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Hot Solar-Wind Helium: Direct Evidence for Local Heating by Alfvén-Cyclotron Dissipation

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A study of solar-wind hydrogen and helium temperature observations collected by the *Wind* spacecraft offers compelling evidence of heating by an Alfvén-cyclotron dissipation mechanism. Observations are sorted by the rate of Coulomb interactions, or collisional age, in the plasma and the differential flow between the two species. We show that helium is preferentially heated perpendicular to the magnetic field direction by more than a factor of 6 when the flow between the species is small relative to the Alfvén wave speed and collisions are infrequent. These signatures are consistent with predictions of dissipation in the presence of multiple ion species. We also report an unexpected result: observations of efficient heating of helium parallel to the magnetic field for large differential flow relative to the sound speed.

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Introduction.—Understanding the cause of the million degree solar corona is an outstanding challenge in solar physics with relevance to general questions of plasma heating [1]. In order to attain high temperatures, many viable theories require the dissipation of waves through the resonant scattering of particles in the plasma [2–5]. In these models, waves couple directly to a subset of ions in phase space, depending on their velocities, masses, and charges, and a simple single-fluid description of the plasma is insufficient. This is consistent with observations of the corona and solar wind that show a nonthermal plasma where heavier ions often have higher temperatures and speeds [6–9].

Figure 1 illustrates the breakdown of temperature equilibrium between hydrogen and helium in the solar wind. We use the subscripts p and α because both species are fully ionized. The histogram of the temperature ratio T_α/T_p is based on the best fit to the core of the ion velocity distribution functions for several million measurements of the solar wind near Earth with the Faraday Cup instruments on the *Wind* spacecraft [10,11]. The distribution has a maximum at $T_\alpha/T_p = 1$, consistent with an isothermal fluid wind, but there is also a peak at $T_\alpha/T_p = 4$, where the two species instead have equal thermal speeds. A process that maintains equal thermal speeds instead of equal temperatures between ion species is in violation of the principle of energy equipartition. This is a stark demonstration of the departure of the solar wind from an ideal gas, and of the need to examine heating mechanisms that couple individually to particles. Further, 23% of the observations, highlighted in gray, have $T_\alpha/T_p \geq 5$; this is evidence of a mechanism that is both wave particle in nature and preferentially coupled to the helium. In this Letter we investigate the solar-wind conditions associated with hot helium, concluding that we have identified strong evidence for preferential heating of ions in the solar wind through Alfvén-cyclotron dissipation.

Several models of dissipation have focused on the absorption of Alfvén-cyclotron fluctuations in a plasma with multiple ion species [3,4,12,13]. In these theories, large

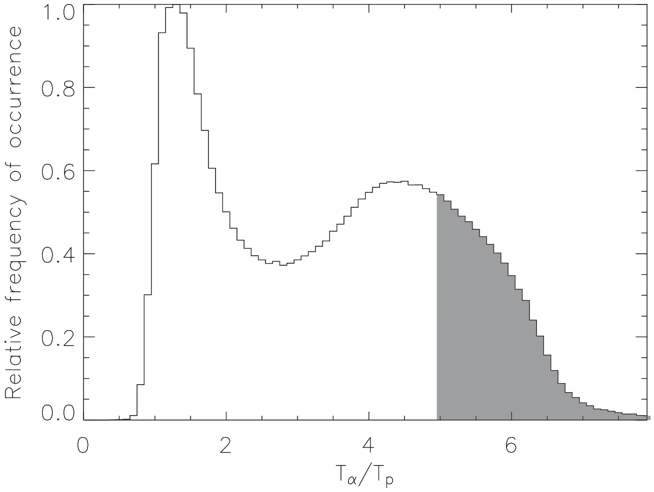

FIG. 1. The relative occurrence of T_α/T_p in the solar wind over the course of the *Wind* mission to date, illustrating the bimodal nature of the dominant components of the plasma, with peaks near equal temperature ($T_\alpha/T_p = 1$) and equal thermal speed ($T_\alpha/T_p = 4$). For 23% of the observations $T_\alpha/T_p > 5$, indicating anomalous heating beyond the already unusual equilibration of thermal speeds.

amplitude Alfvén waves in the corona come into cyclotron resonance with ions and are dissipated. Resonant ions are accelerated, heating them preferentially in the direction perpendicular to the ambient magnetic field. This resonance could occur either because the ion gyrofrequencies drop with increasing coronal height, or because turbulence transports long wavelength Alfvén wave power to smaller, kinetic scales. This mechanism is consistent with spectroscopic observations of heavy ions in the corona, which are often seen to be hotter than protons and to possess large temperature anisotropies, with temperature $T_{\perp j}$ $\perp$ to the ambient magnetic field $\mathbf{B}_{\rm o}$ much larger than the temperature $T_{\parallel j}$ $\parallel$ to $\mathbf{B}_{\rm o}$ [8]. Anisotropies persist in the solar wind seen near Earth, although local instabilities limit $T_{\perp j}/T_{\parallel j}$ to within a factor of 2 of unity [14,15].

Recent numerical simulations of the interaction of Alfvén waves with ions have predicted that the relative heating of ions may also be regulated by differential flow [13,16,17]. This is significant because heavier ions often flow faster than protons. In general the differential flow $\Delta V_{\alpha p} = V_\alpha - V_p$ reaches but rarely exceeds the Alfvén speed, C_A [18–20]. The theories predict that for $\Delta V_{\alpha p} \sim 0$, helium will have a stronger cyclotron resonance than hydrogen, and thus will be heated faster and develop larger temperature anisotropies. On the other hand, if $\Delta V_{\alpha p}/C_A$ is increased, the helium ions come out of resonance with the waves and the protons are heated instead. The first experimental evidence for heating in the solar wind consistent with these simulations was presented in an analysis of four months of solar wind measurements by the *ACE* spacecraft [17,21]. That study demonstrated that increased values of $T_{\perp\alpha}/T_{\parallel\alpha}$ were preferentially seen as $\Delta V_{\alpha p}/C_A$ decreased. The consistency of these initial measurements with the predictions prompted this study.

Observations and analysis.—This work extends the original *ACE* study by Gary *et al.* [22] in three key ways. First, we make use of a large data set of observations with the *Wind* spacecraft that has been extensively used for studies of temperature anisotropies and helium abundance variation [11,13]. Several million observations allow us to sample a broad range of solar-wind conditions. Second, in addition to data selection techniques described in Kasper *et al.* [14], we use an evaluation of the accuracy of the ion measurements in this data set, which reported the uncertainty of $\Delta V_{\alpha p}/V_p$ is less than 1% and about 8% for temperature [10]. Propagating the temperature uncertainty allows us to estimate the typical error in the temperature anisotropy of about 12%, small compared to the results we will report. We will exclude any measurements with $\Delta V_{\alpha p}/V_p < 1\%$ since $\Delta V_{\alpha p}$ would have a large uncertainty. Finally, we also sort the observations by how quickly Coulomb collisions are driving the plasma toward thermal equilibrium. We define the Coulomb collisional age, $A_C = R/(V_{sw}\tau_c)$, where τ_c is the time scale for $\alpha - p$ energy exchange due to small-angle Coulomb scattering, V_{sw} is the speed of the solar wind, and R is the distance from the Sun to *Wind*. A_C is therefore the ratio of the time between Coulomb collisions to the transit time of the solar wind. When $A_C \ll 1$, internal interactions are rare and the plasma is said to be collisionless; when $A_C \gg 1$ the plasma is collisionally old and Coulomb relaxation should reduce the nonthermal signatures. Previous work has shown that large A_c leads to smaller differential flow and $T_p \sim T_\alpha$ [18,23,24]. In Fig. 2, we show the distribution of (a) T_α/T_p as a function of solar wind speed, and (b) T_α/T_p, (c) $T_{\perp p}/T_{\parallel p}$, and (d) $\Delta V_{\alpha p}/C_A$ as functions of A_c. In this view, it is clear that nonthermal effects such as $T_\alpha/T_p \neq 1$ are strongly restricted by growing A_c as Coulomb relaxation enforces thermal equilibrium. Care must be taken to ensure that apparent associations between nonthermal parameters are not actually due to a mutual strong dependence on A_c.

We have shown in Fig. 2 that T_α/T_p is a strong function of A_C. In order to search for the preferential heating of

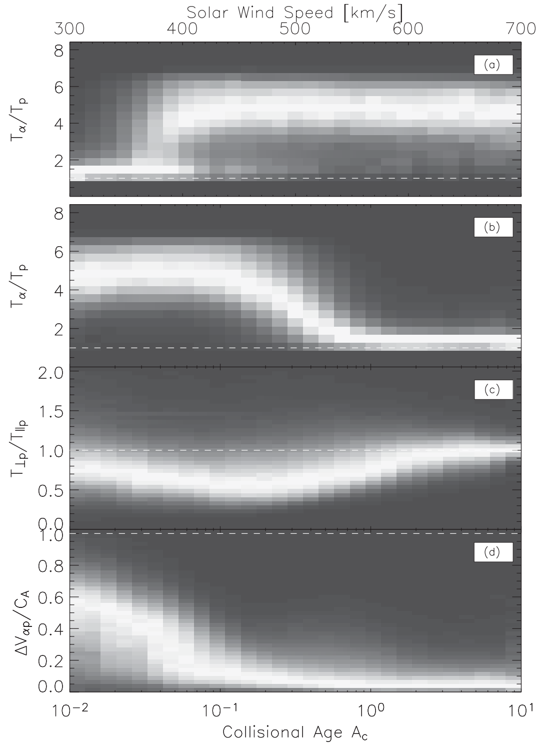

FIG. 2. The breakdown of a simple single-fluid description of the solar wind is strongly ordered by the collisional age A_c of the plasma, as illustrated by the panels in this figure. In (a) we show the distribution of T_α/T_p with solar-wind speed. Statistically, $T_\alpha \sim T_p$ for low speeds, and $T_\alpha/T_p \geq 4$ occurs more often a higher speeds, but the occurrence of nonthermal features is much more strongly ordered by A_c, as can been seen in the distributions of (b) T_α/T_p, (c) $T_{\perp p}/T_{\parallel p}$, and (d) $\Delta V_{\alpha p}/C_A$ with age. For $A_c > 1$, collisions produce thermal equilibrium, with $T_\alpha = T_p$, $T_{\perp p}/T_{\parallel p} = 1$, and $\Delta V_{\alpha p} = 0$. For $A_c < 1$ the plasma is collisionless and nonthermal features persisting from the corona or generated *in situ* are seen.

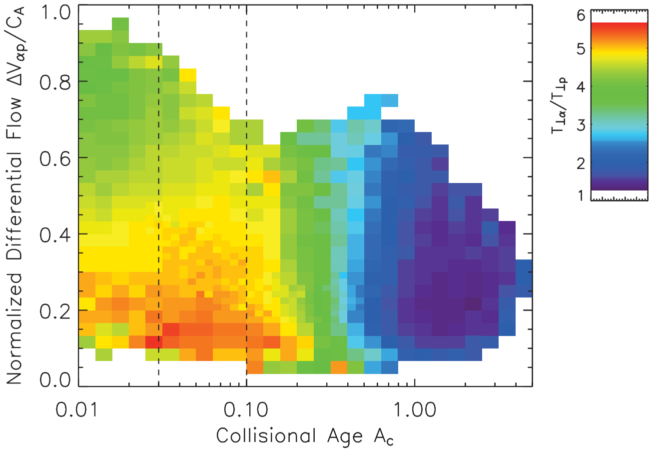

FIG. 3 (color). The ratio $T_{\perp\alpha}/T_{\perp p}$ of the perpendicular component of the ion temperatures as a function of the collisional age A_c and $\Delta V_{\alpha p}/C_A$, the differential flow between the two species normalized by the local Alfvén speed. The overall association of T_α/T_p with A_c seen in Fig. 2 is reproduced here. Additionally, there is a clear indication than in the collisionless regime $A_c < 0.5$, $T_{\perp\alpha}/T_{\perp p}$ is larger when $\Delta V_{\alpha p}/C_A$ is small. The region $0.03 < A_c < 0.1$ indicated by the dashed lines is the focus of the following figures.

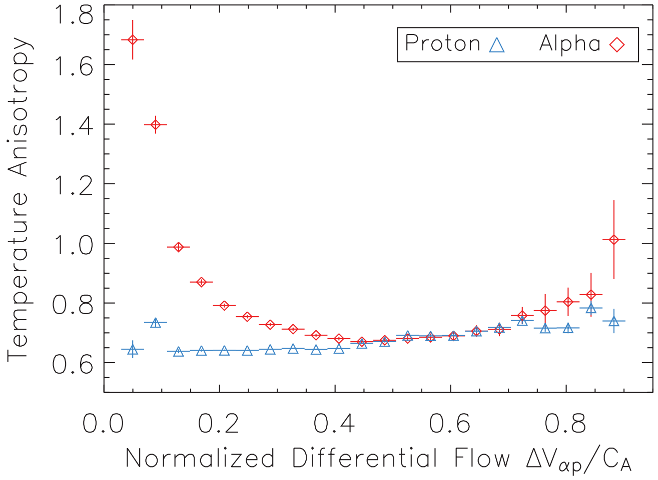

FIG. 4 (color). The average values of ion anisotropies $T_{\perp\alpha}/T_{\parallel\alpha}$ (red diamonds) and $T_{\perp p}/T_{\parallel p}$ (blue triangles) as a function of $\Delta V_{\alpha p}/C_A$ show that the region of anomalous $T_{\perp\alpha}/T_{\perp p}$ at small $\Delta V_{\alpha p}/C_A$ is additionally associated with large alpha temperature anisotropy, a further indication of dissipation of Alfvén waves. In this figure and the next the vertical error bars are the uncertainty in the mean and the horizontal bars indicate the width of each interval.

helium at small $\Delta V_{\alpha p}/C_A$ discussed earlier, we now examine $T_{\perp\alpha}/T_{\perp p}$ as a function of both A_c and $\Delta V_{\alpha p}/C_A$. The color shading in Fig. 3 indicates the median value of $T_{\perp\alpha}/T_{\perp p}$ in each cell. When more observations are available, we use smaller cells, resulting in a uniform statistical uncertainty in $T_{\perp\alpha}/T_{\perp p}$ across the plot. Figure 3 clearly shows that while overall $T_{\perp\alpha}/T_{\perp p}$ decreases with A_c, for most values of A_c $T_{\perp\alpha}/T_{\perp p}$ rises at small $\Delta V_{\alpha p}/C_A$. Looking at plasma with few collisions ($A_c < 0.1$), the concentration of hot helium at small $\Delta V_{\alpha p}/C_A$ is unquestionable. Interestingly, the upturn in $T_{\perp\alpha}/T_{\perp p}$ at small $\Delta V_{\alpha p}/C_A$ can be seen even for $A_c > 1$, where Fig. 2 clearly showed Coulomb collisions rapidly remove nonthermal features. This result suggests that some of the heating happened recently, in the local solar wind. Finally, it is also apparent that the overall dependence of T_α/T_p on A_C has previously obscured the signature of heating at small $\Delta V_{\alpha p}/C_A$, since $\Delta V_{\alpha p}$ is also strongly correlated with A_c.

We now focus on observations in the interval $0.03 < A_c < 0.1$ indicated by the two vertical dashed lines in Fig. 3. Figure 4 is a plot of the average values of $T_{\perp\alpha}/T_{\parallel\alpha}$ and $T_{\perp p}/T_{\parallel p}$ as a function of $\Delta V_{\alpha p}/C_A$ for all the plasma in this range of A_c. The vertical errors bars are the uncertainty in the mean and the horizontal bars indicate the width of the selected intervals in $\Delta V_{\alpha p}/C_A$. In this figure, $T_{\perp p}/T_{\parallel p}$ weakly increases with $\Delta V_{\alpha p}/C_A$, reaching $T_{\perp p}/T_{\parallel p} \sim 0.8$ for $\Delta V_{\alpha p}/C_A \sim 1$ compared to $T_{\perp p}/T_{\parallel p} \sim 0.6$ for $\Delta V_{\alpha p}/C_A = 0$. The small average value of $T_{\perp p}/T_{\parallel p}$ is consistent with the limit imposed by the firehose instability on the expanding solar wind [14]. The slight increase of $T_{\perp p}/T_{\parallel p}$ for large $\Delta V_{\alpha p}/C_A$ may be a sign of increased cyclotron-resonant heating of hydrogen relative to helium, but it is weak. On the other hand, as $\Delta V_{\alpha p}/C_A$ drops below 0.4, $T_{\perp\alpha}/T_{\parallel\alpha}$ rises rapidly, reaching $T_{\perp\alpha}/T_{\parallel\alpha} \sim 1.8$ for $\Delta V_{\alpha p}/C_A \leq 0.1$.

The rapid rise in $T_{\perp\alpha}/T_{\parallel\alpha}$ with decreasing $\Delta V_{\alpha p}/C_A$ in Fig. 4 is a clear indicator that helium is heated more efficiently then hydrogen in directions $\perp$ to $\mathbf{B}_o$ when the relative flow is small. This is consistent with the helium falling out of resonance with Alfvén waves as $\Delta V_{\alpha p}/C_A$ grows. To further test the significance of these results as evidence of Alfvén-cyclotron resonance, we examine $T_{\perp\alpha}/T_{\perp p}$ and $T_{\parallel\alpha}/T_{\parallel p}$ as functions of both $\Delta V_{\alpha p}/C_A$ and $\Delta V_{\alpha p}/C_S$, where C_S is the sound speed. The average value of these parameters are shown in Fig. 5. Several new signatures can now be seen. $T_{\perp\alpha}/T_{\perp p}$ is indeed better ordered when shown as a function of $\Delta V_{\alpha p}/C_A$ instead of $\Delta V_{\alpha p}/C_S$, further proof that this is an Alfvénic phenomenon. For small $\Delta V_{\alpha p}/C_A$, we see that $T_{\parallel\alpha}/T_{\parallel p}$ actually drops, perhaps because helium is being scattered preferentially away from $\mathbf{B}_o$. Finally, we note a surprising new signature that is not consistent with the Alfvénic heating theory, and may instead be an indicator of an additional heating process. Namely, we see that $T_{\parallel\alpha}/T_{\parallel p}$ becomes large for values of $\Delta V_{\alpha p}/C_S > 1$.

Conclusions.—Through a statistical study of solar-wind hydrogen and helium temperatures, we have produced direct evidence for the local heating of ions through the dissipation of kinetic Alfvén waves by cyclotron reso-

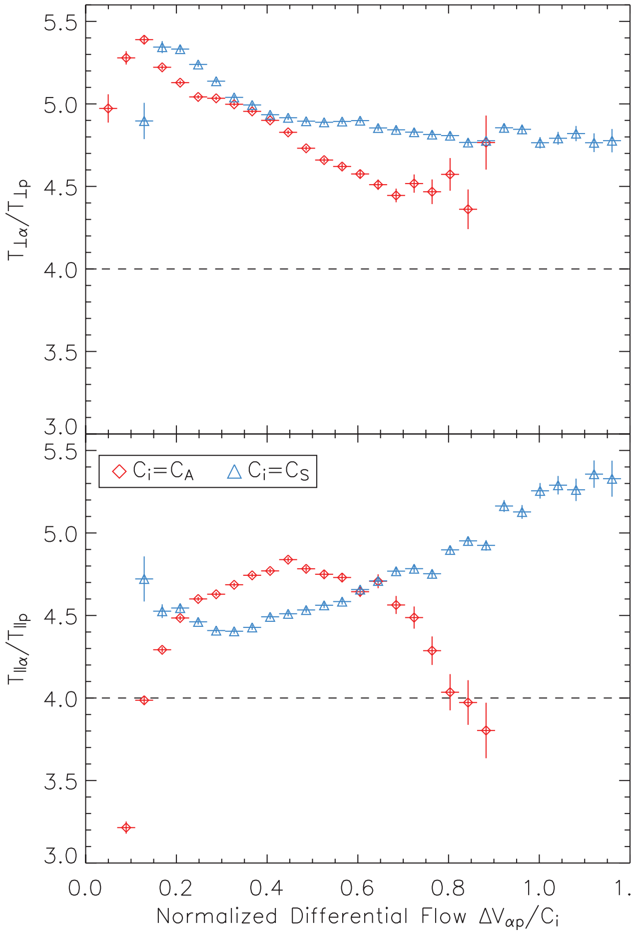

FIG. 5 (color). The median value of the ratio of the perpendicular (upper panel) and parallel (lower panel) temepratures as a function of normalized differential flow. The red diamonds are for $\Delta V_{\alpha p}$ normalized by the Alfvén speed C_A, and the blue triangles use the sound speed C_S. The data in the upper panel clearly demonstrate that the Alfvén speed more strongly organizes $T_{\perp\alpha}/T_{\perp p}$ then the sound speed, supporting the theory that the anomalous heating is due to enhanced absorption of dissipated kinetic Alfvén waves by the helium.

nance, with the relative absorption rates regulated by differential flow. Hot helium is observed when the solar wind is collisionless and when differential flow is small. Enhanced heating at small flow speed is seen even when the collision rate is high, suggesting that it is occurring locally. When the differential flow speed is normalized by the Alfvén wave speed we find that there is a clear transition at $\Delta V_{\alpha p}/C_A \sim 0.6$, while no transition is seen if the local sound speed is used instead. Our results also confirm the imbalanced character of solar-wind turbulence; that is, the fluctuating magnetic energy preferentially propagates away from the Sun. If the waves were propagating both parallel and antiparallel to the background magnetic fields with equal magnitudes, the strong dependence of the alpha perpendicular heating would not be observed, as indicated by both the linear theory of the cyclotron resonance [17] and the hybrid simulations of the wave-particle interaction [21]. This complements earlier results based on the shape of distribution functions [25]. Finally, we have produced evidence of an unknown heating mechanism which leads to large values of $T_{\parallel\alpha}/T_{\parallel p}$ for $\Delta V_{\alpha p}/C_S > 1$. One possible source of parallel heating of the helium is electrostatic ion-acoustic fluctuations excited by the cascade and dissipation of magnetic turbulence; this and other possible parallel heating mechanisms should be studied to determine their relevance.

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[1] J. A. Klimchuk, Sol. Phys. **234**, 41 (2006).
[2] C.-Y. Tu and E. Marsch, J. Geophys. Res. **106**, 8233 (2001).
[3] P. A. Isenberg and B. J. Vasquez, Astrophys. J. **668**, 546 (2007).
[4] S. R. Cranmer and A. A. van Ballegooijen, Astrophys. J. **594**, 573 (2003).
[5] P. A. Isenberg and J. V. Hollweg, J. Geophys. Res. **88**, 3923 (1983).
[6] R. Hernandez, S. Livi, and E. Marsch, J. Geophys. Res. **92**, 7723 (1987).
[7] R. von Steiger *et al.*, Space Sci. Rev. **72**, 71 (1995).
[8] S. R. Cranmer, G. B. Field, and J. L. Kohl, Astrophys. J. **518**, 937 (1999).
[9] P. Bochsler, J. Geis, and R. Joos, J. Geophys. Res. **90**, 10 779 (1985).
[10] J. C. Kasper *et al.*, J. Geophys. Res. **111**, A03 105 (2006).
[11] J. C. Kasper *et al.*, Astrophys. J. **660**, 901 (2007).
[12] Y. Q. Hu and S. R. Habbal, J. Geophys. Res. **104**, 17 045 (1999).
[13] P. Hellinger *et al.*, J. Geophys. Res. **110**, A12 109 (2005).
[14] J. C. Kasper, A. J. Lazarus, and S. P. Gary, Geophys. Res. Lett. **29**, 1839 (2002).
[15] P. Hellinger *et al.*, Geophys. Res. Lett. **33**, L09 101 (2006).
[16] S. P. Gary and K. Nishimura, J. Geophys. Res. **109**, A02 109 (2004).
[17] S. P. Gary, C. W. Smith, and R. M. Skoug, J. Geophys. Res. **110**, A07 108 (2005).
[18] M. Neugebauer, J. Geophys. Res. **81**, 78 (1976).
[19] D. B. Reisenfeld *et al.*, J. Geophys. Res. **106**, 5693 (2001).
[20] E. Marsch *et al.*, J. Geophys. Res. **87**, 35 (1982).
[21] S. P. Gary *et al.*, New J. Phys. **8**, 17 (2006).
[22] S. P. Gary, L. Yin, and D. Winske, J. Geophys. Res. **111**, A06 105 (2006).
[23] J. F. McKenzie, R. A. B. Bond, and M. K. Dougherty, J. Geophys. Res. **92**, 1 (1987).
[24] E. Marsch and H. Goldstein, J. Geophys. Res. **88**, 9933 (1983).
[25] M. Heuer and E. Marsch, J. Geophys. Res. **112**, A03 102 (2007).