Assessing electron heat flux dropouts as signatures of magnetic field line disconnection from the Sun

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[1] Suprathermal electrons focused along magnetic field lines, called the strahl, carry heat flux away from the Sun. Various factors can cause heat flux dropouts (HFDs), including times when the strahl almost vanishes. HFDs are a necessary but insufficient condition for detecting magnetic flux disconnected from the Sun. To quantitatively assess the fraction of HFDs which might be due to disconnected fields, we use four years of suprathermal electron data from the Wind spacecraft to perform a comprehensive survey of heat flux dropouts with durations greater than an hour. Eliminating periods within interplanetary coronal mass ejections or containing counterstreaming electrons, we find that only ∼10% of HFDs have signatures consistent with disconnected flux. **Citation:** Pagel, C., N. U. Crooker, and D. E. Larson (2005), Assessing electron heat flux dropouts as signatures of magnetic field line disconnection from the Sun, *Geophys. Res. Lett.*, *32*, L14105, doi:10.1029/2005GL023043.

1. Introduction

[2] Suprathermal electrons ($E > \sim 80$ eV) in the solar wind can be considered as two distinct populations: a directed strahl and an isotropic background halo component. Electrons constantly escaping from the Sun are focused into the field-aligned strahl by conservation of the magnetic moment and transport heat flux away from the Sun. The halo consists of a background population of suprathermal electrons scattered over very large heliospheric distances. Magnetic focusing acts to narrow the strahl, while scattering processes and the interplanetary potential act to broaden it. Competition between these determines the actual strahl width [*Rosenbauer et al.*, 1977; *Gosling et al.*, 2004]. Observation of the strahl in the solar wind is evidence of direct magnetic connection to the Sun. On a disconnected heliospheric field line one expects to see the strahl disappear and the heat flux to be greatly reduced.

[3] In a study of heat flux dropouts (HFDs), *McComas et al.* [1989] analysed 5 months of ISEE 3 electron data, finding 25 events. The authors suggested that either disconnection from the Sun and/or pitch angle scattering were possible explanations for these dropouts. These HFDs were further examined by *Lin and Kahler* [1992] using electrons of energies 2–8 keV. Particle streaming at higher energies showed that at least eight of the 25 HFDs were still unambiguously connected to the Sun, whereas only two HFDs displayed all the characteristics required for genuine magnetic disconnection. *Fitzenreiter and Ogilvie* [1992] matched 5 of the 25 [*McComas et al.*, 1989] events with HFDs in ISEE 1 data and found a significant strahl at $E >$ 500 eV in 4 cases, where they used a significant asymmetry between the integrated anti-sunward and sunward flux of electrons to detect a strahl. Clearly processes other than magnetic disconnection are responsible for some HFDs. How many HFDs represent true disconnection from the Sun is the question addressed in this paper.

[4] We survey four years of Wind electron data to identify HFDs. We then analyse electron pitch angle distributions to search for streaming that would disqualify HFDs as disconnection events. To reduce the volume of HFDs subjected to this analysis, we first eliminate those in which the heat flux has dropped not because the strahl has disappeared but rather because the strahl electrons have been scattered across pitch angle.

[5] One means of identifying cases of pure scattering was developed by *Pagel et al.* [2005]. Following *Crooker et al.* [2003], they parameterised electron heat flux as an independent sum of suprathermal electron number flux and pitch angle anisotropy. This decomposition allows for a characterisation of HFDs. If an HFD is due to scattering alone, the electron pitch angle distributions will become more isotropic, but there should be no change in the number flux of electrons. On a disconnected magnetic field line, however, the strahl is cut off, and a drop in both pitch angle anisotropy and number flux is expected.

2. Data and Parameters

[6] This study uses Wind data from 1995 to 1998, specifically 10-minute averages of electron flux for energies 80–800 eV from the 3DP instrument, which has an energy range of 3 eV to 30 keV [*Lin et al.*, 1995]. Each time step consists of flux intensities in 13 pitch angle bins between 0° and 180°, from parallel to antiparallel to the magnetic field, respectively. Electron heat flux values are calculated from the third moment of the total electron distribution in the solar wind frame at all energies measured by 3DP. The Wind SWE [*Ogilvie et al.*, 1995] and MFI [*Lepping et al.*, 1995] instruments provide local plasma and field parameters.

[7] To confine the analysis to the ambient solar wind, we exclude all times when Wind was inside the Earth's magnetosphere or within an interplanetary coronal mass ejection

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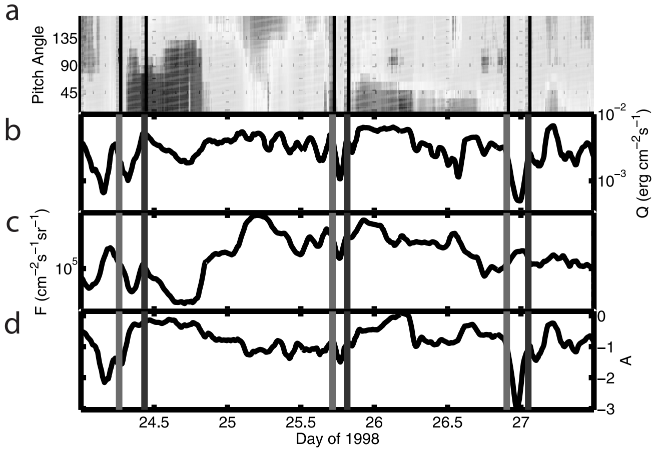

Figure 1. 3 typical HFDs. (a) The colour-coded pitch angle distribution. The colour represents electron number flux on a log scale from 3.2×10^3 to 10^5 cm^{-2}s^{-1}. (b) The electron heat flux, (c) the total number flux of electrons at E = 275 eV, and (d) the pitch angle anisotropy, A_{275}. See color version of this figure in the HTML.

(ICME) as identified by *Cane and Richardson* [2003] or the ISTP event catalogue (http://pwg.gsfc.nasa.gov/scripts/SWCatalog.shtml). Also excluded were periods with more than 10% of the data missing over a 24-hour period. In addition, efforts were made to exclude intervals of counter-streaming electrons due to connection with Earth's bow shock [*Feldman et al.*, 1975, 1982], following the procedure described by *Pagel et al.* [2005]. This sorting process leaves a total of 699 days of data over the four years.

[8] As detailed by *Pagel et al.* [2005], from the pitch-angle binned electron fluxes, the electron number flux integrated over pitch angle, F_E, at each time step for each energy E is: $F_E = \sum_{i=1}^{13} j_i \sin\theta_i$, where j_i is the electron flux in each pitch angle bin and θ_i is the pitch angle. Further, the shape of the electron pitch angle distribution can be parameterised by using a log variance measure, A_E, on the normalised number flux, j_N, in each pitch angle bin for each suprathermal electron energy E: $A_E = \log(Var(j_N))$. Electron heat flux can then be decomposed as the independent sum of the number flux, F_E, and the pitch angle anisotropy, A_E, so that $log(Q) = flog(F_E) + aA_E + c$, where f, a and c are constants. If the HFD is due to disconnection, both F_E and A_E should drop. If, instead, the heat flux drops as a result of only pitch angle scattering, only A_E should drop.

3. The HFD Survey

[9] To identify HFDs, *McComas et al.* [1989] visually inspected the electron pitch angle spectrograms for dropouts in the strahl and selected those where the heat flux fell below 2×10^{-3} erg cm^{-2}s^{-1}. Use of a fixed threshold is not appropriate for an extended survey, however, because the magnitude of the heat flux reflects the number flux of suprathermal electrons [*Scime et al.*, 1994; *Pagel et al.*, 2005], which can vary greatly with solar source region. In view of this variability, we have chosen a relative criterion for identifying HFDs. We developed an automated procedure initially to identify HFDs, and each event was then examined by eye for various criteria as described below.

[10] For the automated HFD identification, we require the log of the electron heat flux, $log(Q)$, to drop by 15% within an hour. This corresponds to a drop of about 50% in the absolute value of the heat flux. The beginning of this drop is then treated as the start of the HFD. The end is determined similarly, by a 15% increase in $log(Q)$ over a one hour period, to ensure identification of a well-defined 'dropout' shape.

[11] This automated algorithm was applied to the 699 days of selected Wind data, and 438 preliminary HFDs were identified. Of these, 187 were due to counterstreaming, presumably because of a previously unidentified ICME or from connection to either the Earth's bow shock or some other downstream shock. These events were removed from the survey.

[12] Of the remaining 251 HFDs, the heat flux fell below the *McComas et al.* [1989] limit in 159 cases, and a further 25 fell within 20% of it. The HFDs ranged in duration from 1.6 to 18 hours, with a mean of 4.4 hours and more than 98% lasted for less than twelve hours. These statistics are comparable to those of the *McComas et al.* [1989] survey (e.g., they found a mean duration of 3.6 hours), implying that we are analysing the same phenomenon. Since we use a relative criterion for identification, we pick up more events than we would using the McComas criteria, with the result that HFDs comprise just over 6% of our data set. We test their suggestion that these HFDs may be signatures of disconnection. Since our intent is not to search for all possible disconnection events, we do not address the possibility of disconnection on very short timescales ($\sim$1 to 2 minutes) or of its occurrence within ICMEs [cf. *Shodhan et al.*, 2000; *Gosling et al.*, 2005a, 2005b].

[13] The 251 identified HFDs were decomposed according to the relation $log(Q) = flog(F_E) + aA_E + c$ introduced in section 2. Figure 1 shows three successive events that illustrate this relationship. The red and blue vertical lines mark the start and end of an HFD, respectively. The top panel shows the colour-coded pitch angle distribution for E = 275 eV, where the yellow-red band either parallel or antiparallel to the magnetic field signifies the strahl. The colour represents the log of the flux counts in each pitch angle bin. The second, third and fourth panels give $log(Q)$, $log(F_{275})$ and A_{275}, respectively. Inspection of these parameters in the three events reveals three different ways in which heat flux can drop. The first shows a drop in $log(F_{275})$ but not A_{275}, the second a drop in both, and the third a drop in A_{275} but not $log(F_{275})$. The third HFD is thus identified as a case of pitch angle scattering and is eliminated as a candidate disconnection. The first HFD is also eliminated, since a drop in number flux with no drop in anisotropy still indicates a strahl, however weak its intensity.

[14] The bar chart in Figure 2 provides a summary of the decomposition of the 251 HFDs (first bar) at 275 eV. A total of 36 HFDs have a drop in A and no drop in $log(F)$ (third bar), indicating pitch angle scattering and eliminating them from further consideration. Also eliminated are 5 events with a drop in $log(F)$ but no drop in A (fourth bar), signifying the continued presence of a strahl, albeit weakened. In the remaining 208 HFDs (second bar), with a drop in both $log(F)$ and A, disconnection remains a possible explanation. We use individual electron pitch angle distri-

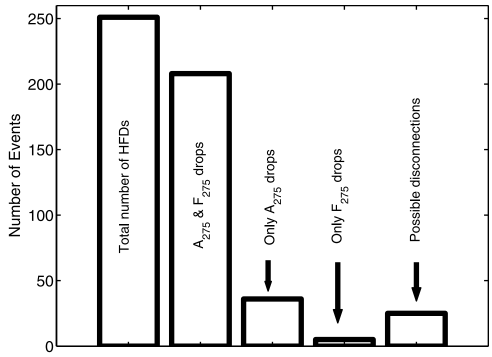

Figure 2. The HFD survey at E = 275 eV. From left to right the bars give the number of HFDs with the total, a drop in both *A* and *F*, a drop only in *A*, a drop only in *log*(*F*) and the number of possible disconnections.

butions (PADs), first at 275 eV and then at 807 eV, to test for this possibility.

[15] For each of these remaining events, the individual pitch angle distributions were examined for a cut-off of the strahl just before, just after and at seven equally-spaced times throughout the HFD. The cut-off of the strahl is more than just the lack of an obvious field-aligned distribution. The strahl is superposed on a background halo, which itself can have intensity fluctuations, depending on the source region of the suprathermal electrons. We assume that within a disconnection event, the electron source region is similar to at least one of the regions on either side of it. Thus, to identify an HFD as a possible disconnection, we require that the fluxes during the event are similar to the halo fluxes in at least one of the regions to either side of the HFD. If however, the pitch angle distribution flattens out during the HFD but remains at a higher flux level than the halo populations on both sides, we assume that this is due to scattering of the strahl electrons.

[16] Figure 3 shows three events which illustrate this procedure. The blue lines show an event that is eliminated as a disconnection because the strahl is apparent throughout, even though it grows broader in width and weaker in flux intensity. The red lines show a possible disconnection: the strahl drops out, and the remaining fluxes are weaker than the halo population after the HFD. The black lines show an event where although the strahl flattens out, the flux values in each bin are significantly higher than the background population both before and after the event. We assume that this signifies scattering rather than disconnection.

[17] We assume that it is possible to have a short period of disconnection embedded in an HFD. However, we do require a strahl dropout in at least two of the PADs within the HFD. Where disconnection seems possible, the events are re-examined carefully, using both pitch angle spectrograms and more frequent time steps (where possible) to look for the true absence of a strahl.

[18] Using this method at E = 275 eV, we eliminate 145 of the 208 events, where most of the eliminated events are those where a strahl remains throughout the HFD. For the remaining 63 events, we use higher-energy electron data to test for disconnection, initially at 807 eV. At this energy, and applying the same procedure as above, we eliminate a further 37 events, leaving 26 surviving candidate disconnections. The process of elimination ends here because at E = 2 keV, only 2 of the 26 remaining events have sufficient counts to be able to determine confidently the pitch angle distributions, both of which exhibiting a dropout in the strahl.

[19] For these 26 HFDs, we refine the possible disconnection start and end times to examine their plasma characteristics and solar wind context. Their mean duration is 2.5 hours, and all have a mean heat flux below the *McComas et al.* [1989] threshold. Fourteen occur at a sector boundary, and a further four are within half a day of it. All but two have an associated increase in plasma proton beta, with a mean increase of 54%. When compared to the 223 HFDs which we consider not to contain disconnected magnetic fields, the 26 events have on average twice as large a value of plasma proton beta and a larger drop in |*B*|. There is no significant dependence on solar wind speed, but only 4 of all the HFDs occur in high speed wind.

[20] If a spacecraft encounters a region which has magnetically disconnected from the Sun only a few hours previously, then one might expect that the highest energy electrons will have been depleted more than those at lower energy since they have a shorter travel time to 1 AU. In 19 of the 26 events we see exactly this energy dependence, as shown for one event in Figure 4, where the integrated fluxes over pitch angle have been normalised to their value one hour before the event to facilitate the comparison. It is clear that the higher-energy populations have been depleted more than the lower energies. Of the 7 events showing no clear energy dependence, we note that 5 of these are the longest disconnection candidates, with an average duration of 6 hours compared to 1.5 hours for the rest. Their lack of energy dependence may signify events that have been

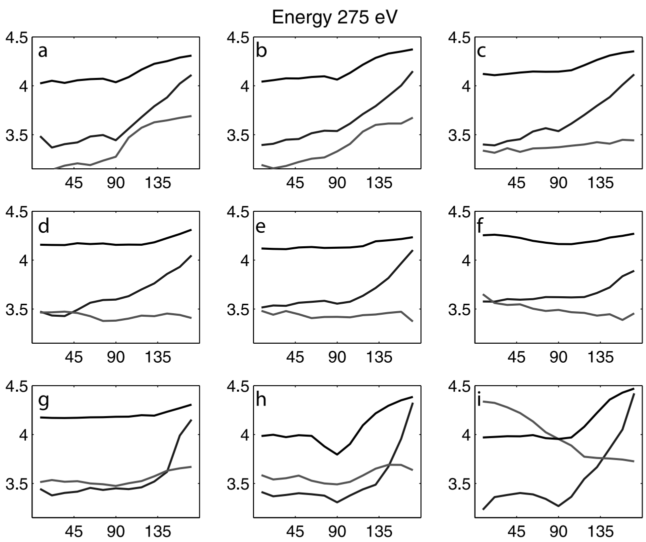

Figure 3. The PADs at E = 275 eV before, during and after 3 HFDs. The y-axis in each plot is the log flux per pitch angle bin, and the x-axis is pitch angle. Just (a) before and (i) after each event; (b)–(h) the pitch angle distributions stepping through the HFD. Event 1 (blue): 1995, day 69, 19:07 to 21:49. Event 2 (red): 1995, day 76, 18:24 to 21:36 and Event 3 (black): 1996, day 251, 08:19 to 11:41. See color version of this figure in the HTML.

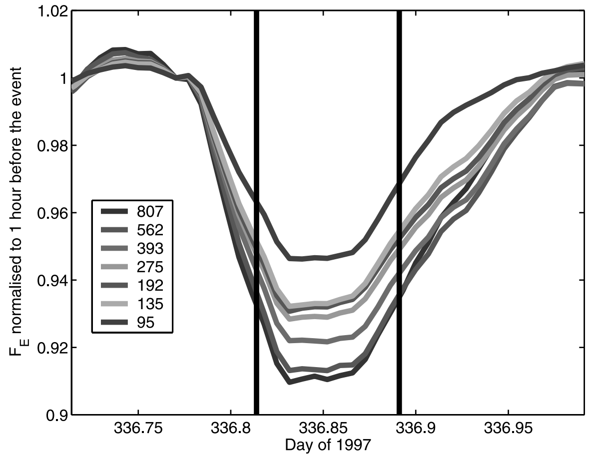

Figure 4. Energy dependence of the integrated number flux of suprathermal electrons through a possible disconnection. The legend gives the different energies in eV. All fluxes have been normalised to their value one hour before the event. Larger drops in integrated number flux correspond to higher energies. See color version of this figure in the HTML.

disconnected for a long time, giving the suprathermal electrons of all energies time to deplete significantly.

4. Discussion

[21] From a comprehensive survey of solar wind data at 1 AU, we conclude that HFDs of duration greater than an hour outside ICMEs are relatively common but that only ~10% have signatures consistent with disconnected flux.

[22] 15% are due to scattering of suprathermal electrons across pitch angle, but the cause of those HFDs where both A_E and F_E drop is as yet undetermined [cf. *Scime et al.*, 1994; *Pagel et al.*, 2005]. Of the 251 HFDs identified in this study, 82% have an associated increase in proton beta. This result confirms and quantifies the *Crooker et al.* [2003] result that most HFDs coincide with high-beta plasma. The finding reported in section 3 that beta is highest in those few HFDs that qualify as possible disconnection events suggests a possible commonality with the more numerous HFDs that do not. Since the latter, for the most part, are thought to be plasma sheets released from the tips of helmet streamers by interchange reconnection [*Crooker et al.*, 2004], the commonality may be the reconnection process, where magnetic fields are annihilated. A reduction in field strength and resulting increase in proton beta would occur both for disconnection, where open fields reconnect with each other, and for interchange reconnection, where open fields reconnect with closed fields. In the case of interchange reconnection, with no cutoff of the strahl, the reduced-field regions would then facilitate isotropisation, since high beta is conducive to certain plasma instabilities that may scatter suprathermal electrons [e.g., *Gary et al.*, 1999].

[23] *Gosling et al.* [2005b] report on a rare case of in situ reconnection between open field lines across the sector boundary where for a few minutes the spacecraft necessarily encountered disconnected field lines because the reconnection site initially was sunward of the spacecraft. The authors identified the reconnected field lines on the basis of accelerated flow and magnetic field signatures. They thus were able to confirm that the expected electron signature, an HFD caused by a dropout of the strahl, does exist on disconnected field lines. Combined with the results presented here, we conclude that an HFD is a necessary but far from sufficient signature of disconnected flux.

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