CIR.

Hereafter we examine the strahl parameters (the strahl number density \(n_s\), PA width at half maximum \(\Theta_s\), Kappa index \(\kappa_s\), and kinetic temperature \(T_{\text{eff}}\)) and halo parameters (the halo number density \(n_h\), Kappa index \(\kappa_h\), and kinetic temperature \(T_{\text{eff}}\)) at \(\sim 0.15\)–1.5 keV, respectively, between uncompressed slow and fast wind, between compressed slow and fast wind, between uncompressed and compressed slow wind and between uncompressed and compressed fast wind for the selected 59 CIRs.

2.1. Uncompressed Slow and Fast Wind (R1 and R4)

In both uncompressed slow (R1) and fast (R4) wind (Figure 4), the strahl electrons at \(\sim 0.15\)–1.5 keV show no obvious correlation between the \(n_s, \Theta_s \) and \(\kappa_s\) (or \(T_{\text{eff}}\)), while these strahl electrons exhibit a strong positive correlation between \(\kappa_s\) and \(T_{\text{eff}}\) consistent with the quiet-time solar wind observations (Tao et al. 2016). Such a positive correlation between \(\kappa_s\) and \(T_{\text{eff}}\) likely results from the formation process of strahl at the Sun (Tao et al. 2016).

Among the solar wind parameters (Figure 5), \(n_s\) exhibits a positive correlation with the solar wind electron temperature \(T_e\) and IMF magnitude \(|B|\), while \(T_e\) shows no obvious correlation with \(|B|\) (Figure 6(a)); \(n_s\) has no clear correlation with the solar wind speed \(V_{\text{sw}}\), proton temperature \(T_p\) and proton density \(n_p\). The ratio of \(n_s\) over \(n_p\) also shows a positive correlation with \(T_e\) and \(|B|\), while \(n_s\) has no correlation with \(T_p\) and \(|B|\). These positive correlations of \(n_s\) (or \(n_s/n_p\)) with \(T_e\) and \(|B|\) behave almost the same in both uncompressed slow and fast wind, likely reflecting the presence of some generation process of strahl in both slow and fast wind. In addition, \(n_s\) shows no obvious correlation with the electron plasma \(\beta_e = 0.403 \times n_{ps} T_e / B^2\) (Figure 7), but \(n_s\) exhibits a weak negative correlation with the electron collisional age (the number of transverse collisions experienced by a thermal electron during the solar wind expansion over the density

\[
\begin{align*}
\text{gradient scale} \quad C_e = 2.966 \times 10^{4} V_{\text{sw}} / V_{\text{eq}} & \quad (\text{Salem et al. 2003}, \text{where the collisional frequency} \nu_{\text{eq}} \simeq 1.966 \times 10^{-4} n_{\text{sw}} T_e^{-3/2} \\
\text{and} \quad n_{\text{sw}} & \quad = n_p).
\end{align*}
\]

Among the solar wind parameters (Figures 5 and 7), \(\Theta_s\) shows a negative correlation with \(V_{\text{sw}}\) as well as with \(T_p\) (likewise due to the close relationship between \(V_{\text{sw}}\) and \(T_p\), as shown in Figure 6(i)); \(\Theta_s\) has no obvious correlation with \(T_e\) and \(|B|\). The negative correlation between \(\Theta_s\) and \(V_{\text{sw}}\) also behaves almost the same in both uncompressed slow and fast wind, suggesting that the scattering efficiency of strahl in the IPM is related to \(V_{\text{sw}}\). On the other hand, both \(\kappa_s\) and \(T_{\text{eff}}\) show no correlation with the solar wind parameters.

In both uncompressed slow (R1) and fast (R4) wind (Figure 4), the halo electron parameter at \(\sim 0.15\)–1.5 keV \((n_h, n_s, T_{\text{eff}})\) shows a positive correlation with the corresponding strahl parameter \((n_s, \kappa_s, T_{\text{eff}})\). It indicates that the halo generation process in the IPM would retain the strahl properties
that reflect the nature of strahl formation process at the Sun. Among the solar wind parameters (Figures 8 and 9), $n_h$ only exhibits a correlation with $T_e$. Thus, the $n_s/n_h$ ratio shows a positive correlation with $T_e$ but no correlation with $|B|$; the $n_s/n_h$ ratio has no clear correlation with $T_e$ but a positive correlation with $|B|$. These suggest that the halo generation process appears to retain the correlation of $n_s$ with $T_e$ but erase the correlation of $n_s$ with $|B|$. In addition, the $n_s/n_h$ ratio shows a weak negative correlation with $\beta_e$ and $C_e$ (Figure 9).

Note that at $\sim$0.15–1.5 keV, the fitted $\kappa_s$ and $\kappa_h$ range from $\sim$5 to $\sim$20, similar to the results of quiet-time strahl and halo electrons at $\sim$0.1–1.5 keV (Tao et al. 2016); however, they are significantly larger than the fitted Kappa indexes of strahl and halo electrons at energies below $\sim$1 keV at 1 au (Maksimovic et al. 2005; Štverák et al. 2009). Such a difference is likely due to an higher electron energy range used in this paper and Tao et al. (2016).

### 2.2. Compressed Slow and Fast Wind (R2 and R3)

In both compressed slow (R2) and fast (R3) wind (Figure 10), the strahl electrons at $\sim$0.15–1.5 keV show no obvious correlation between $n_s$, $\Theta_s$, and $\kappa_s$ ($T_{\text{str}}$), while the strahl electrons exhibit a strong positive correlation between $\kappa_s$
and $T_{\text{effs}}$. Among the solar wind parameters (Figures 11 and 12), the strahl $n_i$ exhibits a positive correlation with the solar wind electron temperature $T_e$ and IMF magnitude $|B_i|$. $n_i$ shows no clear correlation with the solar wind speed $V_{sw}$, proton temperature $T_p$ and proton density $n_p$. $n_i$ has a weak negative correlation with the electron plasma $\beta_e$ and collisional age $C_r$. The $n_i/n_p$ ratio shows a positive correlation with $T_e$, but no clear correlation with $|B_i|$. $\Theta_i$ shows a negative correlation with $V_{sw}$ (and $T_p$), while $\Theta_s$ has no obvious correlation with $T_e$. $|B_i|$, $n_p$ (not shown), $\beta_e$ and $C_r$. Both $\kappa_i$ and $T_{\text{effs}}$ (not shown) show no obvious correlation with the solar wind parameters. These strahl correlations look similar to those in uncompressed wind.

In both compressed slow (R2) and fast (R3) wind (Figure 10), the halo electron parameter at $\sim 0.15-1.5$ keV ($n_h$, $\kappa_h$ or $T_{\text{effh}}$) also shows a positive correlation with the corresponding strahl parameter ($n_i$, $\kappa_i$ or $T_{\text{effs}}$). Among the solar wind parameters (Figures 13 and 14), both $n_h$ and $n_h/n_p$ exhibit a positive correlation with $T_e$, but no obvious correlation with $|B_i|$. The $n_h/n_p$ ratio has a positive correlation with $|B_i|$ but no correlation with $T_e$. $n_i/n_p$ shows a negative correlation with $\beta_e$ but no obvious correlation with $C_r$. These halo correlations also appear similar to those in uncompressed wind.

### 2.3. Uncompressed and Compressed Slow Wind (R1 and R2)

In slow wind (Figure 15), the strahl number density $n_i$ in the uncompressed R1 ranges from $\sim 2 \times 10^{-3}$ to $\sim 6 \times 10^{-2}$ cm$^{-3}$ with an average value of $\sim 2 \times 10^{-2}$ cm$^{-3}$, while $n_i$ in the compressed R2 ranges from $\sim 3 \times 10^{-3}$ to $\sim 10^{-1}$ cm$^{-3}$ with an average value of $\sim 3 \times 10^{-2}$ cm$^{-3}$. The strahl PA width $\Theta_s$ in the uncompressed R1 ranges from $\sim 31^\circ$ to $\sim 76^\circ$ with an average value of $\sim 46^\circ$, while $\Theta_s$ in the compressed R2 ranges from $\sim 34^\circ$ to $\sim 63^\circ$ with an average value of $\sim 46^\circ$. The strahl Kappa index $\kappa_s$ in the uncompressed R1 ranges from $\sim 5.5$ to $\sim 27.6$ with an average value of $\sim 10.4$, while $\kappa_s$ in the compressed R2 ranges from $\sim 4.4$ to $\sim 17.9$ with an average value of $\sim 11.2$. The strahl kinetic temperature $T_{\text{effs}}$ in the uncompressed R1 ranges from $\sim 36$ to $\sim 83$ eV with an average value of $\sim 63$ eV, while $T_{\text{effs}}$ in the compressed R2 ranges from $\sim 42$ to $\sim 82$ eV with an average value of $\sim 66$ eV. According to the Kolmogorov–Smirnov (KS) test (a non-parametric test used to detect whether two distributions are different; Press et al. 1992), $n_i$ significantly larger in compressed slow wind than uncompressed slow wind, while $\Theta_i$, $\kappa_i$ and $T_{\text{effs}}$ distribute similarly between uncompressed and compressed slow wind.

Figure 16 shows that the halo number density $n_h$ in the uncompressed R1 ranges from $\sim 2 \times 10^{-2}$ to $\sim 2 \times 10^{-1}$ cm$^{-3}$ with an average value of $\sim 6 \times 10^{-2}$ cm$^{-3}$, while $n_h$ in the compressed R2 ranges from $\sim 2 \times 10^{-2}$ to $\sim 3 \times 10^{-1}$ cm$^{-3}$ with an average value of $\sim 8 \times 10^{-2}$ cm$^{-3}$. The halo Kappa index $\kappa_h$ in the uncompressed R1 ranges from $\sim 5.2$ to $\sim 14.6$ with an average value of $\sim 10.4$, while $\kappa_h$ in the compressed R2 ranges from $\sim 5.2$ to $\sim 14.8$ with an average value of $\sim 10.4$. The halo kinetic temperature $T_{\text{effh}}$ in the uncompressed R1 ranges from $\sim 44$ to $\sim 71$ eV with an average value of $\sim 61$ eV, while $T_{\text{effh}}$ in the compressed R2 ranges from $\sim 46$ eV to $\sim 71$ eV with an average value of $\sim 61$ eV. According to the KS test, $n_h$ is significantly larger in compressed slow wind than uncompressed slow wind, while $\Theta_h$, $\kappa_h$ and $T_{\text{effh}}$ distribute similarly between uncompressed and compressed slow wind.

Figure 17 shows that the $n_i/n_p$ ratio in the uncompressed R1 ranges from $\sim 10^{-4}$ to $\sim 10^{-2}$ with an average value of $\sim 2 \times 10^{-3}$, while $n_i/n_p$ in the compressed R2 ranges from $\sim 10^{-4}$ to $\sim 10^{-3}$ with an average value of $\sim 10^{-2}$. The $n_h/n_p$ ratio in the uncompressed R1 ranges from $\sim 2 \times 10^{-3}$ to $\sim 2 \times 10^{-2}$ with an average value of $\sim 8 \times 10^{-3}$, while $n_h/n_p$ in the compressed R2 ranges from $\sim 10^{-3}$ to $\sim 10^{-2}$ with an average value of $\sim 6 \times 10^{-3}$. The $n_i/n_p$ ratio in the uncompressed R1 ranges from $\sim 4 \times 10^{-2}$ to $\sim 1.1$ with an average value of $\sim 0.3$, while $n_h/n_p$ in the compressed R2 ranges from $\sim 5 \times 10^{-2}$ to $\sim 1.4$ with an average value of $\sim 0.4$. According to the KS test, $n_i/n_p$ distributes similarly between

![Figure 10](image-url)
uncompressed and compressed slow wind, while $n_s/n_p$ (and thus $n_s/n_h$) is significantly smaller (larger) in compressed slow wind than in uncompressed slow wind.

### 2.4. Uncompressed and Compressed Fast Wind (R4 and R3)

In fast wind (Figure 18), the strahl number density $n_s$ in the uncompressed R4 ranges from $\sim 4 \times 10^{-3}$ to $\sim 7 \times 10^{-2}$ cm$^{-3}$ with an average value of $\sim 2 \times 10^{-2}$ cm$^{-3}$, while $n_s$ in the compressed R3 ranges from $\sim 10^{-3}$ to $\sim 10^{-2}$ cm$^{-3}$ with an average value of $\sim 4 \times 10^{-2}$ cm$^{-3}$. The PA width $\Theta_s$ in the uncompressed R4 ranges from $\sim 29^\circ$ to $\sim 57^\circ$ with an average value of $\sim 41^\circ$, while $\Theta_s$ in the compressed R3 ranges from $\sim 27^\circ$ to $\sim 60^\circ$ with an average value of $\sim 43^\circ$. The strahl Kappa index $\kappa_s$ in the uncompressed R4 ranges from $\sim 4.3$ to $\sim 17.2$ with an average value of $\sim 10.5$, while $\kappa_s$ in the compressed R3 ranges from $\sim 6.1$ to $\sim 16.9$ with an average value of $\sim 11.4$. The strahl kinetic temperature $T_{\text{eff}s}$ in the uncompressed R4 ranges from $\sim 38$ to $\sim 79$ eV with an average value of $\sim 64$ eV, while $T_{\text{eff}s}$ in the compressed R3 ranges from $\sim 49$ to $\sim 81$ eV with an average value of $\sim 67$ eV. According to the KS test, $n_s$ is significantly larger in compressed fast wind than uncompressed fast wind, while $\kappa_s$ and $T_{\text{eff}s}$ distribute similarly between uncompressed and compressed fast wind. $\Theta_s$ is also significantly larger in compressed fast wind than uncompressed fast wind, likely due to the correlation between $\Theta_s$ and $V_{sw}$.

Figure 19 shows that the halo number density $n_h$ in the uncompressed R4 ranges from $\sim 2 \times 10^{-2}$ to $\sim 2 \times 10^{-1}$ cm$^{-3}$...
with an average value of $\sim 8 \times 10^{-2}$ cm$^{-3}$, while $n_h$ in the compressed R3 ranges from $3 \times 10^{-2}$ to $3 \times 10^{-1}$ cm$^{-3}$ with an average value of $\sim 10^{-1}$ cm$^{-3}$. The halo Kappa index $\kappa_h$ in the uncompressed R4 ranges from $4.2 \sim 16.1$ with an average value of $\sim 10.0$, while $\kappa_h$ in the compressed R3 ranges from $4.8 \sim 15.0$ with an average value of $\sim 10.6$. The halo kinetic temperature $T_{\text{eff}_h}$ in the uncompressed R4 ranges from $40 \sim 71$ eV with an average value of $\sim 61$ eV, while $T_{\text{eff}_h}$ in the compressed R3 ranges from $43 \sim 71$ eV with an average value of $\sim 61$ eV. According to the KS test, $n_h$ is significantly larger in compressed fast wind than uncompressed fast wind, while $\kappa_h$ and $T_{\text{eff}_h}$ distribute similarly between uncompressed and compressed fast wind.

Figure 20 shows that the ratio of $n_i/n_p$ in the uncompressed R4 ranges from $10^{-3}$ to $10^{-2}$ with an average value of $\sim 5 \times 10^{-3}$, while $n_i/n_p$ in the compressed R3 ranges from $8 \times 10^{-5}$ to $10^{-2}$ with an average value of $\sim 4 \times 10^{-3}$. The ratio of $n_i/n_p$ in the uncompressed R4 ranges from $6 \times 10^{-3}$ to $4 \times 10^{-2}$ with an average value of $\sim 2 \times 10^{-2}$, while $n_i/n_p$ in the compressed R3 ranges from $2 \times 10^{-3}$ to $3 \times 10^{-2}$ with an average value of $\sim 10^{-2}$. The $n_i/n_p$ ratio in the uncompressed R4 ranges from $8 \times 10^{-2}$ to $1.0$ with an average value of $\sim 0.4$, while $n_i/n_p$ in the compressed R3 ranges from $3 \times 10^{-2}$ to $1.3$ with an average value of $\sim 0.4$. According to the KS test, $n_i/n_p$ (and $n_h/n_p$) distribute similarly between uncompressed and compressed fast wind, while $n_h/n_p$ appears significantly smaller in compressed fast wind than in uncompressed fast wind.

### 3. Summary and Discussion

In this paper, we comprehensively investigate the $\sim 0.15$–$1.5$ keV strahl and halo electrons observed by the Wind 3DP instruments at 1 au around 59 CIRs from 1995 through 1997. We find that the strahl (halo) electrons appear to behave similarly in both slow and fast wind around these CIRs, suggesting the strahl (halo) electrons are formed by a similar/same process in both slow and fast wind. At $\sim 0.15$–$1.5$ keV, the strahl number density $n_s$ positively correlates with the solar wind electron temperature $T_e$ and IMF magnitude $|B|$, while the strahl PA width $\Theta_s$ decreases with the solar wind speed $V_{sw}$. The halo number density $n_h$ positively correlates only with $T_e$. Compared to uncompressed wind, the strahl $\kappa_s$, $T_{\text{eff}_s}$, $\Theta_s$, and $n_s/n_h$, as well as the halo $\kappa_h$ and $T_{\text{eff}_h}$, behave similarly in compressed wind. However, the $n_h/n_p$ ratio appears smaller in compressed slow (fast) wind than in uncompressed slow (fast) wind. These results provide new information for understanding the formation of strahl and halo electrons.

It is generally believed that slow and fast wind have different source regions: the steady fast wind comes from open magnetic field lines in coronal holes at high latitudes, while the unsteady slow wind originates from helmet streamer, edges of active regions and opening loops (e.g., Sheeley et al. 1997; McComas et al. 2000; Marsch 2006). For the selected 59 CIRs, however, the observed strahl and halo electrons at $\sim 0.15$–$1.5$ keV behave similarly in both uncompressed slow and fast wind and in both compressed slow and fast wind. In both uncompressed slow and fast wind (Figures 4–5 and 8), $\kappa_s$ ($\kappa_h$) positively correlates with $T_{\text{eff}_s}$ ($T_{\text{eff}_h}$), $n_s$ positively correlates with $T_e$ and $|B|$, $\Theta_s$ negatively correlates with $V_{sw}$, $n_h$ positively correlates with $T_{\text{eff}_h}$, and the halo parameter positively correlates with the corresponding strahl parameter. Even in both typical slow ($V_{sw} < 350$ km s$^{-1}$) and fast ($V_{sw} > 500$ km s$^{-1}$) wind, these correlations show a consistent tendency. These observations suggest that the strahl electrons are formed by a similar/same process occurring at the Sun in both slow and fast wind, while the halo generation process retains most of the strahl properties.

In uncompressed wind around the CIRs at 1 au, both the strahl $n_s$ and halo $n_h$ at $\sim 0.15$–$1.5$ keV positively correlate with the solar wind electron temperature $T_e$, probably resulting from the strahl generation process. In the exospheric models (e.g., Maksimovic et al. 2001; Zouganelis et al. 2004), the flux of escaping electrons increases as the coronal electron temperature $T_{\text{coro}}$, suggesting that the strahl $n_i$ increases with $T_{\text{coro}}$. Thus, the observed positive correlation between $n_i$ and $T_e$ could indicate a positive relationship between $T_e$ in the solar wind source region and $T_{\text{coro}}$ in the corona, caused by some unknown processes. In fact, Maksimovic et al. (2020) showed that $T_e$ is anticorrelated with $V_{sw}$ and thus is presumably correlated with the solar wind minor ion ratio (indicative of $T_{\text{coro}}$) in the pristine solar wind, using the PSP observations at $\sim 0.15$ au and the Helios observations at $\sim 0.3$ au. However, Yang et al. (2020) reported no clear correlation between $n_i$ and $O^+ / O^{6+}$ for the quiet-time observations at 1 au. Future studies are needed to investigate the radial evolution of the relationship between the strahl parameters, $T_e$ and $T_{\text{coro}}$, probably combined with measurements from Solar Orbiter and PSP close to the Sun (Muller et al. 2013; Fox et al. 2016).
In uncompressed wind around the CIRs at 1 au, the strahl density \( n_s \) at \( \sim 0.15–1.5 \) keV also positively correlates with the IMF magnitude \( |B| \), but the halo density \( n_h \) at \( \sim 0.15–1.5 \) keV has no clear correlation with \( |B| \) (Figures 5 and 8). One possibility is that this positive correlation between \( n_s \) and \( |B| \) observed at 1 au is due to the interplanetary expansion of the magnetic flux tube that the strahl electrons propagate within. If the \( |B| \) at different solar source regions is close, then the \( |B| \) at 1 au could reflect the degree of expansion of magnetic flux tubes from the corona to 1 au: the larger degree of expansion the smaller \( |B| \) at 1 au. Thus, \( n_s \) may be correlated with \( |B| \) at 1 au. The absence of a clear correlation between \( n_h \) and \( |B| \) at 1 au suggests that the halo formation process throughout the IPM (within and beyond 1 au) can erase the relationship between \( n_s \) and \( |B| \), while it retains the relationship between \( n_s \) and \( T_e \). In addition, the solar wind density \( n_p \) shows no clear correlation with \( |B| \) at 1 au, probably indicating that \( n_p \) may also depend on other factors (e.g., the type of solar wind source region) besides the expansion. Another possibility is that the positive correlation between \( n_s \) and \( |B| \) is caused by a plasma \( \beta \)-dependent scattering process of strahl electrons (e.g., Pagel et al. 2005). However, both \( n_s \) and \( n_h \) show no clear correlation with \( \beta_e \).

**Figure 13.** (a)–(d) and (h): Scatter diagrams of the halo electron density \( n_h \) vs. solar wind electron temperature \( T_e \), IMF magnitude \( |B| \), speed \( V_{sw} \), proton temperature \( T_p \) and proton density \( n_p \) in R2 (green) and R3 (brown). (e)–(g): Scatter diagrams of the \( n_h/n_p \) ratio vs. \( T_e \), \( |B| \) and \( V_{sw} \) in R2 and R3. (i)–(l): Scatter diagrams of the \( n_s/n_h \) ratio vs. \( T_e \), \( |B| \), \( V_{sw} \) and \( T_p \) in R2 and R3.

**Figure 14.** (a)–(d): Scatter diagrams of the halo electron density \( n_h \) vs. the electron plasma \( \beta_e \) and collisional age \( C_e \) in R2 (green) and R3 (brown). (e)–(d): Scatter diagrams of the \( n_s/n_h \) ratio vs. \( \beta_e \) and \( C_e \) in R2 and R3.
while the $n_s/n_h$ ratio has a weak negative correlation with $\beta_e$, in slow and fast wind at 1 au (Figures 7 and 9). The observed strahl PA width $\Theta_s$ also exhibits no obvious correlation with $|B|$ or $\beta_e$.

In uncompressed wind around the CIRs at 1 au, the strahl electron PA width $\Theta_s$ at $\sim$0.15–1.5 keV shows a negative correlation with $V_{sw}$, as well as with $T_p$ (likely due to the close relationship between $V_{sw}$ and $T_p$). This negative correlation between $\Theta_s$ and $V_{sw}$ behaves consistently in the slow wind prior to CIRs and fast wind following CIRs. It suggests that the scattering efficiency of strahl in the IPM, probably as well as the formation efficiency of halo, may be related to $V_{sw}$ in both slow and fast wind. Previous studies suggested some possible scattering mechanisms including Coulomb collisions or
wave–particle interactions (e.g., Salem et al. 2003; Vocks et al. 2005; Saito & Gary 2007; Kajdič et al. 2016; Horaites et al. 2018; Verscharen et al. 2019; Cattell et al. 2020). Salem et al. (2003) showed that the collisional age $C_r$, the number of transverse Coulomb collisions experienced by a solar wind thermal electron, depends on $V_{sw}$. However, our results report that the strahl $\Theta_s$ exhibits no obvious correlation with $C_r$, while the $n_s/n_h$ ratio shows a weak negative correlation with $C_r$, in slow and fast wind observed at 1 au. On the other hand, many studies showed that whistler waves, especially the oblique whistler wave, can scatter the strahl electrons (Vasko et al. 2019; Verscharen et al. 2019; Cattell et al. 2020;
Using the PSP observations, Jagarlamudi et al. (2021) also reported an anticorrelation between the whistler wave occurrence rate and $V_{sw}$.

Tao et al. (2016) suggested that a smaller (larger) Kappa index $\kappa$ can indicate a more (less) efficient electron acceleration for both the strahl and halo electrons. For the 59 CIRs observed at 1 au (Figures 15–16 and 18–19), the $\kappa$ of both the strahl and halo in compressed wind appears to distribute similarly to that in uncompressed solar wind, according to the KS test. Among the 59 CIRs, eight have a forward shock and four have a reverse shock formed at 1 au. Even in these 12 CIRs with a forward or reverse shock, the strahl (halo) $\kappa$ in compressed

![Figure 19. Comparison of the halo parameters between uncompressed (R4) and compressed (R3) fast wind for the 59 CIRs. (a)–(c) Scatter diagrams of the halo $n_h$, $\kappa_h$ and $T_{effh}$ between R4 and R3. The dashed lines represent a 1:1 ratio. The red triangles (squares) denote the eight (four) CIRs with a forward (reverse) shock formed at 1 au, and the black solid circles indicate the other 47 CIRs. (d)–(f) Normalized histograms of the halo $n_h$, $\kappa_h$ and $T_{effh}$ in R3 (brown) and R4 (light blue). The arrows indicate the average value and the horizontal error bars show the 1σ uncertainties.](image)

![Figure 20. Comparison of the density ratios between uncompressed (R4) and compressed (R3) fast wind for the 59 CIRs. (a)–(c) Scatter diagrams of $n_s/n_h$, $n_s/n_p$ and $n_h/n_p$ between R4 and R3. The dashed lines represent a 1:1 ratio. (d)–(f) Normalized histograms of $n_s/n_h$, $n_s/n_p$ and $n_h/n_p$ in R3 (brown) and R4 (light blue). The arrows indicate the average value and the horizontal error bars show the 1σ uncertainties.](image)
wind appears not significantly smaller than that in uncompressed wind. On the other hand, the strahl (halo) parameter correlations (e.g., $\kappa$ versus $T_{\text{eff}}$, $n_i$ versus $T_e$, $n_i$ versus $|B|$, $\Theta_e$ versus $V_{sw}$, $n_h$ versus $T_e$, and $n_i/n_h$ versus $\beta_e$) in compressed wind also appear similar to those in uncompressed wind (not shown), for the 59 CIRs. These suggest that CIRs close to the Sun are an effective acceleration source of the strahl and halo electrons. Solar Orbiter and PSP will provide the in-situ measurements for investigating whether the CIRs close to the Sun might be converted into the core electrons or superhalo electrons, due to some unknown processes.

For the 59 CIRs at 1 au, the number density ratio between the $\sim$0.15–1.5 keV strahl and solar wind, $n_s/n_p$, distributes similarly between compressed and uncompressed slow (fast) wind (Figures 13 and 16). However, the number density ratio between the halo and solar wind, $n_h/n_p$, is significantly smaller in compressed slow (fast) wind than in uncompressed slow (fast) wind. In compressed solar wind, thus, the halo electrons might be converted into the core electrons or superhalo electrons, due to some unknown processes.

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References

Cattell, C., Short, B., Breneman, A., & Grul, P. 2020, ApJ, 897, 126
Feldman, W. C., Asbridge, J. R., Bame, S. J., Montgomery, M. D., & Gary, S. P. 1975, JGR, 80, 4181
Fox, N. J., Velli, M. C., Bale, S. D., et al. 2016, SSRv, 204, 7
Gary, S. P., & Saito, S. 2007, GeoRL, 34, L14111
Halekas, J., Whittlesey, P., Larson, D., et al. 2020, ApJS, 246, 22
Hammond, C. M., Feldman, W. C., McComas, D. J., Phillips, J. L., & Forsyth, R. J. 1996, A&A, 316, 350
Horaites, K., Boldyrev, S., Wilson, L. B., Vin as, A. F., & Merka, J. 2018, MNras, 474, 115
Jagarlamudi, V., de Wit, T. D., Froment, C., et al. 2021, A&A, 650, 10
Jian, L., Russell, C. T., Luhmann, J. G., & Skoug, R. M. 2006, SoPh, 239, 337
Kajdič, P., Alexandrova, O., Maksimovic, M., Lacombe, C., & Farzakerley, A. 2016, ApJ, 833, 172
Lepping, R. P., Acunà, M. H., Burlaga, L. F., et al. 1995, SSRv, 71, 207
Lin, R. P., Anderson, K. A., Ashford, S., et al. 1995, SSRv, 71, 125
Liu, Z., Wang, L., Shi, Q., et al. 2020, ApJ, 889, L2
Livadiotis, G., & McComas, D. J. 2010, ApJ, 714, 971
Maksimovic, M., Bale, S., Berčič, L., et al. 2020, ApJS, 246, 62
Maksimovic, M., Pierrard, V., & Lemaire, J. 2001, Physics of Space: Growth Points and Problems (Berlin: Springer), 181
Maksimovic, M., Pierrard, V., & Riley, P. 1997, GeoRL, 24, 1151
Maksimovic, M., Zouganelis, I., Chaufray, J., et al. 2005, JGRA, 359, 110
Marsch, E. 2006, LrSf, 3, 1
McComas, D. J., Baraclough, B. L., Funsten, H. O., et al. 2000, JGRA, 105, 10419
Montgomery, M. D., Bame, S. D., & Hundhausen, A. J. 1968, JGR, 73, 4999
Muller, D., Mansen, R. G., St. Cyr, O. C., & Gilbert, H. R. 2013, SoPh, 285, 25
Ogilvie, K. W., Chornay, D. J., Frizenreiter, R. J., et al. 1995, SSRv, 71, 55
Pajer, C., Crooker, N., Larson, D., Kahler, S., & Owens, M. 2005, JGR, 110, A01103
Pierrard, V., & Lazar, M. 2010, SoPh, 276, 153
Pierrard, V., Lazar, M., Poedts, S., et al. 2016, SoPh, 291, 21
Pierrard, V., Maksimovic, M., & Lemaire, J. 2001, Ap&SS, 277, 195
Pilipp, W. G., Miggenrieder, H., Montgomery, M. D., et al. 1987, JGR, 92, 1075
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes in C (Cambridge: Cambridge Univ. Press)
Rosenthaler, H., Schwenn, R., Marsch, E., et al. 1977, JGR, 42, 561
Saito, S., & Gary, S. P. 2007, JGRA, 112, A06116
Salem, C., Bale, S. D., & Maksimovic, M. 2007, in Proc. Second Solar Orbiter Workshop, ed. E. Marsch et al. (Athens: ESA Publications), SP-641
Salem, C., Hubert, D., Lacombe, C., et al. 2003, ApJ, 585, 1147
Sheeley, N., Wang, Y.-M., Hawley, S., et al. 1997, ApJ, 41, 472
Simnett, G. M., Sayle, K., Tappin, S., & Roelof, E. 1995, SSRv, 72, 327
Štverák, Š., Maksimovic, M., Trávníček, P. M., et al. 2009, JGRA, 114, A5
Tao, J., Wang, L., Zong, Q., et al. 2016, ApJ, 820, 22
Vasko, I., Krasnoselskikh, V., Tong, Y., et al. 2019, ApJL, 871, L29
Verscharen, D., Chandran, B. D., Jeong, S.-Y., et al. 2019, ApJ, 886, 136
Vocke, C., Salem, C., Lin, R., & Mann, G. 2005, ApJ, 627, 540
Wang, L. 2009, PhD thesis, Univ. California, Berkeley
Wang, L., Lin, R. P., & Krucker, S. 2011, ApJ, 727, 121
Wang, L., Lin, R. P., Salem, C., et al. 2012, ApJL, 753, L23
Yang, L., Wang, L., Li, G., et al. 2019, ApJ, 875, 104
Yang, L., Wang, L., Zhao, L., et al. 2020, ApJL, 896, L5
Zouganelis, I., Maksimovic, M., Meyer-Vernet, N., Lamy, H., & Issautier, K. 2004, ApJ, 606, 542