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Ion temperature anisotropies in the Earth's high-latitude magnetosheath: Hawkeye observations

L. C. Tan[1,2], S. F. Fung[1], R. L. Kessel[1], S.-H., Chen[1,2], J. L. Green[1], T. E. Eastman[3]

Abstract. We present here for the first time observations of the inverse correlation between the ion temperature anisotropy and plasma beta in the Earth's high-latitude magnetosheath. Hot proton data with energies of 0.3-8 keV were obtained from magnetosheath passages by the Hawkeye spacecraft which had a polar orbit with an apogee of 20-21 R_E. A newly developed technique has been used to calculate the distribution functions of protons in their non-streaming frame in which their first-order anisotropy is absent. The ion-energy dependence of distribution functions indicates the existence of two hot ion components. Thus the correlation has been examined for each hot ion component separately. We have analyzed three Hawkeye magnetosheath passes during which the magnetosheath's magnetic field was close to the spacecraft spin plane, so that the two-dimensional Hawkeye sensor can adequately sample temperature anisotropies. Results of our analyses are consistent with the theoretical prediction given by Gary et al. [1994; 1995] that a universal inverse-correlation relationship exists between the temperature anisotropy and plasma beta of hot ions.

Introduction

Recently, there has been considerable interest in examining how the electromagnetic ion cyclotron instability could constrain ion temperature anisotropies in the Earth's magnetosheath and other space plasma environments [Gary et al., 1994, 1995, and references therein]. In the magnetosheath, heating near the bow shock and draping of the magnetosheath's magnetic field against the magnetopause result in an ion temperature anisotropy $T_\perp / T_\parallel > 1$, where T is the ion temperature, and the subscripts $\perp$ and $\parallel$ refer to directions perpendicular and parallel to the background magnetic field $\vec{B}_0$, respectively. The anisotropic distribution of ions can excite the ion cyclotron instability which then leads to enhanced electromagnetic fluctuations. These fluctuations can pitch-angle scatter the ions, constraining the plasma to be marginally unstable. By using the linear Vlasov theory and hybrid computer simulations Gary et al. [1994] deduced a general anisotropy/beta (β) relationship that

$$T_\perp / T_\parallel = 1 + a / \beta_\parallel^{\,b} \quad (1)$$

with a= 0.55 and b= 0.51.

In addition, Gary et al. [1995] also considered the two-component ion distribution consisting of a cool (eV) and a hot (keV) proton components, using observations from the outer magnetosphere. They noted that the anisotropy/beta relation remained valid for the hot protons if their density was relatively small (e.g., ≤ 0.2 of the total [hot plus cool] proton density) and temperature was much higher. The computer simulations indicate that the anisotropy/beta correlation is really an upper bound (UB) on the temperature anisotropy of hot protons which can also be expressed as

$$(T_\perp / T_\parallel)_{UB} = 1 + a_h / \beta_{\parallel h}^{\,b_h}, \quad (2)$$

where the subscript h denotes hot protons.

By using AMPTE/CCE observations, Anderson et al. [1994] and Fuselier et al. [1994] found that a= 0.85, b= 0.48 at $\beta_\parallel$= 0.02-10, and a= 0.83, b= 0.58 at $\beta_\parallel$= 1-50 for the subsolar magnetosheath regions downstream of quasi-perpendicular and quasi-parallel bow shocks, respectively. On the other hand, Phan et al. [1994] found from a statistical study of AMPTE/IRM magnetosheath observations that a= 0.58 and b= 0.53 at $\beta_\parallel$= 0.05-100.

So far, all studies on ion temperature anisotropies in the Earth's magnetosheath were carried out at relatively low-latitudes (<30°) by using AMPTE (except a more recent study by Phan et al. [1996]) observations. Also, in Phan et al. [1994, 1996] the magnetosheath observations were restricted to small distances from the magnetopause. Therefore, more observational evidence, especially at higher latitudes and deeper into the magnetosheath are necessary to examine the universal nature of equations (1) and (2). We have hence performed a study of magnetosheath ion-temperature anisotropies by using plasma observations obtained from the Hawkeye spacecraft. For our examined three magnetosheath passes the average magnetic latitude was 66±6°, and the depth into the magnetosheath reached 5±2 R_E.

It is noted that in many applications plasma parameters such as density, temperature, and beta have been calculated based on the moment method [e.g., Kessel et al., 1989] in either the spacecraft or plasma frame which is deduced from the flow velocity determined also from the moment method. Since the temperature (second-order) anisotropy of ions is not an invariant under coordinate transformations [Daly et al., 1985; Tan et al., 1997], it should be calculated in the non-streaming frame in which their first-order anisotropy is absent. The temperature anisotropy thus determined may be significantly different (even in sign!) from that calculated in either the spacecraft or plasma frame. Therefore, in our examination we will use the new technique developed by Tan et al. [1997] to search for the non-streaming frame of suprathermal ions.

Hawkeye Spacecraft

The NASA Langley Space Flight Center/University of Iowa Hawkeye spacecraft (or Explorer 52) was launched on June 3, 1974 with its initial apogee over the north pole. The spacecraft flew in a polar orbit with an inclination of nearly 90°, an apogee of 20-21 R_E, a perigee of less than 1.7 R_E, and a period of 51.3 hours. It was spin-stabilized and had a rotational period of approximately 11 seconds. The spin axis was pointed in the direction with a right accession of 300° and a declination of 7°. The low energy proton-electron differential energy analyzer (LEPEDEA) was a two-

[1]Space Physics Data Facility, NASA/Goddard Space Flight Center, Greenbelt, Maryland.
[2]Raytheon STX Corporation, Lanham, Maryland.
[3]Institute for Physical Science and Technology, University of Maryland, College Park, Maryland.

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dimensional plasma detector with a field of view that swept out a 30° band about the spin plane. A full two-dimensional energy-angle distribution was obtained every 3.5 minutes. The measured energy range of ions used in this work was between 0.3 keV and 10 keV within 8 logarithmic energy channels. Since there was no ion identification in LEPEDEA, below all observed ions are assumed to be protons. More information on the Hawkeye spacecraft can be found in Gurnett and Frank [1978], and recently in Chen et al. [1997].

Data Analysis

In order for the two-dimensional LEPEDEA sensor to correctly sample ion temperature anisotropies, we require that the background magnetic field is close to the spacecraft spin plane. With θ_B being the angle between the local magnetic field vector and the spacecraft spin axis, the criterion of $|<\theta_B>-90°| < 30°$ is used to select our magnetosheath passes for analysis.

Further, in view of the relatively finite field of view (±15°) of the LEPEDEA sensor it is important to check what magnetosheath ion components are observable. It is known [e.g., Gosling et al., 1989] that downstream of supersonic bow shocks there exist a relatively dense and cool core ion component and a suprathermal ion shell. Because of an inertially fixed spin axis, in each year of Hawkeye operation there were only short periods during which the Sun was nearly in the spacecraft spin plane (i.e., the angle α_s between the solar direction and the spacecraft spin plane is small), so that the collimated core ion component can be observed by the LEPEDEA sensor. On the other hand, the suprathermal shell should be observable by the LEPEDEA all the times.

We will first examine periods with small value of α_s. Since in most cases with $\alpha_s < 15°$ the moment method estimates the bulk flow speed $V_F \geq 300$ kms^{-1}, the technique developed by Tan et al. [1997] can be used to examine all but the low-energy end of Hawkeye observations because of its limitation of $v > V_F$, where v is the ion speed. In cases with an extremely low V_F value ($V_F \leq 100$ kms^{-1}) such as shown in the left panel of Figure 1 the analysis technique is valid even at the lowest measured energy. Here the ion distribution functions are plotted in the non-streaming frame (denoted by an asterisk) so

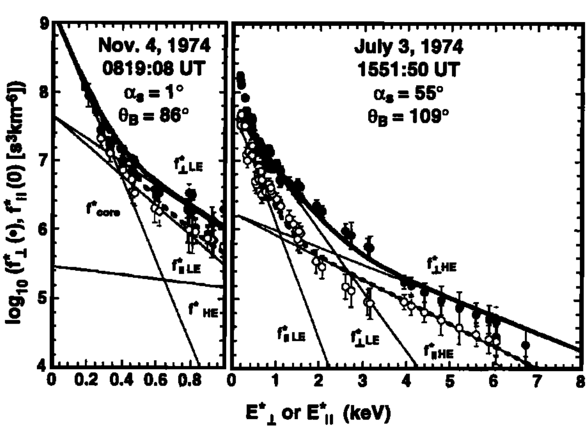

Figure 1. In the non-streaming frame for two sampling time intervals of 3.5 minute length the ion distribution functions $f^*_\perp$ and $f^*_\parallel$ are plotted against the ion energies $E^*_\perp = m_p v^{*2}_\perp / 2$ and $E^*_\parallel = m_p v^{*2}_\parallel / 2$ (m_p is the proton mass), respectively. The low-energy (LE) hot ion component is dominant between 0.3 and 1 keV. The high-energy (HE) hot ion component is significant above 2 keV. The core ion component is only seen below 0.3 keV when α_s was small (the left panel).

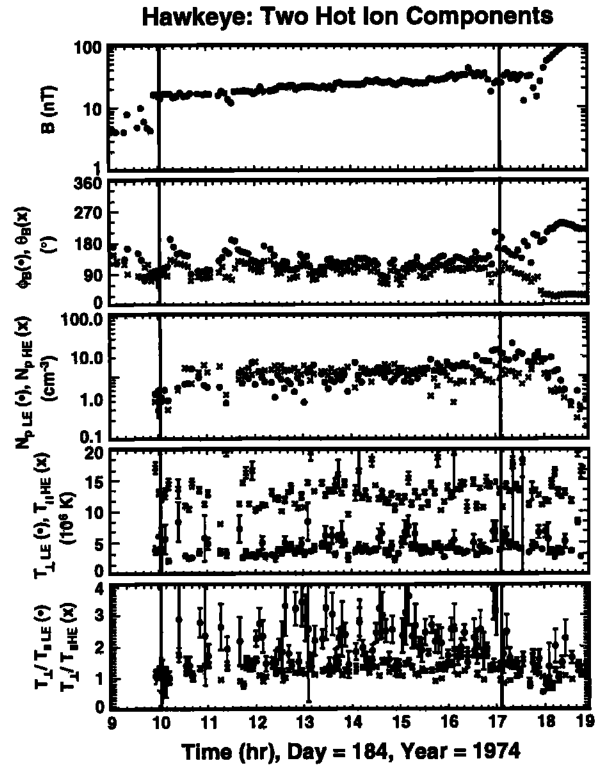

Figure 2. For a typical magnetosheath passage of the Hawkeye spacecraft the time profiles of the magnetic field and plasma parameters including (from top to bottom) B (the magnetic field magnitude), θ_B, ϕ_B (the azimuthal angle of the magnetic field projected into the spacecraft spin plane), N_p, $T_\perp$ and $T_\perp / T_\parallel$ for both LE and HE hot ion components.

that both $f^*_\perp$ and $f^*_\parallel$ are symmetric about the origin. Since the observed total ion distribution cannot be approximated by a single bi-Maxwellian distribution, we will use the following general procedure to separate and analyze different ion components. First, the f^* data in E^* = 2-8 keV are fitted by a bi-Maxwellian distribution in order to find the high-energy (HE) hot ion component f^*_{HE}. Then the $f^* - f^*_{HE}$ data in E^* = 0.3-1 keV are fitted by another bi-Maxwellian distribution in order to find the low-energy (LE) hot ion component f^*_{LE}. Finally, the $f^* - f^*_{HE} - f^*_{LE}$ data below E^* = 0.3 keV are used to find the core ion distribution f^*_{core}. In the left panel of Figure 1 no statistically significant temperature anisotropy is found for the core component. Therefore, only a mean core temperature T_{core} = (8±1)x10^5 K (i.e., 70±10 eV) is given. This T_{core} value is lower than both the $T_{\perp LE}$ [(3.0±0.2)x10^6 K or 260±20 eV] and $T_{\parallel LE}$ [(2.3±0.1)x10^6 K or 200±10 eV] of the LE component.

When α_s = 50-60° and $V_F \approx 100$ kms^{-1}, the narrow-aperture LEPEDEA sensor could not detect the collimated core ion component. This is the case shown in the right panel of Figure 1 where only a few data points appear at E^* < 0.3 keV. However, both LE and HE hot ion components are fully observable. It is seen that both hot ion components have $T_\perp > T_\parallel$ in general. In addition, the intercepts of $\log(f^*_{LE})$ (7.7±0.1) and $\log(f^*_{HE})$ (6.2±0.1) are close to that obtained in the small-α_s case (7.7±0.1 and 5.5±0.1, respectively) described above, indicating that both hot ion components have wide angular distributions. Thus by making a constant $f^*_\perp$ assumption on a plane perpendicular to $\vec{B}_0$, we can accomplish a three-dimensional density calculation in order to obtain the hot proton densities N_{pj}, and the plasma $\beta_{\parallel j}$ [Gary et al., 1995],

$$\beta_{\parallel j} = 8\pi N_{pj} T_{\parallel j} / B_0^2 \qquad (3)$$

with j = "LE" or "HE".

The thick lines in Figure 1 are the sum of all fitted distributions. It is remarkable that a good agreement between observations and fits is obtained for $E^* = 1$-2 keV, though the data in this energy range have not been used for fitting. For a typical magnetosheath passage the magnetic field and plasma parameters deduced from the Hawkeye observations are shown in Figure 2. The error bars in temperatures are determined by using the bootstrap method [Diaconis and Efron, 1983].

Observations

1. July 3, 1974 (Day of Year [Doy] = 184) 1001-1708 UT

During this magnetosheath passage the Hawkeye spacecraft was located downstream of a quasi-perpendicular bow-shock with a magnetic latitude (MLAT) of 64-67°, magnetic local time (MLT) of 13-15 hours, α_s = 55° and $<\theta_B>$-90°= 10±17°. The upstream solar wind speed V_{sw} and alpha-to-proton ratio $(\alpha / p)_{sw}$ were 440-480 kms^{-1} and ~0.04, respectively. The variations of $T_\perp / T_\parallel - 1$ with $\beta_{\parallel j}$ in the non-streaming frame are shown in Figure 3 where both LE and HE components satisfying the same variation tendency. By applying the least squares fit we obtain a = 0.61±0.01 and b= 0.57±0.02 with a linear correlation coefficient r = -0.78 (the probability that the two parameters are not correlated is P_c = 6.8x10^{-24}) for equation (1). Also, in Figure 3 the data points above the one-σ limit of the least-squares fitting result are used to determine the upper bound of observed data. We obtain a_h= 1.5±0.1 and b_h= 0.51±0.06 for equation (2).

2. July 31, 1974 (Doy = 212) 0511-1215 UT

The Hawkeye spacecraft was located in the magnetosheath downstream of a quasi-perpendicular bow-shock with MLAT = 60-61°, MLT = 11-12 hours, α_s = 62° and $<\theta_B>$-90° = -10±20°. Also, the upstream solar wind V_{sw} and $(\alpha / p)_{sw}$ were 400-430 kms^{-1} and 0.08-0.12, respectively. In comparison to equation (1) we have a = 0.61±0.02 , b = 0.58±0.03, r = -0.72 (P_c = 4.0x10^{-15}) (see Figure 4). Further, we have a_h = 1.8±0.3 , b_h = 0.64±0.08 for equation (2).

3. Aug. 4, 1974 (Doy = 216) 1124-1805 UT

The Hawkeye spacecraft was located in the magnetosheath downstream of a mixed with time quasi-perpendicular and quasi-parallel bow shocks, with MLAT = 67-76°, MLT = 10-13 hours, α_s = 62°, and $<\theta_B>$- 90° = 13±20°. The upstream solar wind V_{sw} and $(\alpha / p)_{sw}$ were 560-660 kms^{-1} and ~0.04, respectively. We have a = 0.60±0.02, b = 0.46±0.03, r = -0.62 (P_c = 1.2x10^{-13}) for equation (1) (see Figure 5). Also, we have a_h = 2.0±0.1, b_h = 0.4±0.2 for equation (2). It is unclear if the observed smaller b value is correlated with the different bow shock characteristics.

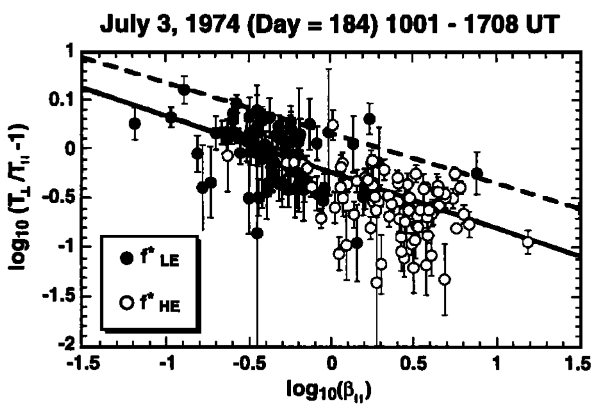

Figure 3. During the Hawkeye magnetosheath passage on July 3, 1974 (Doy = 184) at 1001-1708 UT the $T_\perp / T_\parallel - 1$ data are plotted against $\beta_\parallel$. The solid and dashed lines express the average variation tendency and the upper bound of observed data, respectively.

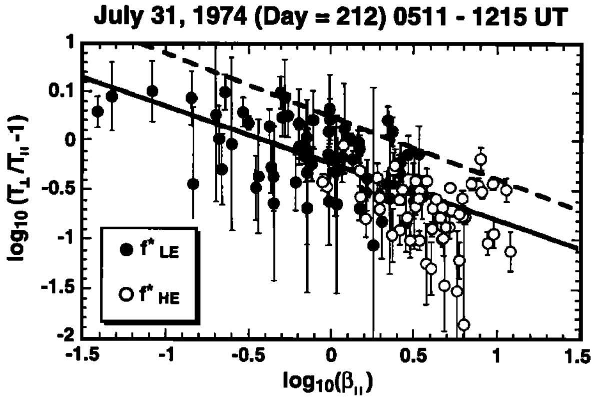

Figure 4. Same as Figure 3 during the Hawkeye magnetosheath passage on July 31, 1974 (Doy = 212) at 0511-1215 UT.

Summary and Discussion

From Hawkeye observations we have selected and analyzed in detail three magnetosheath passes during which the magnetic field was close to the spacecraft spin plane. Two separate hot ion components with different plasma characteristics are needed to fit the total ion distribution in the energy range of 0.3-8 keV. Both hot ion components, however, tend to obey the same anisotropy/beta correlation. This is true even under different solar wind speed and composition. By comparing to equation (1) our results can be expressed as a= 0.61±0.01 and b= 0.55±0.02 in the domain of $\beta_\parallel$= 0.1-10, relatively close to the theoretical predictions of Gary et al. [1994]. Also, by comparing to equation (2) we have a_h = 1.8±0.1, b_h = 0.55±0.05 for the upper bound of magnetosheath ions. The correlation parameters determined by us will have important implications for modeling anisotropic plasmas in the Earth's magnetosheath [e.g., Denton et al., 1995].

Our results are somewhat different from the AMPTE/CCE observations by the deduced a value. It is noted that the ion

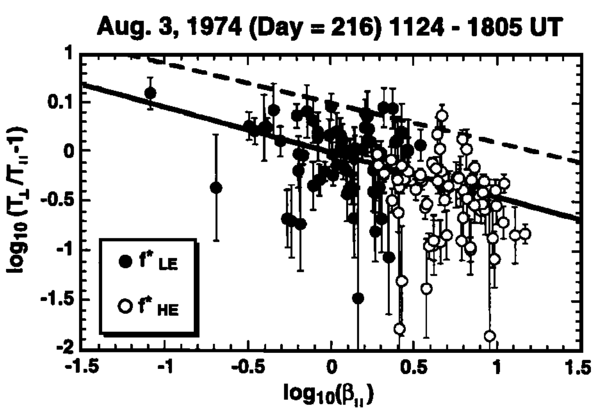

Figure 5. Same as Figure 3 during the Hawkeye magnetosheath passage on Aug. 4, 1974 (Doy = 216) at 1124-1805 UT.

energy range (0-150 keV/e) sampled by the AMPTE/CCE spacecraft was much wider than that in Hawkeye observations (0.3-8 keV/e). Since two hot ion components are necessary to fit the Hawkeye observations, there could be more hot ion components to cover the entire AMPTE/CCE energy range. In previous AMPTE/CCE analyses, however, only the average plasma distribution were used. It is possible that the procedure to estimate the average plasma distribution would introduce additional errors. We have tested this possibility by using the Hawkeye data. A weighted average procedure with the weight being proportional to the partial hot ion density has been applied to the observations shown in Figure 3. Thus the correlation parameters become a= 0.81±0.03, b= 0.38±0.05, r = -0.56 (P_c = 4.6x10^{-13}), being very close to the results of the AMPTE/CCE observations [Anderson et al., 1994; Fusilier et al., 1994].

It should be noted that there may be alternative interpretation of our two hot-ion component observations. Obviously, our analysis results cannot be understood in terms of the well-known "cool core + hot shell" ion distribution model. These results are also not consistent with essentially all other existing observations in the Earth's magnetosheath. In particular, the physics of the low-energy (LE) hot ion component requires further study. It cannot be made of specularly reflected ions in the downstream region because it is too low in temperature. Also, it cannot simply be the core ion component because it is too low in density.

There may be a possibility that the LE component is actually the core component with a significantly underestimated density (N_{core}), but an approximately correct temperature (T_{core}). Since the $N_{p\,HE}/(N_{p\,HE}+N_{core})$ ratio should not exceed 0.2 in order to match the Rankine-Hugoniot equation at the shock [Gosling et al. 1989], we expect that $N_{core}/N_{p\,HE} \geq 4$. Because that $N_{p\,LE}/N_{p\,HE} \approx 1$ from Figure 2, we should have $N_{core}/N_{p\,LE} \geq 4$, and hence $\beta_{\parallel core}/\beta_{\parallel LE} \geq 4$. It is interesting to examine the effect of an adjusted $\beta_{\parallel core} = 5\beta_{\parallel LE}$ on the anisotropy/beta relation. By shifting the LE data (solid dots) rightward by a factor of 5 but keeping the HE data (open cycles) stationary, we have carried out a new fitting for the composite core + HE components. For the observations shown in Figure 3 the new fitting parameters become a= 0.75±0.01 and b= 0.51±0.02, only slightly different from that previously given for the composite LE + HE components.

If the LE component is not physical there would be other puzzles in understanding our observations. First, it would be very difficult to imagine why the collimated core ions can be detected by the narrow-aperture LEPEDEA sensor when α_c > 50°. Second, the LE component is observed to have a finite temperature anisotropy which obeys the same anisotropy/beta relation as the HE component does. Third, our observed T_{LE} is at least one order of magnitude higher than the core temperature predicted by Gary et al. [1995]. It is therefore possible that the LE component is originated from the core component, but energized by local stochastic acceleration processes in the Earth's magnetosheath.

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L. C. Tan, S. F. Fung, R. L. Kessel, S.-H., Chen , and J. L. Green, NASA/Goddard Space Flight Center, Code 632, Greenbelt, MD 20771. (email: ltan@nssdca.gsfc.nasa.gov)

T. E. Eastman, Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742.

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