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Introduction to special section on Entropy Properties and Constraints Related to Space Plasma Transport

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[1] Studies of entropy provide physical insight into space plasma transport, intermittency, turbulence, and information flow in the heliosphere and magnetosphere. Nonconservation of entropy in space plasmas can result from magnetic reconfiguration as well as nonadiabatic processes such as turbulent transport, thermal energy transport due to nonadiabatic particle drifts, energizations, mixing of two or more plasma populations, etc. Examination of entropy properties may provide insight into processes leading to plasma entry across the magnetopause on the dayside and nightside and processes leading to the tail "pressure balance inconsistency" and may provide constraints on which processes are most important in the dynamical transition related to substorms. Moreover, entropy-based information theory can be used to characterize the dynamics of the magnetosphere. This paper summarizes the special section that highlights state-of-the-art theoretical and observational studies of entropy, the pressure balance inconsistency, and other entropy-related issues such as those mentioned above.

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1. Basic Entropy Properties

[2] Entropy is a fundamental thermodynamical property that describes system organization. In its most basic form, entropy is a measure of the number of states available to a system. In the study of classical thermodynamics, it is often helpful to consider particles in a box and the entropy changes when one wall moves in and out, e.g., a piston. Although in space there is no box or piston, one may consider a magnetic flux tube as analogous to a box with the particle mirror points as the walls. Then, for example, in the Earth's magnetotail, as a flux tube or magnetic field line convects earthward, the flux tube shortens and the volume diminishes, which can be considered as analogous to the piston wall moving inward, reducing the volume of the box. Entropy conservation would imply constraints on the final pressure, density, and temperature of plasma in the flux tube given the initial conditions at an originating location.

[3] Entropy is conserved when the plasma response is adiabatic. Several papers in this special section discuss two types of entropies: specific entropy (s) and total entropy (S) (the symbols used to denote these two entropies unfortunately may differ across the papers). *Birn et al.* [2009] provide a formalism for the derivation of these entropies. The entropy per unit mass in an ideal, isotropic plasma is $\sigma = C \log(p^{1/\gamma}/\rho)$, where p is the plasma pressure, ρ is mass density, γ is the polytropic index, and C is a constant. For an entropy-conserving process, $s = p/\rho^{\gamma}$ is equivalently conserved and is commonly referred to as the specific or local entropy. In the ideal magnetohydrodynamnic (MHD) description, the pressure response is typically prescribed by an adiabatic equation of state such that $\mathrm{d}s/\mathrm{d}t = 0$. The specific entropy, s or σ, should be rigorously conserved in an ideal MHD fluid element and is an intensive variable in that it does not depend on system size.

[4] In contrast, the total entropy of a flux tube of unit magnetic flux is obtained by integrating the entropy per unit volume, $\rho\sigma$, over the flux tube volume (V) [*Birn et al.*, 2009]. Equivalently, the pressure equation implies an integral constraint on the total mass content of a flux tube, $M = \int \rho\, \mathrm{d}l/B$ which is proportional to $S = \int p^{1/\gamma}\, \mathrm{d}l/B$ m, where $\mathrm{d}l$ is infinitesimal length along B and B is magnetic field line. In the case that the plasma is isotropic, as commonly observed in the plasma sheet [e.g., *Wing and Johnson*, 2009; *Johnson and Wing*, 2009], and in equilibrium, the pressure is constant along the field line, then $S = p^{1/\gamma}V$. Steady convection or slow/adiabatic changes through a sequence of equilibria will conserve $S = p^{1/\gamma}V$ or, equivalently, pV^{γ} on a flux tube. Although not precisely the entropy of the flux tube, this quantity S is entropy-like in nature [*Birn et al.*, 2009], and we refer to it as the total or global entropy; however, S is also sometimes also called the specific entropy in that it is a measure of the entropy per unit flux. Because S is proportional to the mass/volume of the flux tube, it is in an extensive variable.

[5] Understanding entropy can also be useful for understanding how a system organizes and whether it is stable. For example, entropy conservation places constraints on regions

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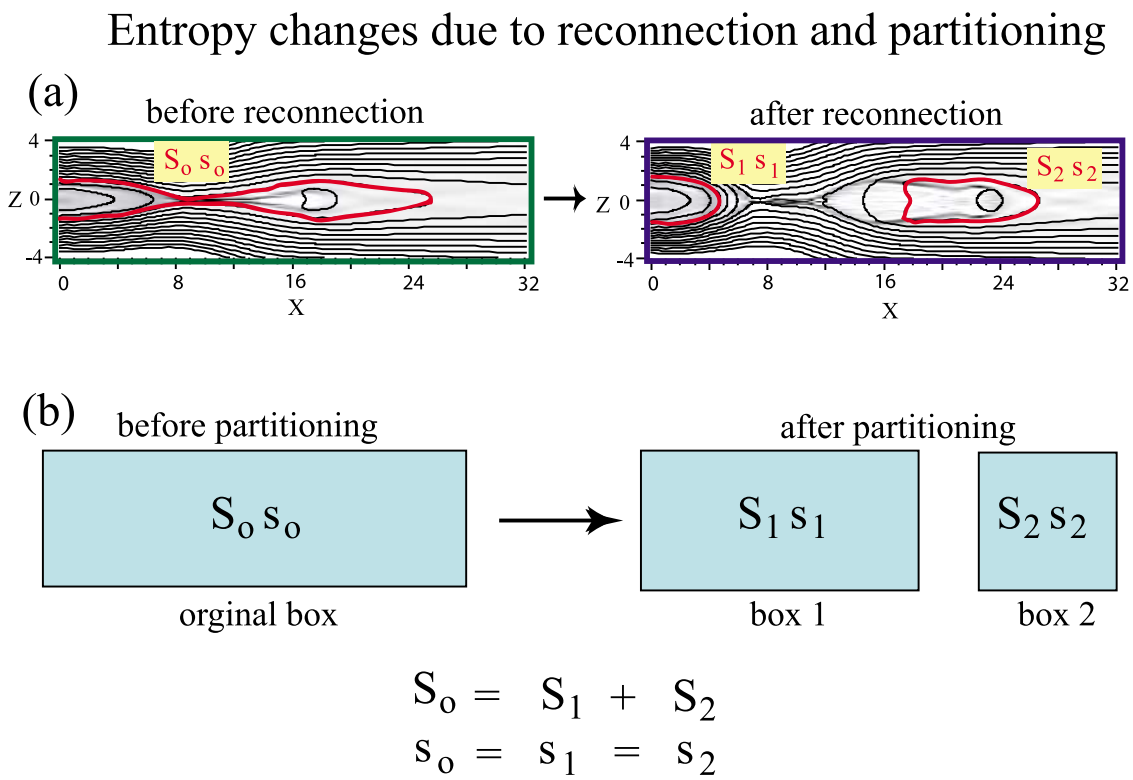

Figure 1. Entropy changes in (a) reconnection and (b) partitioning particles in a box. In Figure 1a [from *Birn et al.*, 2006], (left) before reconnection, the red magnetic field line has total and specific entropies, S_o and s_o, respectively, where S is total entropy (extensive variable), s is specific entropy (intensive variable), and the subscript o denotes original or initial. (right) After reconnection, the original red field line splits into two: (1) newly closed field line convecting earthward with entropies S_1 and s_1 and (2) plasmoid convecting tailward with entropies S_2 and s_2. This is analogous to partitioning particles in a box on the left into two boxes, box 1 and box 2 in Figure 1b (right). The original box has total and specific entropies, S_o and s_o, respectively, and the corresponding entropies for boxes 1 and 2 are S_1, s_1, S_2, and s_2, respectively, where the subscripts 1 and 2 denote box 1 and box 2, respectively. In both Figures 1a and 1b, $S_o = S_1 + S_2$, but $s_o = s_1 = s_2$.

that can be accessed by various plasma populations. When plasma of solar wind origin enters the magnetosphere, how and where it enters places significant constraints on how the plasma sheet forms and where captured plasma can access. When there are changes in magnetospheric populations through plasma entry, ionospheric outflows, or through topological changes, entropy serves as a governing principle to understand how the system would evolve. For example, a reduction in entropy can lead to earthward plasma transport by interchange instability to reach a more stable magnetospheric configuration as discussed by *Birn et al.* [2009] in the context of bursty bulk flows and *Johnson and Wing* [2009] in the context of plasma sheet filling for northward IMF.

[6] Slow changes in the magnetospheric state may also be governed by a constraint of entropy conservation, which may be used to examine evolution of the substorm growth phase leading eventually to an unstable magnetospheric configuration. Moreover, it may also be possible to exploit entropy conservation as a global constraint to link magnetospheric states with different topology (e.g., stretched tail versus tail + plasmoid) and estimate the amount of energy that would be released by the reconfiguration without knowing the full details of the dynamics of the reconfiguration or the dissipation mechanism [*Zaharia and Birn*, 2007].

[7] More details of the entropy formalism are given by *Wolf et al.* [2009], *Birn et al.* [2009], and *Kaufmann and Paterson* [2009] in this special section.

2. Entropy Changes due to Magnetic Field Topological Change

[8] It is important to realize that a process that reduces S may not necessarily reduce s because of the intensive/extensive nature of the variables and vice versa. For example, *Birn et al.* [2009] and *Wing and Johnson* [2009] discuss a process that reduces S significantly but leaves s relatively unchanged. These authors discuss entropy changes in magnetic field reconnection process in which a closed field line splits into two parts: (1) a newly closed field line albeit with reduced length and (2) a tailward convecting plasmoid. The newly closed field line has much lower S and V compared to those in the original flux tube, while the remainder resides in the newly formed plasmoid. If the reconnection only changes the properties of the plasma in a small dissipation region ($\mathbf{j} \cdot \mathbf{E}'$, where $\mathbf{E}' = \mathbf{E} + \mathbf{v} \times \mathbf{B}$) and there is no slippage, then s remains more or less unchanged before or after reconnection. Moreover, the sum of S of the plasmoid and S of the newly closed field line should roughly equal to S of

the original field line. Using the particle in the box analogy, this process is similar to partitioning an original box into two parts, boxes 1 and 2, as depicted in Figure 1. If S_o and s_o are the total and specific entropies of the original box, respectively, then, after partitioning, $S_1 + S_2 = S_o$, but $s_1 = s_2 = s_o$, where the subscripts 1 and 2 refer to the boxes 1 and 2, respectively.

[9] *Birn et al.* [2009] demonstrate that the above properties seem to hold not just in MHD but also in their particle-in-cell (PIC) simulations, despite the fact that MHD and PIC simulations have different dissipation mechanisms and PIC simulations have waves that are not found in MHD. In their simulations, after the reconnection, the newly closed field line, which has smaller entropy and flux tube compared to the surrounding flux tubes, can initiate the unstable growth of ballooning and interchange instability, resulting in the earthward propagation of the flux tube. The earthward propagation of the localized depleted flux tube volume and entropy or bubbles was suggested by *Pontius and Wolf* [1990], but an interesting finding by *Birn et al.* [2009] is that the more depleted the flux tube, the closer to Earth it can penetrate.

3. Entropy Changes due to Plasma Mixing

[10] Entropy changes can result from mixing of plasmas having different entropy. Thus, entropy can constrain and differentiate the processes at the boundary of two plasma regimes. An example is presented by *Johnson and Wing* [2009], who report an investigation of s changes in the plasma sheet due to solar wind/magnetosheath ion entry during periods of northward interplanetary magnetic field (IMF). It appears that colder solar wind entry lowers the temperatures and s at both dawn and dusk flanks of the plasma sheet. However, when considered separately (from the nominal hot plasma sheet component), the entropy of the cold, dense plasma sheet material is higher than local magnetosheath entropy by a factor of 5–20 or more. Three mechanisms are commonly invoked for magnetosheath plasma entry into the plasma sheet during northward IMF, namely, cusp reconnection [e.g., *Song and Russell*, 1992], Kelvin-Helmholtz instability (KHI) [e.g., *Otto and Fairfield*, 2000], and kinetic Alfvén waves (KAW) [e.g., *Johnson and Cheng*, 1997]. *Johnson and Wing* [2009] investigated whether these three mechanisms can adequately account for the observed increase of s that results from the entry process in the cold magnetosheath population. Their study notes that cusp reconnection may not account for the observed increase of s without heating or plasma loss from field lines (such as from diffusion). However, KAWs can effectively heat the plasma and hence, it can operate either by itself or in conjunction with other entry mechanisms, e.g., cusp reconnection or KHI, to increase s. In contrast to cusp reconnection, KHI may provide a more significant increase in the local entropy of the cold population as it expands to fill closed magnetospheric flux tubes. Another interesting finding is that s of the cold component (magnetosheath) ions appears to increase by a factor of 5 from the flanks to the center (midnight meridian) of the plasma sheet. The formation of a plasma depletion layer for northward IMF conditions may lead to conditions favorable for interchange instability to operate on the flanks leading to plasma transport into the center of the plasma sheet, but the entropy increase could also result from nonideal processes, such as eddy turbulence in the plasma sheet [*Borovsky et al.*, 1998].

4. Pressure Balance Inconsistency

[11] An influential paper on total entropy (S) violation, which was coined "pressure balance inconsistency," was published about thirty years ago [*Erickson and Wolf*, 1980]. As an aside, *Wolf et al.* [2009] notes that "entropy inconsistency" would have been a more appropriate term. Although progress has been made in the intervening years, the problem posed by *Erickson and Wolf* [1980] still remains relevant today. Using completely different approaches from one another, several papers in this special section explore some aspects of pressure balance inconsistency [*Wolf et al.*, 2009; *Wing and Johnson*, 2009; *Kaufmann and Paterson*, 2009; *Wang et al.*, 2009; *Lyons et al.*, 2009].

[12] *Wolf et al.* [2009] consider the consequences of the first and second adiabatic invariant (μ and J, respectively) conservation on the pressure balance inconsistency. Their calculations show that μ and J conservation leads to higher average particle energization than if there were strong pitch angle scattering, i.e., isotropic plasma sheet. In other words, if entropy were conserved, then fully adiabatic drifting particles must gain more energy than in the isotropic case, worsening the pressure balance inconsistency.

[13] *Wolf et al.* [2009] consider two nonmutually exclusive mechanisms for resolving pressure balance inconsistency: (1) gradient/curvature drifts and (2) plasma sheet bubbles, which are flux tubes with significantly lower S than their neighbors [*Pontius and Wolf*, 1990], as discussed in section 2. These bubbles would move earthward until their S equals that of their neighbors.

[14] The results presented by *Wolf et al.* [2009] show that given $\kappa^2 = R_c/a_c = 4$ [*Delcourt et al.*, 1996], where R_c is the radius of curvature of the field line and a_c is the maximum Larmor radius of the particle, the vast majority of ions that contribute to plasma sheet pressure should be isotropic beyond 8–12 R_E. This isotropic or nearly isotropic property of the plasma sheet, which has been overwhelmingly confirmed [e.g., *Kistler et al.*, 1992; *Spence et al.*, 1989; *Huang and Frank*, 1994; *Wing and Newell*, 1998] is exploited in the analysis technique used by *Wing and Johnson* [2009] and *Johnson and Wing* [2009].

[15] *Wing and Johnson* [2009] show that the growth phase S profile exhibits pressure balance inconsistency. Interestingly, the losses of S and the content of the flux tube volume (N) are moderate in the midtail region, but increase steeply at the inner edge of the plasma sheet. The s profile shows a clear dawn-dusk heat flux at the inner edge of the plasma sheet. Taken together, the S and s profiles suggest that curvature/gradient drifts, which become more dominant closer to Earth and which can cause particles to leave the flux tube and hence N losses, can play a significant role in the pressure balance inconsistency.

[16] *Wang et al.* [2009] also find the pressure balance inconsistency in their observations and attribute it to the magnetic drift. Their study obtains the S and N observational profiles for different convection strengths and AE levels. These profiles show S and N decrease significantly earthward, consistent with *Wing and Johnson* [2009]. *Wang et al.*

[2009] consider the ideal MHD and Rice convection Model (RCM) transport physics in evaluating their S and N profiles. In ideal MHD, the plasma moves with electric drift only, whereas in RCM, the plasma moves with electric and magnetic drifts. The earthward reduction of S along the electric drift path is inconsistent with ideal MHD. For the RCM model, they consider the drift path for particles with a given energy k. If the particle motion is strictly guided by electric and magnetic field only, then along the drift path $dS_k/dt = 0$ and $dN_k/dt = 0$, where $S_k = p_k V^{5/3}$, $N_k = n_k V$, and n is number density. This condition appears to roughly describe the observations for higher-energy particles, when magnetic drift plays a significant role in transport (slow-flow). The magnetic drift results in a significant earthward decrease of S. The transport from the flanks to the center of the plasma sheet does not fit the description of ideal MHD nor RCM transport and *Wang et al.* [2009] suggest that diffusion may play a role. This is, in fact, a main topic in the paper by *Johnson and Wing* [2009], as discussed in section 4, and would be a significant effect for diffusion coefficients in the range of $D \sim 10^{10}$ to 10^{11} m^2/s consistent with observational estimates from *Borovsky et al.* [1998] for eddy diffusion and *Chaston et al.* [2008, 2009] for kinetic Alfven wave diffusion.

[17] *Kaufmann and Paterson* [2009] also find pressure balance inconsistency and the association of the gradient of S to the gradient of N [cf. *Wing and Johnson*, 2009; *Wang et al.*, 2009], but their study uses a completely different approach and introduces the Boltzman H function in the entropy analysis of Geotail data. *Kaufmann and Paterson* [2009] show rather interestingly that a consequence of the nearly constant ratio of T_i/T_e is that changes in the electron and ion entropy per particle are similar. Assuming that the entropy change is reversible ($dS = dQ/T$, where dS and dQ are the change of entropy and heat absorbed, respectively), the nearly constant ratio of $T_i/T_e \sim 7$ would imply that ions absorb about 7 times as much heat as electrons. Therefore, the heat sources and sinks needed to explain the entropy change can almost all be associated with the ions. *Kaufmann and Paterson* [2009] also report that T_i/T_e ratio slightly decreases earthward, implying that electron temperature and entropy per particle increases slightly faster than that of ions when moving earthward.

[18] *Kaufmann and Paterson* [2009] also examine the reasonableness of the Maxwellian assumption in specific entropy calculation and suggest that $p/n^{5/3}$ significantly overestimates ion s and that this overestimate is larger at $X = -28\ R_E$ than at $X = -10\ R_E$. This suggests that as the ions convect earthward, they approach equilibrium, which the authors attribute to pitch angle scattering and isotropization of the ion distribution.

[19] *Lyons et al.* [2009] discuss the relationship between changes in flux tube particle content and field-aligned currents and show how a pressure gradient in the direction of the magnetic drift leads to a divergence of particle flux, or equivalently, perpendicular current. The divergence in perpendicular current must be balanced by a field-aligned current. *Lyons et al.* [2009] insightfully argue that the existence of the region 2 current system can also be viewed as a signature of the violation of entropy conservation resulting from the magnetic drift that reduces S earthward and leads to the development of an azimuthal pressure gradient as shown in RCM simulations under enhanced convection. Thus, their study ties for the first time the pressure balance inconsistency to the region 2 field-aligned currents. Their study also suggests that earthward reduction of S within the vicinity of the Harang reversal may play an important role in the development of an unstable magnetospheric configuration and substorm.

5. Entropy in Information Theory

[20] Entropy can also provide the basis for information theory, which can be used to analyze the dynamics of a system. An example of such application in magnetosphere is provided by *Balasis et al.* [2009]. Their study uses several entropy measures (Tsallis entropy [*Tsallis*, 1998], approximate entropy [*Pincus*, 1991], and Hurst exponent [*Turcotte*, 1997]) to analyze Dst during storm and nonstorm ("normal") times. Moreover, Hurst exponent can be used to characterize the persistence of a system, e.g., whether the trend of the fluctuations will continue ("persistent") or differ ("antipersistent") in the next time interval. *Balasis et al.* [2009] find that the nonstorm intervals have higher entropies and lower persistence than storm intervals. Their paper concludes that Tsallis entropy, which is based on a nonextensive statistical theory, rather than Boltzmann-Gibbs statistical mechanics, can better describe the dynamics of the magnetosphere because it is a nonequilibrium system with large variabilities.

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