RADIAL AND MERIDIONAL TRENDS IN SOLAR WIND THERMAL ELECTRON TEMPERATURE AND ANISOTROPY: ULYSSES

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Abstract. Ulysses plasma measurements from 1.15 to 5.31 AU and from S6.4° to S48.3° solar latitude are used to assess the trends in the solar wind thermal electron temperature and anisotropy. Improved spacecraft potential corrections and data products have been incorporated. The radial temperature gradient is steeper than in previous determinations, but flatter than adiabatic. When normalized to 1 AU, temperature decreases with increasing latitude. Little change in the average thermal anisotropy has been seen during the mission.

1. Introduction

Solar wind electron distributions include thermal or "core" and suprathermal or "halo" populations. Measurements from various spacecraft have been used to assess the radial gradient in core temperature, with little consensus emerging except that the gradient is flatter than the adiabatic value of $T \propto R^{-4/3}$. Voyager/Mariner results from 0.45 to 4.76 AU yielded a power-law exponent of -0.37 (Sittler and Scudder, 1980), Helios measurements yielded a range of exponents from -0.48 to -0.84 (Pilipp *et al.*, 1990), and a preliminary Ulysses study yielded an exponent of -0.56 (Phillips *et al.*, 1993). Electron temperature measurements were previously unavailable for a wide range of solar latitude; however, Phillips and Gosling (1990) predicted a temperature increase and a change in distribution anisotropy with increasing latitude for the high-speed wind.

2. Observations

We use 3-d measurements from the electron spectrometer of the Ulysses solar wind plasma experiment (Bame *et al.*, 1992), plus 32-sec averaged magnetic field observations from the dual magnetometer experiment (Balogh *et al.*, 1992). Improvements in data analysis relative to a previous study (Phillips *et al.*, 1993) include: (1) incorporation of a vector correction for spacecraft potential (Scime *et al.*, 1994); (2) calculation of core temperatures via numerical integration rather than bi-Maxwellian fitting; (3) determination of parallel and perpendicular temperatures based on the measured field; (4) deletion of spectra altered by the active RF sounder on Ulysses. Data were obtained from November 22, 1990 through the end of 1993, were binned by solar rotation, and were truncated to avoid partial rotations. The resulting data sets are: (1) in-ecliptic, 25,591 spectra from 1.15 to 5.31 AU, 17 solar rotations; (2) out-of-ecliptic, 32,158 spectra from 5.40 AU at S6.4° to 3.83 AU at S48.3°, 27 rotations.

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The anisotropy of the core distributions, defined here as $T_{\parallel}/T_{\perp}$, provides insight into the overall plasma transport processes. Figure 3 shows $T_{\parallel}/T_{\perp}$ vs. R for selected in-ecliptic data (left panel) and vs. heliographic latitude for selected out-of-ecliptic data (right). The prevailing anisotropy shows a slight upward trend with increasing R for the in-ecliptic data. This is in contrast to the model of Phillips and Gosling (1990), which predicted a reduction in the prevailing $T_{\parallel}/T_{\perp}$ with increasing heliocentric distance, at least for the high-speed wind. The discrepancy suggests that non-adiabatic processes preferentially increase $T_{\parallel}$. The out-of-ecliptic data (right) show considerable variation in anisotropy (note the interval near 30° latitude where ~50% of the observations have $T_{\parallel}/T_{\perp} < 1$) but on average do not show a consistent meridional trend. The existence of distributions with $T_{\parallel}/T_{\perp} < 0.8$ is striking when compared with 1 AU ecliptic data, where only very small $T_{\perp} < T_{\parallel}$ anisotropies have been noted (Phillips et al., 1989). Southward of 33°, the prevailing anisotropy increases slightly with increasing latitude; this trend is in qualitative agreement with the Phillips and Gosling prediction.

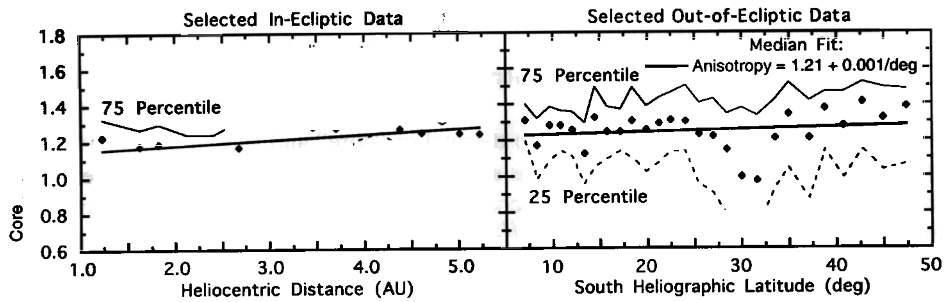

Fig. 3. Median (diamonds), plus 25 and 75 percentile core anisotropy, $T_{\parallel}/T_{\perp}$, binned by solar rotation, vs. heliocentric distance (left panel) and heliographic latitude (right). Heavy traces and equations represent power-law fits to medians.

In order to examine some of the overall characteristics of the core temperature and anisotropy without the need for normalization, we have chosen the Ulysses mission phase during which the spacecraft was between 5.0 and 5.4 AU. This interval was over 13 months long and included a solar latitude range of S5.8° to S24.5°; the resulting selected data set comprises 14,070 3-d spectra. Figure 4 shows medians of core electron density (top panel), $T_{\parallel}$ (bottom, solid diamonds), and $T_{\perp}$ (bottom, circles), binned by $T_{\parallel}/T_{\perp}$. The top panel indicates that Coulomb collisions probably play a significant role in regulating the distribution shapes: the nearly isotropic distributions have, on average, the highest densities, while anisotropies of either sense are accompanied by lower densities. The bottom panel shows that $T_{\parallel}$ is substantially more variable than is $T_{\perp}$. Similar trends in ISEE-3 measurements at 1 AU motivated the development of the Phillips and Gosling (1990) model, in which the core distributions are controlled by a combination of collisional isotropization and expansion in a spiral magnetic field. One difference between the 1 AU and 5+ AU data is that the $T_{\perp} > T_{\parallel}$ spectra had the highest observed densities at 1 AU but had intermediate densities at 5+ AU; this qualitative trend was predicted by the model (Phillips *et al.*, 1989; Phillips and Gosling, 1990).

Figure 1 (left panel) shows percentiles of core temperature for the in-ecliptic measurements, binned by solar rotation. Medians of temperature and heliocentric distance (R) have been fit to a power law, yielding $T \propto R^{-0.82}$. The right panel is an identical display for in-ecliptic data without shocked intervals (*e.g.*, Balogh *et al.*, this issue), coronal mass ejections, magnetic connections to the Jovian bow shock (Moldwin et al., 1993), and the extended electron foreshocks typical for corotating shocks (Gosling et al., 1993). Data thus chosen will be referred to henceforth as "selected" data. For this selected subset of 16,229 spectra, the power law exponent is -0.91 and the temperature variability (range between 25 and 75 percentiles) is generally less than for the entire in-ecliptic set (left).

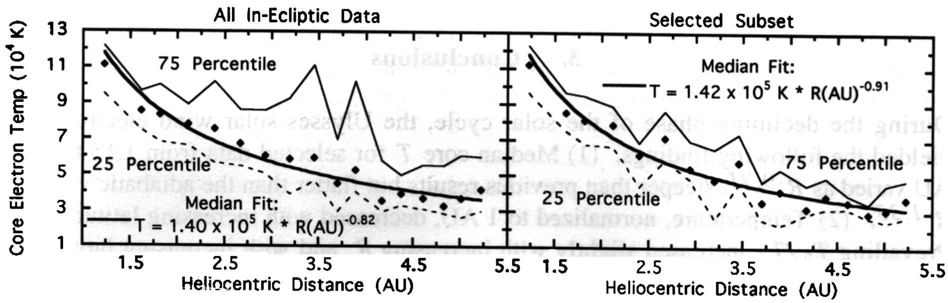

Fig. 1. Median (diamonds), plus 25 and 75 percentile core electron temperature vs. heliocentric distance, binned by solar rotation, for all in-ecliptic data (left) and a subset described in text (right). Heavy traces and equations represent power-law fits to medians.

Figure 2 (left) shows percentiles of core temperature vs. south heliographic latitude, with a linear fit to the medians, for selected out-of-ecliptic data from Jupiter encounter in February 1992 through the end of 1993. This data subset includes 19,318 spectra. Figure 2 (right) shows the same data normalized to 1 AU using the $T \propto R^{-0.91}$ fit from the in-ecliptic data. Note that the measured temperature (left) appears to have no consistent latitude dependence, while the normalized temperature (right) declines with increasing latitude as a result of the decreasing heliocentric distance of the spacecraft.

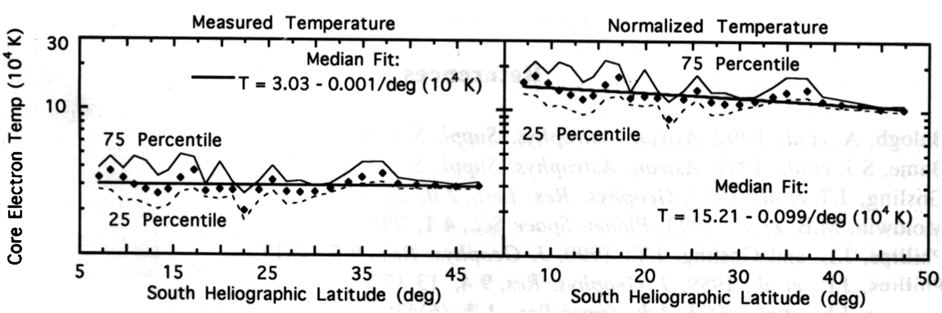

Fig. 2. Median (diamonds), plus 25 and 75 percentile measured core temperature vs. heliographic latitude, binned by solar rotation, for selected out-of-ecliptic data through 1993 (left panel); right panel shows temperature normalized to 1 AU.

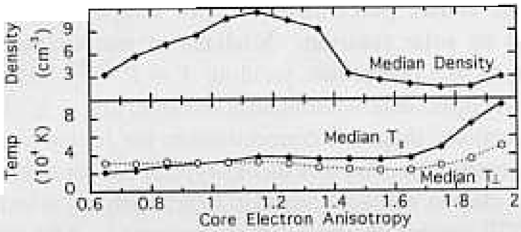

Fig. 4. Median density (top), and parallel and perpendicular temperature components (bottom), binned by core anisotropy, for a selected subset of electron spectra beyond 5 AU.

3. Conclusions

During the declining phase of the solar cycle, the Ulysses solar wind electron data yielded the following findings. (1) Median core T for selected data from 1.15 to 5.31 AU varied as $R^{-0.91}$, steeper than previous results but flatter than the adiabatic value of $R^{-1.33}$. (2) Temperature, normalized to 1 AU, decreased with increasing latitude. (3) Prevailing $T_{\|}/T_{\perp}$ increased slightly with increasing R, and with increasing latitude in the latest data. (4) Characteristics of T and $T_{\|}/T_{\perp}$ beyond 5 AU resemble those at 1 AU, though intervals of very low $T_{\|}/T_{\perp}$ first appear at greater R. Assessment of the Phillips and Gosling (1990) model produced mixed results. Noteworthy disagreements were a non-adiabatic radial gradient in T, a lack of decrease in $T_{\|}/T_{\perp}$ with increasing R, and a poleward cooling trend. Although it is impossible to ensure that the measured gradients represent spatial and not temporal variations, the relatively short (3-year) observational interval, and the data selection used, should minimize temporal effects.

Acknowledgments

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