Parameterizing the Wind 3DP Hat Flux Electron Data

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1. INTRODUCTION

Solar-wind heat flux electrons have provided a powerful tool for determining the solar magnetic polarities of the interplanetary magnetic field (IMF) [1, 2]. Those electrons, with energies $E > 80$ eV, stream antisunward parallel to positive polarity field lines and antiparallel to negative polarity field lines, independently of the local field directions. By determining whether the pitch angle distribution (PAD) is concentrated at 0° or 180°, i.e., parallel or antiparallel to the field, respectively, we can establish the solar polarities of the IMF. It is possible to detect fields locally turned back to the Sun or, with bidirectional electron (BDE) flows, the closed fields of ICMEs (Figure 1).

The first plots of HF flow directions were based on a solar-pointing coordinate system and required a visual comparison of the observed IMF direction with the HF flow direction to estimate the PAD (e.g., [3, 4]). HF plots from current spacecraft are done in a coordinate system fixed on the IMF direction, which immediately yields the PAD. While simplifying the analysis, it does not avoid the considerable variation among PADs (e.g., [5, 6]) which sometimes leaves the net HF flow direction or the presence of bidirectionality [3] in doubt. In addition, the PADs are usually plotted with a color table which may or may not be normalized for the total number of electrons observed in the PADs. The recent reports of HF depletions at 90° PA [6, 7] suggest another possible HF diagnostic of IMF structure, but the identification and magnitude of these features is compromised when we are limited to a subjective analysis based on the color-coded PAD contour plots.

2. ANALYSIS

To provide quantitative diagnostics for the different types of PADs, we are beginning to analyze the 3DP [8] HF electron PAD data in terms of Fourier cosine harmonics using the following least-squares fit to the
FIGURE 2. Graphical presentations of the terms of the fits to equation (1). The $A_2$ and $A_4$ terms are important for bidirectionality and depletions, respectively. Dotted lines show profiles of negative values.

13-point HF PAD intensities

$$\log I(\theta) = A_0 + A_1\cos(\theta) + A_2\cos(2\theta) + A_3\cos(3\theta) + A_4\cos(4\theta)$$

where $\theta$ is the PA, which ranges from $0^\circ$ to $180^\circ$. Because of the large dynamic range of the HF intensities, we do a logarithmic rather than a linear fit to the intensity $I$. Plots of the five harmonic terms as functions of $\theta$ are shown in Figure 2. Note that a bidirectional flow [3] should have a significant positive $A_2$ term and a depletion [6, 7] a significant negative $A_4$ term. We have now calculated the five harmonic components for all the WIND 3DP HF data from 1995 through 1999 in 10-min intervals for electron energies of 125, 250, and 500 eV.

To examine the signatures of the various $A_n$ we selected 3 days with very different characteristic PADs (Figure 3): 1 Jan 1995 has a poorly defined and relatively flat PAD; 3 Aug 1996 has a well defined $0^\circ$ PAD and 25 Jun 1998 has a BDE PAD, with peaks at $0^\circ$ and $180^\circ$, most of the day.

2.1. $A_2$ and the BDE Diagnostic

$A_2$ is the key parameter for detecting BDE flows. Figure 4 shows the plot of $\log I(\theta)$ for various ratios of $A_2/A_1$ when $A_2$ and $A_1 > 0$. We see that bidirectionality is not apparent until $A_2/A_1 \sim 1$. Selecting an arbitrary value of $A_2/A_1$ to define periods of bidirectionality will be a critical choice for our anticipated 3DP survey. We note that Richardson and Reames [9] chose $A_2/A_1 > 0.8$ for their survey of bidirectional energetic ($\sim 1$ MeV) ion flows.

Our goal here is to get a general impression of the parametric variations among the three days with the very different PADs as determined by eye. We plotted $\log(|A_2|)$ against $\log(|A_1|)$ for the 10-min intervals of each of the three selected days and at each of the three electron energies used in the harmonic analysis. Figure 5 shows the results. The diagonal lines of the plots enable us to compare the magnitudes of $A_2$ with $A_1$. We see first that the plots are very similar for each of the three selected electron energies, suggesting that the particular energy range chosen as the standard for analysis is not critical. We also find that $A_2$, nearly always positive throughout each period, exceeds 0.2 for most of the BDE
period, looking for a separate population of points in the plot A2 versus Ai data points for the whole 1995-1999 A2 < Ai in the directed PADs, perhaps as expected, we reversed from that of Ai if both terms have the same alone. In Figure 6 we show plots of log(|A3|) against Ai, the flow direction is reversed from that indicated by PAD points, but is rarely that large in the flat and directed PADs. In addition, while A2 > Ai in the BDE PADs and A2 < Ai in the directed PADs, perhaps as expected, we also find that usually A2 > Ai in the flat PADs. As a possible strategy for selecting criteria for BDEs, we could plot A2 versus Ai data points for the whole 1995-1999 period, looking for a separate population of points in the approximate ranges defined by A2 ≥ Ai and A2 > 0.2.

### 2.2. A3 and the HF Flow Diagnostic

The most important goal in this analysis is to determine when we have a sufficiently clearly defined HF flow direction to decide the IMF polarity. From Figure 2 we see that when A3 and A1 have the same sign and A3 > A1, the flow direction is reversed from that indicated by A1 alone. In Figure 6 we show plots of log(|A3|) against log(|Ai|). Points above the diagonal line indicate cases in which A3 is large enough to result in a net HF flow reversed from that of A1 if both terms have the same sign. A substantial number of points in the flat and BDE PADs suggest such reverse flows. However, a complication here is that about 20-30% of the A3 points have signs opposite those of the corresponding A1 values and therefore enhance the net HF flow. In addition, large values of A2 could act to diminish the net HF flows determined from the A1 and A3 values alone.

The ambiguities involved in trying to sort out a set of relationships among A1, A2, and A3 suggest that a better approach may be simply to calculate the net HF Qe over all electron energies. We have done this and show the plots for the three days in Figure 7. The red trace is Qe parallel to the magnetic field direction, and the purple and green traces show the Qe in directions orthogonal to the IMF. The magnitudes of the purple plots, calculated along the axis perpendicular to the plane of the IMF direction and the Sun, are comparable to the uncertainties of the calculated Qe along the IMF and can be used as filters for valid HF flow directions. In particular, we see that for much of the 1 Jan 1995 flat PAD plot the magnitudes of many of the perpendicular HF points are comparable to the matching points of the parallel points, suggesting poorly defined HF directions. On the other hand, the parallel HF is much greater than the perpendicular HFs for all of the directed PAD plot of 3 August 1996. Note that the HF calculation used here does not produce the systematic 20° deviations between the Qe and B directions found by Salem et al. [10].

### 2.3. A4 and Depletions

The inclusion of the A4 harmonic shown in Figure 2 enables us to look for the cases of depletions [6, 7], the significant decreases symmetrically centered on 90° PA. Figure 8 shows plots of log(|A4|) against log(|A2|) with the positive and negative values of log(|A4|) plotted on separate panels. Recall that A2 is nearly always positive in our selected data sets, producing a broad PAD depression at 90°. A negative A4 term is consistent with the further narrow, symmetric depression at 90° that characterizes depletions. In most cases of Figure 8 |A4| < |A2| and A4 is negative (bottom panels). While these limited
results suggest that depletions may be defined by the criteria that $A_4 < 0$ and $|A_4| > 0.5 \times |A_2|$, a much larger survey of the 3DP data parameters will be required to justify those criteria.

3. DISCUSSION

The five-year data base of the 3DP HF electron data has been analyzed in terms of the first four Fourier cosine coefficients over 10-min averages. We intend to develop quantitative criteria for the $A_n$ coefficients that will enable us to determine IMF solar polarities and to find periods of BDEs and depletions. In this initial work we have examined characteristic parametric tradeoffs among the $A_n$ for three selected days with very different kinds of PADs.

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