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Ion Cyclotron Damping in the Solar Corona and Solar Wind

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Abstract. The solar corona is the hot, ionized outer atmosphere of the Sun. Coronal plasma expands into interplanetary space as a supersonic bulk outflow known as the solar wind. This tenuous and unbounded medium is a unique laboratory for the study of kinetic theory in a nearly collisionless plasma, as well as magnetohydrodynamic waves, shocks, and jets. Particle velocity distributions in the solar wind have been probed directly by spacecraft (outside the orbit of Mercury), and indirectly by ultraviolet spectroscopy (close to the Sun). Fluctuations in the plasma properties and in electromagnetic fields have been measured on time scales ranging from seconds to years. Despite more than a half-century of study, though, the basic physical processes responsible for heating the million-degree corona and accelerating the solar wind past the Sun's escape velocity are still not known with certainty. Understanding the basic physics of the solar wind is necessary to predict the Sun's impact on the Earth's climate and local space environment.

This presentation will review the kinetic origins of several physical processes that are currently believed to be important in depositing energy and momentum in coronal particle velocity distributions. Because ions in the solar wind are heated and accelerated more than would be expected in either thermodynamic equilibrium or via a mass-proportional process, an ion cyclotron resonance has been suggested as a likely mechanism. Other evidence for gyroresonant wave dissipation in the corona will be presented, and possible generation mechanisms for the (as yet unobserved) high-frequency cyclotron waves will be reviewed. The mean state of the coronal and heliospheric plasma is intimately coupled with kinetic fluctuations about that mean, and theories of turbulence, wave dissipation, and instabilities must continue to be developed along with steady state descriptions of the solar wind.

INTRODUCTION

Most stars eject matter from their atmospheres and fill a surrounding volume with hot, low-density plasma. In the case of the Sun, indirect evidence for this phenomenon has been available for millennia. When primitive peoples saw the crown-like solar corona during a total eclipse, and shimmering aurorae in the northern and southern skies, they were viewing the beginning and end points of the solar wind flow that intercepts the Earth. The first scientific understanding of the solar wind came at the beginning of the 20th century from three unrelated directions: (a) observed correlations between sunspot activity, geomagnetic storms, and aurorae, (b) the presence of coronal plasma with temperatures exceeding 10^6 K, inferred from eclipse spectroscopy, and (c) observations of gas in the tails of comets being accelerated rapidly away from the Sun [1,2,3]. In 1958, Eugene Parker [4] synthesized these empirical clues into a theoretical model of a steady-state fluid flow. Parker's key insight was that high temperatures in the corona can provide enough energy per particle to produce a natural transition from a subsonic (bound, negative total energy) state near the Sun to a supersonic (outflowing, positive total energy) state in interplanetary space. The existence of a continuous solar wind was verified by the *Mariner 2* probe, sent to Venus in 1962, which detected alternating dense, low-speed (300–500 km s^{-1}) streams and tenuous, high-speed (500–800 km s^{-1}) streams [5]. This paper reviews the physics of the high-speed solar wind, which represents the most structure-free "ambient" state of the plasma [6,7].

Astronomers studying the solar corona are at a double disadvantage compared to most laboratory plasma physicists. First, we must deal with the Sun as it is and cannot control our experiments. Second, we are usually either very far from the experiment (in the case of photon measurements of the corona), or can only sample a limited one-dimensional trajectory through the plasma (in the case of deep-space probes). Despite these limitations, though, solar and space physicists have assembled a large, multi-decade set of particle and field measurements, from the surface of the Sun to past the orbit of Pluto. Theoretical models of how the solar corona is heated and how the solar wind is accelerated depend on the constraints offered by these measurements.

There are several important reasons for studying the Sun and its surrounding plasma. The corona and solar wind exhibit a wide range of densities—between 10^{10} and 10^{-4} particles per cm^3—that bridges the gap between strongly collisional and strongly collisionless conditions. Basic kinetic and magnetohydrodynamic (MHD) processes such as gyroresonant wave heating, turbulent cascade, shock acceleration, and magnetic reconnection have been detected in the solar wind, and direct comparisons with laboratory experiments have been fruitful [8]. On the more practical side, an understanding of how the solar wind is produced is a necessary precursor to being able to predict the Sun's long-term effects on the Earth's local space environment. When the solar wind impacts the Earth's magnetosphere, it can interrupt communications, threaten satellites and the safety of orbiting astronauts, and disrupt ground-based power grids [9]. Variations in the high-speed component of the solar wind (the component thought to be energized by ion cyclotron waves) have also been shown to have an effect on the Earth's climate [10].

OBSERVATIONS

The outer solar atmosphere contains several distinct layers with qualitatively different properties. The relatively placid *photosphere* ($T \approx 6,000$ K) marks the boundary between diffusion and free escape of visible photons. Above the photosphere, the *chromosphere* is a thin layer heated by acoustic waves and shocks ($T \approx$ 20,000 K). A rapid transition to the hot *corona* ($T \gtrsim 10^6$ K) occurs approximately 0.003 solar radii ($R_\odot$) above the photosphere. The base of the corona is a continually replenished ensemble of closed magnetic loops and open flux tubes, but above a height of $\sim$0.1 $R_\odot$ the open field lines begin to dominate (see Figure 1). At the minimum of the 11-year sunspot cycle, the large-scale magnetic field is predominantly dipolar, with high-speed wind emerging from polar *coronal hole* regions and low-speed wind emerging from bright equatorial *streamer* complexes. The plasma β (i.e., the ratio of gas to magnetic pressure) is much less than 1 in coronal holes at heights less than $\sim$5 $R_\odot$, and is of order 1 in streamers. Further from the Sun, β exceeds 1 everywhere and the gas pressure of the wind stretches

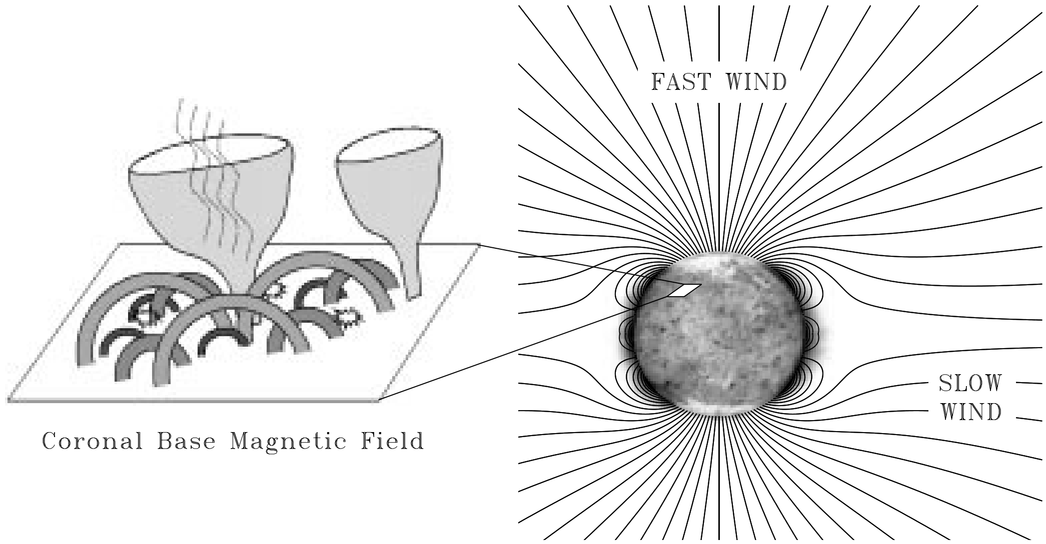

FIGURE 1. Schematic view of the solar magnetic field at the minimum of the 11-year sunspot cycle. The stochastic distribution of small-scale loops and open flux tubes at the base [11] gives way to a more ordered set of field lines in the extended corona [12]. The ultraviolet image of the solar disk (dark colors represent brighter regions) was taken by the EIT instrument on the *SOHO* spacecraft [13].

out the field lines into interplanetary space.

The two most useful means of measuring the properties of solar wind plasma have been *in situ* spacecraft detection and the remote sensing of coronal photons. The primary results of such measurements are summarized below. Other diagnostic techniques that cannot be discussed in detail in this brief review are the scintillation of radio waves passing through the corona [14], the analysis of backscattered solar radiation by interstellar atoms [15], and using comets as probes of the solar wind energy budget [16].

Spacecraft have measured particle velocity distribution functions and electromagnetic fields as close to the Sun as 60 $R_\odot$ (*Helios 1* and *2*), and as far as 12,000 $R_\odot$ (*Voyager 2*). Departures from Maxwellian velocity distributions have been used as sensitive constraints on the kinetic physics on microscopic scales. Electron distributions are isotropic at low energies, but contain magnetic field-aligned beams at high energies that seem to be the collisionless, adiabatically focused remnants of hotter plasma near the Sun [6]. Proton distributions are isotropic far from the Sun, but at distances closer than about 100 $R_\odot$ they exhibit higher temperatures perpendicular to the field than in the parallel direction. The proton magnetic moment (proportional to $T_\perp/B$) is not conserved in this region, indicating perpendicular energy deposition [17]. Ions of a half dozen abundant elements have been measured by various spacecraft, and in the high-speed component of the wind they tend to flow *faster* than the bulk proton/electron wind and have temperatures that *exceed* the mass-proportionality expected for equal thermal speeds; i.e., $(T_i/T_j) \gtrsim (m_i/m_j)$, for $m_i > m_j$ [18].

In situ instruments have also measured fluctuations in magnetic field strength, velocity, and density on time scales ranging from 0.1 second to months and years. Both propagating waves (mainly Alfvénic in nature) and nonpropagating, pressure-balanced structures advecting with the wind are observed. Nonlinear interactions between different oscillation modes create strong turbulent mixing, and Fourier spectra of the fluctuations show clear power-law behavior—indicative of inertial and dissipation ranges—in agreement with many predictions for fully developed MHD turbulence [19,20].

Because spacecraft measurements have not been able to probe the wind where its acceleration occurs (typically at heights between 2 and 10 $R_\odot$), we have relied on complementary observations of photons from the corona to study this key region. One minor complication with these data is that the corona has an extremely low opacity, so all measurements are integrations over an extended line of sight. The localized plasma properties can be extracted reliably, however, when the coronal geometry is known [21,22]. The emission from the extended corona is also orders of magnitude dimmer than the disk of the Sun. The technique of occulting the disk in *coronagraph* telescopes—often combined with spectroscopy to isolate individual ion properties—has led to a dramatic increase in our knowledge about the acceleration region of the wind.

The Ultraviolet Coronagraph Spectrometer (UVCS) aboard the *Solar and Heliospheric Observatory* (*SOHO*), launched in 1995, has been the first spaceborne instrument able to constrain ion temperature anisotropies and differential outflow speeds in the acceleration region of the wind [23]. UVCS measured O^{5+} perpendicular temperatures exceeding 3×10^8 K at a height of 2 $R_\odot$, with $T_\perp / T_\parallel \approx$ 10–100. Temperatures for both O^{5+} and Mg^{9+} are significantly greater than mass-proportional when compared to hydrogen, and outflow speeds for O^{5+} may exceed those of hydrogen by as much as a factor of two [21,23]. These results are similar in character to the *in situ* data, but they imply more extreme departures from thermodynamic equilibrium in the corona. Because of the perpendicular nature of the heating, and because of the ordering $T_{\rm ion} \gg T_p > T_e$, UVCS observations have led to a resurgence of interest in models of coronal ion cyclotron resonance (see below).

HEATING AND ACCELERATION PROCESSES

There is heating everywhere above the solar photosphere. Figure 2 is an overview of the thermal properties and relevant time scales in the high-speed solar wind that emerges from coronal holes. The energy deposition, here plotted as a net heating rate per proton (i.e., proportional to $n^{\gamma-1} \partial (P n^{-\gamma}) / \partial t$, for number density n, pressure P, and ratio of specific heats γ = 5/3) can be divided heuristically into four regions (see numbered curves):

1. *Chromospheric heating* occurs immediately above the photosphere where the plasma is mostly neutral, and the plasma density is high enough for many collisions to occur per Larmor gyroperiod. Thus, nonmagnetic mechanisms such as acoustic wave dissipation tend to be considered as the dominant source of energy deposition [26], but magnetic effects still may be important [27]. The production of acoustic and MHD "noise" by the strong turbulent convection in the solar interior has been studied for several decades [e.g., 28].

2. *Base coronal heating* "turns on" abruptly about 0.003 $R_\odot$ above the photosphere and seems to extend out several tenths of a solar radius. The effective heating rate

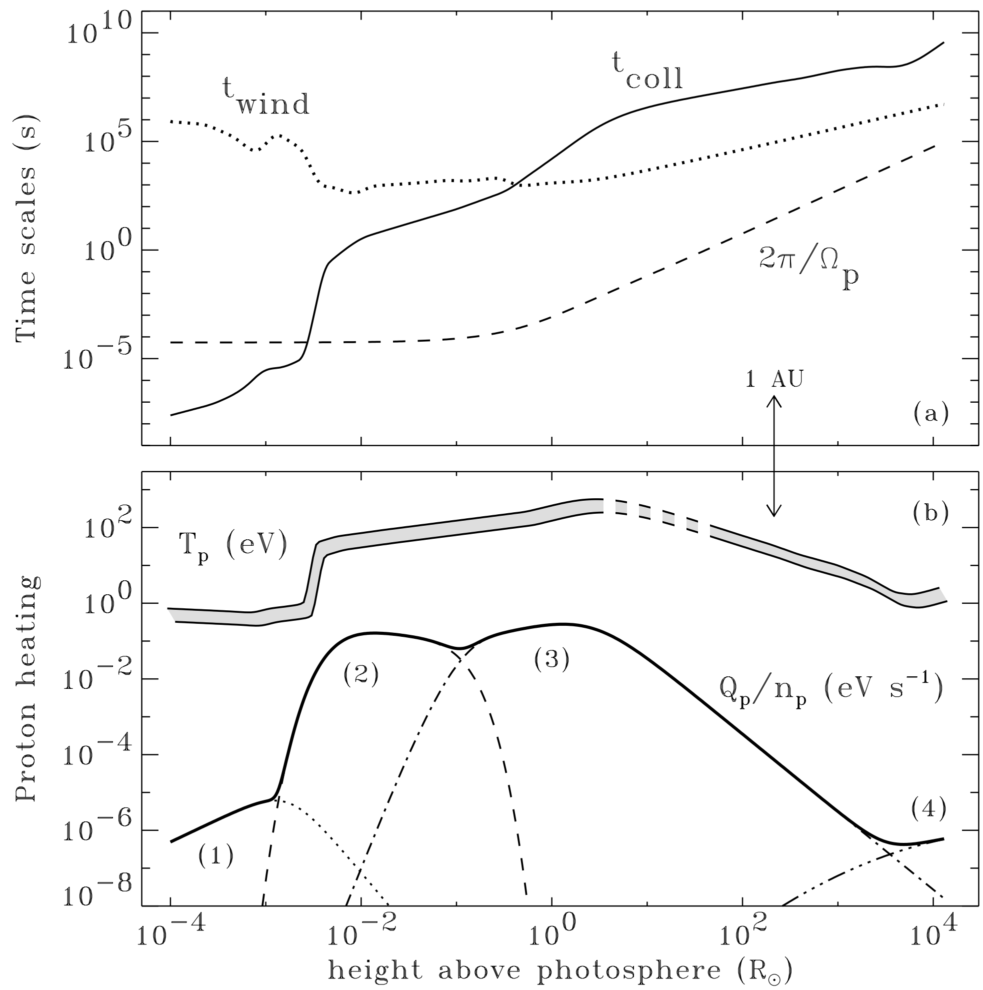

FIGURE 2. (a) Plasma time scales plotted as a function of distance from the solar photosphere: the proton Larmor gyroperiod (dashed line), the mean time between proton-proton Coulomb collisions (solid line), and the wind expansion time over one density scale height (dotted line). (b) Proton temperature T_p and heating rate per proton Q_p/n_p derived from measured plasma properties [6,23,24,25]. The four regions heated by different processes are labeled by numbers (see text). The region of unobserved T_p is denoted with hatching, and the orbit of the Earth at 1 AU = 214 $R_\odot$ is labeled with an arrow.

shown in Figure 2 includes the strong downward heat conduction generated by this sharp temperature gradient. Most suggested heating mechanisms involve the storage and release of magnetic energy in small-scale twisted/braided flux tubes [26,29]. The magnetic energy is probably dissipated as heat by Coulomb collisions (via, e.g., viscosity, thermal conductivity, ion-neutral friction, or electrical resistivity) because many collisions can occur in a plasma parcel before the solar wind carries it away.

3. *Extended coronal heating* must occur over a large range of distances, far into the regions where the wind expands through a density scale height before any collisions can occur (i.e., where $t_{\text{wind}} = [u_p\, d(\ln n_p)/dr]^{-1}$ is smaller than $t_{\text{coll}} \approx 0.8 T_p^{3/2}/n_p$). At distances greater than 2 to 3 $R_\odot$, the proton temperature gradient is noticeably

shallower than that expected from pure adiabatic expansion [30], indicating gradual heating of the collisionless plasma (see below).

4. Heating near the distant *termination shock*, where the solar wind meets the interstellar medium, may occur when neutral interstellar atoms enter the heliosphere and become ionized, forming a beam or ring-like velocity distribution that is unstable to the generation of MHD waves [25]. Evidence for this final stage of solar wind energization is scant, since as of 2001 the *Voyager 2* probe has not yet passed through the termination shock.

The remainder of this paper discusses the extended heating in region 3, where the primary solar wind acceleration occurs. The vast majority of proposed physical processes involve the transfer of energy from propagating magnetic fluctuations (waves, shocks, or turbulence) to the particles. This broad-brush consensus arises because the ultimate source of energy must be solar in origin, and thus it must somehow *propagate* out to the distances where the heating occurs [20,31].

It is not known how or where the fluctuations responsible for extended heating are generated. Some have suggested that left-hand polarized ion cyclotron waves are generated impulsively at the base of the corona and propagate virtually unaltered to where they are damped [7]. A related idea is that the same basal impulsive events generate fast shocks that fill the extended corona and convert some of their energy into anisotropic heating and ion acceleration [32]. Problems with these ideas include: (a) the neglect of minor ions that can easily absorb a basal fluctuation spectrum before any primary plasma constituents (protons or He^{2+}) can come into resonance [33,34], and (b) a significant shortfall in observed density fluctuations, compared to predictions consistent with the basal wave generation models [35].

More numerous are proposed scenarios of local wave generation; i.e., where "secondary" fluctuations arise throughout the corona as the result of either turbulent cascade, plasma instability, or mode conversion [e.g., 36,37,38]. The most likely dissipation mechanism seems to be ion cyclotron resonance, since Landau damping mainly tends to heat electrons in a low-β plasma [39] and collisional damping is negligible. Ion cyclotron frequencies in the corona are typically 10 to 10,000 Hz, but the oscillation frequencies observed on the surface of the Sun (generated mainly by convection) are of order 0.01 Hz. Any wave generation mechanism must therefore bridge a gap of many orders of magnitude in frequency (or wavenumber). Most models of MHD turbulence [40,41] favor the transfer of energy from small to large wavenumbers transverse to the background magnetic field ($\mathbf{k} \cdot \mathbf{B} \approx 0$). However, ion cyclotron damping of Alfvénic fluctuations (believed to be the only mode that can survive into the solar wind) requires large *parallel* wavenumbers ($k_{\parallel} \approx \Omega_{\text{ion}}/V_A$) that seemingly are not produced by MHD cascade. This inability to produce ion cyclotron waves locally in the corona is a major roadblock in our attempts to understand the origin of the observed anisotropic heating and preferential ion acceleration.

Despite our present lack of understanding about how ion cyclotron waves may be generated, there has been no shortage of attempts to "work backward" from the observational constraints to derive further details of the required wave properties and their kinetic effects. In addition to moment-based models assuming bi-Maxwellian distributions [e.g., 33,38], there has been a recent flurry of activity to understand

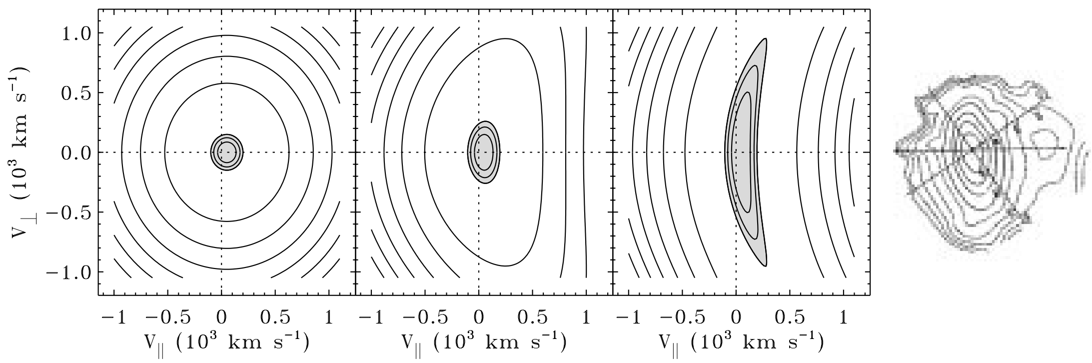

FIGURE 3. The left panels show numerical velocity distributions after 0, 5, and 80 minutes of ion cyclotron diffusion, with an input wave power spectrum consistent with extrapolations of *in situ* power down into the corona [20,33,44]. The gray regions denote the most populated "cores" of the distributions, having greater than $1/e$ of the peak phase space density. The right panel shows a representative fast-wind *Helios* proton distribution at 0.3 AU [6], not to scale.

kinetic departures from simple parameterized velocity distributions [42,43,44]. Figure 3 shows a representative calculation of quasi-linear velocity space diffusion of an O^{5+} distribution initially in thermal equilibrium with the protons. Strong $T_\perp \gg T_\parallel$ anisotropies arise naturally, and preferential acceleration comes from both the curvature of resonant surfaces in velocity space and from the mirror force on large-$T_\perp$ ions.

Considerable progress has been made in the last decade in characterizing the plasma state of the corona and solar wind. The observations have guided theorists to a certain extent, but *ab initio* kinetic models are still required before we can claim a full understanding of the physics. Future spectroscopic measurements of the corona are expected to provide constraints on specific departures from bi-Maxwellian velocity distributions [44], and NASA's *Solar Probe* (if funded) will make *in situ* measurements as close to the Sun 4 $R_\odot$. To digest these observations, the lines of communication must be kept open between the plasma physics and astrophysics communities.

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More information can be found on the Web: http://cfa-www.harvard.edu/∼scranmer/

REFERENCES

1. Parker, E. N., *Interplanetary Dynamical Processes*, Interscience Publishers, New York, 1963.
2. Hundhausen, A. J., *Coronal Expansion and Solar Wind*, Springer-Verlag, Berlin, 1972.
3. Golub, L., and Pasachoff, J. M., *The Solar Corona*, Cambridge Univ. Press, Cambridge, UK, 1997.

4. Parker, E. N., *Astrophys. J.* **128**, 664–676 (1958).
5. Neugebauer, M., *J. Geophys. Res.* **102**, 26,887–26,894 (1997).
6. Feldman, W. C., and Marsch, E., "Kinetic Phenomena in the Solar Wind," in *Cosmic Winds and the Heliosphere*, edited by J. R. Jokipii et al., University of Arizona Press, Tucson, 1997, pp. 617–676.
7. Axford, W. I., McKenzie, J. F., Sukhorukova, G. V., Banaszkiewicz, M., Czechowski, A., and Ratkiewicz, R., *Space Science Reviews* **87**, 25–41 (1999).
8. Gekelman, W., *J. Geophys. Res.* **104**, 14,417–14,435 (1999).
9. Baker, D. N., *Adv. Space Research* **22**, 7–16 (1998).
10. Soon, W., Baliunas, S., Posmentier, E. S., and Okeke, P., *New Astronomy* **4**, 563–579 (2000).
11. Dowdy, J. F., Jr., Rabin, D., and Moore, R. L., *Solar Physics* **105**, 35–45 (1986).
12. Banaszkiewicz, M., Axford, W. I., and McKenzie, J. F., *Astron. Astrophys.* **337**, 940–944 (1998).
13. Moses, D., Clette, F., Delaboudinière, J.-P., et al., *Solar Physics* **175**, 571–599 (1997).
14. Mullan, D. J., and Yakovlev, O. I., *Irish Astron. J.* **22**, 119–136 (1995).
15. Bertaux, J. L., Lallement, R., and Quémerais, E., *Space Science Reviews* **78**, 317–328 (1996).
16. Ip, W.-H., and Axford, W. I., "Theories of Physical Processes in the Cometary Comae and Ion Tails," in *Comets*, edited by L. L. Wilkening, Univ. of Arizona Press, Tucson, 1982, pp. 588–634.
17. Schwartz, S. J., and Marsch, E., *J. Geophys. Res.* **88**, 9919–9932 (1983).
18. Collier, M. R., Hamilton, D. C., Gloeckler, G., Bochsler, P., and Sheldon, R. B., *Geophys. Res. Letters* **23**, 1191–1194 (1996).
19. Goldstein, M. L., Roberts, D. A., and Matthaeus, W. H., *Ann. Rev. Astron. Astrophys.* **33**, 283–326 (1995).
20. Tu, C.-Y., and Marsch, E., *Space Science Reviews* **73**, 1–210 (1995).
21. Cranmer, S. R., Kohl, J. L., Noci, G., et al., *Astrophys. J.* **511,** 481–501 (1999).
22. Strachan, L., Panasyuk, A. V., Dobrzycka, D., Kohl, J. L., Noci, G., Gibson, S. E., and Biesecker, D. A., *J. Geophys. Res.* **105**, 2345–2356 (2000).
23. Kohl, J. L., Noci, G., Antonucci, E., et al., *Solar Physics* **175**, 613–644 (1997).
24. Fontenla, J. M., Avrett, E. H., and Loeser, R., *Astrophys. J.* **406**, 319–345 (1993).
25. Zank, G. P., Matthaeus, W. H., Smith, C. W., and Oughton, S., "Heating of the Solar Wind beyond 1 AU by Turbulent Dissipation," in *Solar Wind Nine*, edited by S. R. Habbal et al., AIP Conference Proceedings 471, New York, 1999, pp. 523–526.
26. Narain, U., and Ulmschneider, P., *Space Science Reviews* **54**, 377–445 (1990).
27. Goodman, M. L., *Astrophys. J.* **533**, 501–522 (2000).
28. Osterbrock, D. E., *Astrophys. J.* **134**, 347–388 (1961).
29. Parker, E. N., *Astrophys. J.* **372**, 719–727 (1991).
30. Barnes, A., Gazis, P. R., and Phillips, J. L., *Geophys. Res. Letters* **22**, 3309–3312 (1995).
31. Hollweg, J. V., *Rev. Geophys. Space Phys.* **16**, 689–720 (1978).
32. Lee, L. C., and Wu, B. H., *Astrophys. J.* **535**, 1014–1026 (2000).
33. Cranmer, S. R., Field, G. B., and Kohl, J. L., *Astrophys. J.* **518**, 937–947 (1999).
34. Cranmer, S. R., *Astrophys. J.* **532**, 1197–1208 (2000).
35. Hollweg, J. V., *J. Geophys. Res.* **105**, 7573–7582 (2000).
36. Hollweg, J. V., *J. Geophys. Res.* **91**, 4111–4125 (1986).
37. Matthaeus, W. H., Zank, G. P., Oughton, S., Mullan, D. J., and Dmitruk, P., *Astrophys. J.* **523**, L93–L96 (1999).
38. Hu, Y. Q., Habbal, S. R., and Li, X., *J. Geophys. Res.* **104**, 24819–24834 (1999).
39. Habbal, S. R., and Leer, E., *Astrophys. J.* **253**, 318–322 (1982).
40. Shebalin, J. V., Matthaeus, W. H., and Montgomery, D., *J. Plasma Phys.* **29**, 525–547 (1983).
41. Goldreich, P., and Sridhar, S., *Astrophys. J.* **485**, 680–688 (1997).
42. Isenberg, P. A., Lee, M. A., and Hollweg, J. V., *Solar Physics* **193**, 247–257 (2000).
43. Galinsky, V. L., and Shevchenko, V. I., *Phys. Rev. Letters* **85**, 90–93 (2000).
44. Cranmer, S. R., *J. Geophys. Res.* (2001), in press.