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Direct comparison of transverse ion acceleration mechanisms in the auroral region at solar minimum

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Abstract. Previous studies have shown that most ion conics in the auroral zone are associated with either broadband extremely low frequency (BBELF) or electromagnetic ion cyclotron (EMIC) emissions. EMIC emissions, which are correlated with preferential acceleration of He$^+$, are concentrated in the premidnight sector; BBELF emissions, which are found at all local times, are not associated with preferential acceleration of any species. We present a case study of five auroral passes which include ion conics associated with EMIC and BBELF waves at different locations. Our data indicate that EMIC waves can be locally important for accelerating outflowing He$^+$ in the aurora. However, although this study's design exaggerates the contribution of EMIC waves to transverse ion acceleration, we find in each case that BBELF waves produce higher energy fluxes of upflowing ions. Therefore, events with BBELF emissions dominate the overall ion outflow.

1. Introduction

In the years since *Sharp et al.* [1977] first deduced the existence of a mechanism that accelerates ions transversely to the magnetic field at auroral latitudes, ion conics have come to be recognized as a ubiquitous feature of the aurora. Since that time many studies have attempted to determine the mechanisms which create this heating. Suggested wave modes include heating by lower hybrid cavitons [e.g., *Kintner et al.*, 1986], electromagnetic ion cyclotron (EMIC) waves [e.g., *Erlandson et al.*, 1994], and a variety of broadband extremely low frequency (BBELF) modes including solitary kinetic Alfvén waves [*Knudsen and Wahlund*, 1998], ion acoustic waves [*Wahlund et al.*, 1998], inhomogeneous energy density driven instability [*Amatucci et al.*, 1998; *Koepke et al.*, 1999], and electrostatic solitary waves [*Ergun et al.*, 1998]. Recently, the following consistent picture has emerged from rocket and satellite observations at altitudes below 4200 km [*Lynch et al.*, 1996; *Knudsen et al.*, 1998; *André et al.*, 1998; *Lund et al.*, 1997]: most of the transverse ion heating is due to one or more of the BBELF modes, but EMIC waves also contribute, particularly on the nightside. While lower hybrid waves may be important at sounding rocket altitudes, they are less important above 2000 km.

One important constraint on models of ion outflow is the species dependence of the transverse acceleration. For BBELF waves, the surprising answer is that the degree of energization is independent of ion mass [*Knudsen et al.*, 1994; *Norqvist et al.*, 1996; *Lund et al.*, 1997]. By contrast, when EMIC waves accompany an ion conic, He$^+$ is most effectively heated [*Lund et al.*, 1998], and O$^+$ is heated more effectively than H$^+$ [*Erlandson et al.*, 1994]. Such a preferential heating is needed to explain the observed He$^+$ fluxes in a sizeable fraction of the upflowing ion events examined by *Collin et al.* [1988]. The X-type He$^+$ distributions observed in the dayside outer magnetosphere have been interpreted as signatures of preferential heating by EMIC waves [*Anderson and Fuselier*, 1994], and a similar mechanism is believed to account for anomalously high ^{3}He abundances in impulsive solar flares [*Temerin and Roth*, 1992; *Roth and Temerin*, 1997].

Because more than one wave mode can accelerate ions transversely to the geomagnetic field, a comparison of how effectively such acceleration mechanisms operate under similar conditions can shed light on the relative importance of these mechanisms. Previous studies of

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O^+ outflow [*André et al.*, 1998; *Norqvist et al.*, 1998] have shown that BBELF waves are responsible for most of the number flux; however, these studies do not investigate energy fluxes or outflow of lighter ions. Because EMIC waves can selectively enhance the energies and number fluxes of certain species [*Temerin and Roth*, 1992; *Lund et al.*, 1998], we must ask whether EMIC waves can dominate the outflow of He^+ in particular or whether BBELF ion conics remain most important in accounting for the energy fluxes and number fluxes of outflowing ions. This paper presents a direct comparison of transverse heating by BBELF and EMIC waves under similar conditions. The next section shows an auroral pass in which transverse heating by both BBELF and EMIC waves occurs. Using data from several such passes, we then compare the relative importance of the two mechanisms in terms of energies, energy fluxes, number fluxes, and densities.

2. Data

The Fast Auroral Snapshot Explorer (FAST) was launched August 21, 1996, into a 4200 × 350 km orbit with 83° inclination. *Carlson et al.* [1998] give an overview of the mission. FAST carries the Time-of-flight Energy Angle Mass Spectrograph (TEAMS), which simultaneously measures three-dimensional distributions of H^+, He^{2+}, He^+, and O^+ at 0.001–12 keV and also provides a mass spectrum over the range 1–60 amu/q [*Möbius et al.*, 1998].

We examine here the five passes through the auroral zone which meet the criteria below. All of these passes are between 2100 and 0100 magnetic local time. The selected passes contain examples of both BBELF and EMIC waves associated with ion conics; this condition was imposed in order to allow a comparison between the two mechanisms at nearby locations (separation of less than 5° in invariant latitude, one hour in magnetic local time, and 200 km in altitude) under as nearly the same geomagnetic and solar activity conditions as possible. We further required that the satellite collected fast survey data (time resolution of 2.5 s for H^+ and O^+ and 5 s for He^+ and a Nyquist frequency for δE of either 1024 or 256 Hz) during both ion conic events. A summary of the events selected is given in Table 1.

Data from one of these five passes are shown in Figure 1, which shows two minutes of data from a nightside (22.9 MLT) auroral pass on January 24, 1997. This orbit was geomagnetically quiet ($Kp = 1-$). An ion conic associated with BBELF waves is seen at 1245:25–1245:45, and an ion conic associated with EMIC waves is seen at 1246:10–1246:30. The ion conic with the EMIC waves is followed immediately by an upward ion beam; this morphology is not unusual at these altitudes.

In this example the BBELF waves are electrostatic, although examples of BBELF waves with a magnetic component exist (not shown). The BBELF waves coincide with bursts of upgoing field-aligned electrons, which are a candidate for the free energy source of the waves.

The EMIC waves are seen as a narrowband emission ($\Delta f/f \sim 0.1$) at frequencies of 100–150 Hz; the local proton gyrofrequency, denoted by the black line in the bottom panel of Figure 1, is ~ 200 Hz. A second band of waves, which appears at ~ 40 Hz for a few seconds near 1246:30, is consistent with EMIC waves on the He^+ branch of the dispersion relation; similar waves were reported in Viking data [*Gustafsson et al.*, 1990]. These waves occur along with bursts of field-aligned electrons at energies below the "inverted-V" peak, but the corre-

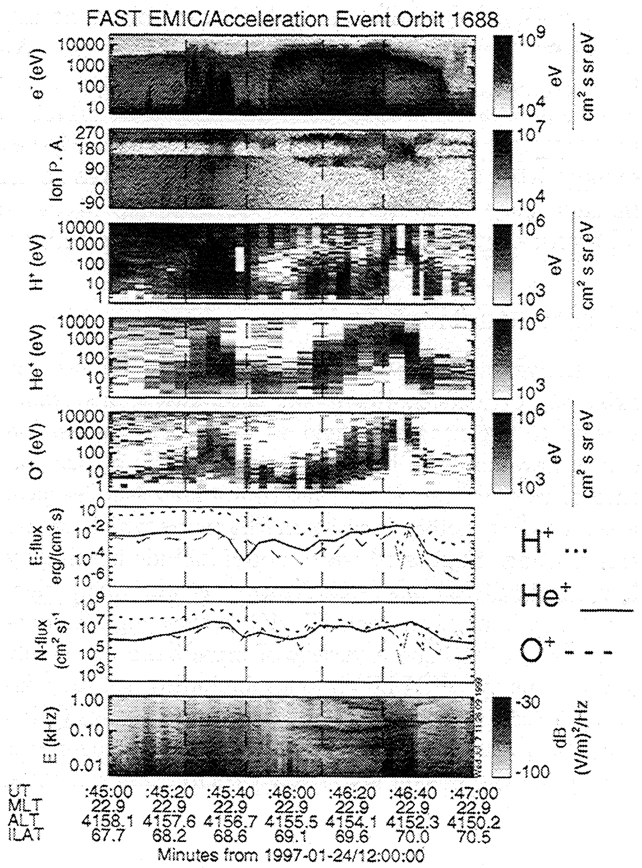

Figure 1. Two minutes of data from a nightside auroral pass on January 24, 1997. From top to bottom, the panels show the electron energy spectrogram (all pitch angles), the ion pitch angle spectrogram for 3–25000 eV from an electrostatic analyzer, the H^+ energy spectrogram, the He^+ energy spectrogram, the O^+ energy spectrogram, energy flux (excluding the plasma sheet population) for the three major ion species, number flux (excluding the plasma sheet population) for the three major ion species, and the ELF electric field spectrogram with a line denoting the local proton gyrofrequency. Plasma sheet ions were excluded by setting the upper energy limit of the integrations to the energy above 100 eV with the lowest energy flux. A BBELF ion conic is seen at 1245:30–1245:50, and an EMIC ion conic is seen at 1246:10–1246:30 (these intervals are indicated with vertical dashed lines).

Table 1. Data Used in This Study

Orbit	1688	1731	1789	1797	1959
Date (1997)	Jan. 24	Jan. 28	Feb. 2	Feb. 3	Feb. 18
Kp	1−	4	3+	0+	1
BBELF Events					
Start, UT	1245:25	1210:20	2105:00	1446:00	1426:15
Duration, s	20	60	60	20	15
MLT	22.9	22.4	0.9	22.4	21.4
Altitude, km	4160	4150	3800	3970	3110
Invariant latitude	68.6	64.9	74.5	66.5	69.1
H^+ energy, eV	450	448	713	721	330
He^+ energy, eV	204	609	821	728	160
O^+ energy, eV	169	958	910	920	115
n_{H^+}/n_i	0.630	0.394	0.244	0.273	0.149
n_{He^+}/n_i	0.193	0.111	0.308	0.125	0.342
n_{O^+}/n_i	0.165	0.487	0.435	0.595	0.749
EMIC Events					
Start, UT	1246:10	1211:50	2102:30	1446:40	1423:40
Duration, s	20	60	60	20	15
MLT	22.9	22.4	0.3	22.4	21.2
Altitude, km	4150	4140	3900	3940	3290
Invariant latitude	69.5	67.0	72.1	67.4	65.0
H^+ energy, eV	89.6	109	134	59.0	101
He^+ energy, eV	605	525	775	124	306
O^+ energy, eV	131	477	205	88.3	105
n_{H^+}/n_i	0.309	0.544	0.316	0.103	0.283
n_{He^+}/n_i	0.097	0.102	0.082	0.146	0.072
n_{O^+}/n_i	0.589	0.346	0.592	0.749	0.638

UT, durations, and locations of events are approximate.

lation is not one-to-one. Although some VLF whistler mode waves are seen at the same time as the EMIC waves, the EMIC waves are better correlated with the ion heating; this pattern has also been seen in Freja data [*Erlandson et al.*, 1994; *André et al.*, 1998].

3. Direct Comparison of Mechanisms

The ratios of the He^+ energy to the O^+ energy fall in the range 0.64–1.39 for the BBELF events and 1.10–4.62 for the EMIC events, with the latter ratio larger on each pass. Similarly, the ratios of the He^+ energy to the H^+ energy are 0.45–1.36 for the BBELF events and 2.10–6.75 for the EMIC events. For the EMIC events we find $E_{He^+} > E_{O^+} > E_{H^+}$, consistent with our earlier report [*Lund et al.*, 1998]; the mass ordering of energies in the BBELF events, although monotonic, is not consistent from one event to the next.

Figure 2 shows the relative importance of BBELF and EMIC waves in ion heating for the events listed in Table 1. We see that in all five cases, the ratio of energy fluxes between the EMIC event and the BBELF event is larger for He^+ than for H^+ or O^+, as would be expected for preferential acceleration of He^+ by EMIC waves. This pattern, however, does not hold for number fluxes; in two of the five cases the overall number flux is at least as high in the EMIC event as in the BBELF event while the He^+ number flux actually drops. This result is contrary to the prediction of He^+ flux enhancements for the Temerin-Roth acceleration mechanism, although the range of parameters appropriate in the auroral zone differ greatly from the range of parameters considered by *Temerin and Roth* [1992], which are appropriate for impulsive solar flares. The EMIC events are also not associated with enhancements in the relative or absolute He^+ density. This point is illustrated in Figure 3 for the pass shown in Figure 1; the He^+ concentration, shown by the squares, is enhanced only poleward of the EMIC event. The discrepancy between these results and the predictions of *Temerin and Roth* [1992] could arise because the acceleration by EMIC waves is occurring at a higher altitude than the source region of the plasma, and some transverse ion heating, possibly by lower hybrid waves, may occur at these lower altitudes [*Lund et al.*, 1998].

We also see from Figure 2 that for all five passes studied, the BBELF event has the higher overall energy flux, and that the ratio of overall energy fluxes is smaller than the ratio of overall number fluxes for the EMIC events compared with the BBELF events. This result also holds for H^+ and O^+ separately. The BBELF emissions therefore are more effective than the EMIC emissions at heating H^+ and O^+. This result is expected since BBELF emissions by definition can be cyclotron resonant with all three major species at a given altitude and can maintain this resonance over a sizeable altitude range even if the spectral shape is indepen-

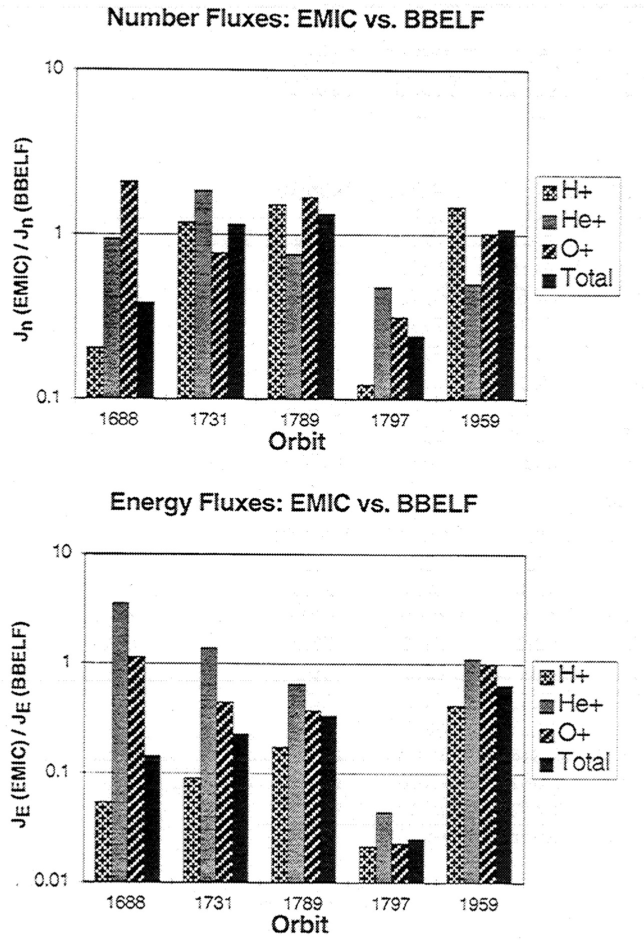

Figure 2. (top) Ratios of number fluxes in the EMIC events to number fluxes in the BBELF events for H^+, He^+, O^+, and all ions for the five orbits listed in Table 1. (bottom) Ratios of energy fluxes for these events. The fluxes are integrated over time for each event.

dent of altitude. In fact, a previous study of Freja data [*Norqvist et al.*, 1996] showed that as little as 3% of the energy at the O^+ gyrofrequency in BBELF emissions can account for the observed O^+ energization. EMIC emissions, being narrow-banded, can only be resonant in a narrow altitude range. The fundamental resonance with He^+ seems more efficient than the harmonic resonance with O^+; indeed, three of the five passes have a higher He^+ energy flux in the EMIC event than the BBELF event. Since their frequency is below the local proton gyrofrequency, EMIC waves cannot be cyclotron resonant with H^+ at or anywhere below the observation point, so minimal effects on H^+ are observed.

There are indications that EMIC waves may play a larger role in transverse ion acceleration during geomagnetically active periods than during quiet periods. We have found that the occurrence probability of EMIC ion conics increases with *Kp* [*Lund et al.*, 1999] in a manner consistent with the *Kp* dependence reported for EMIC waves alone [*Saito et al.*, 1987]. In addition, of the five passes examined here, all but the two most magnetically quiet had higher total number fluxes during the EMIC events than during the BBELF events. However, a study by *Norqvist et al.* [1998], which examined only O^+ outflow, showed that number fluxes in BBELF events are also well-correlated with *Kp*. A more detailed study would be needed to determine which effect is more important.

Note also that because we have restricted this study to passes in which both EMIC and BBELF emissions are associated with ion conics, we have artificially confined this study to the premidnight sector, where EMIC emissions are most prevalent [*Saito et al.*, 1987; *Erlandson and Zanetti*, 1998]. BBELF emissions, by contrast, are found at all local times [*André et al.*, 1998; *Lund et al.*, 1997]. While EMIC emissions can be locally important for He^+ outflow in the aurora, a fair comparison of the two mechanisms would show an even more lopsided dominance of BBELF emissions in transverse ion acceleration in the aurora.

4. Conclusion

Even though this study's design overemphasizes the importance of EMIC waves compared to BBELF waves in transverse acceleration of ions, we find no clear trend as to which mechanism is more important locally in determining He^+ outflow, while the BBELF ion conics produce a larger outflow of H^+ and O^+, as well as a larger total ion outflow, than the EMIC ion conics. Furthermore, we find that, contrary to our expectations for a mass-selecting acceleration mechanism, the EMIC waves in these events are not correlated with enhanced He^+ densities. Since we have found no preference for

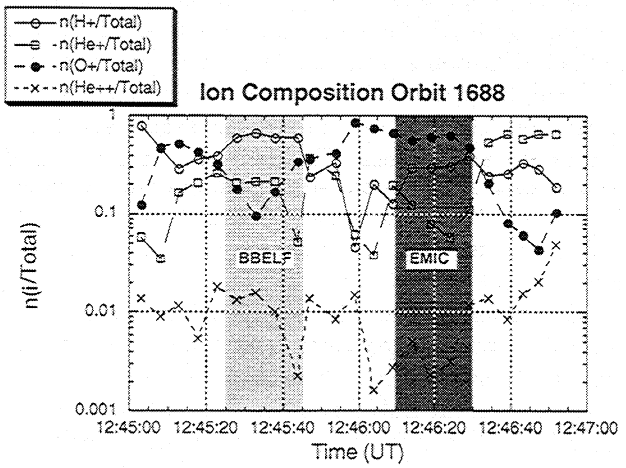

Figure 3. Fractional ion composition of the plasma during the period shown in Figure 1. The shaded regions correspond to the BBELF (light) and EMIC (dark) ion heating events from this pass. H^+ is shown with open circles, He^+ with squares, O^+ with solid circles, and He^{++} with crosses.

ion heating by EMIC waves in spite of this bias, we conclude that BBELF waves provide the most important mechanism for producing ion conics at auroral latitudes.

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References

Amatucci, W. E., D. N. Walker, G. Ganguli, D. Duncan, J. A. Antoniades, J. H. Bowles, V. Gavrishchaka, and M. E. Koepke, Velocity-shear-driven ion cyclotron waves and associated transverse ion heating, *J. Geophys. Res.*, , *103*, 11,711, 1998.

Anderson, B. J., and S. A. Fuselier, Response of thermal ions to electromagnetic ion cyclotron waves, *J. Geophys. Res.*, , *99*, 19,413, 1994.

André, M., P. Norqvist, L. Andersson, L. Eliasson, A. I. Eriksson, L. Blomberg, R. E. Erlandson, and J. Waldemark, Ion energization mechanisms at 1700 km in the auroral region, *J. Geophys. Res.*, , *103*, 4199, 1998.

Carlson, C. W., R. F. Pfaff, and J. G. Watzin, The Fast Auroral SnapshoT (FAST) mission, *Geophys. Res. Lett.*, , *25*, 2013, 1998.

Collin, H. L., W. K. Peterson, J. F. Drake, and A. W. Yau, The helium components of energetic terrestrial ion upflows: Their occurrence, morphology, and intensity, *J. Geophys. Res.*, , *93*, 7558, 1988.

Ergun, R. E., et al., FAST observations of large-amplitude solitary structures, *Geophys. Res. Lett.*, , *25*, 2041, 1998.

Erlandson, R. E., and L. J. Zanetti, A statistical study of auroral electromagnetic ion cyclotron waves, *J. Geophys. Res.*, , *103*, 4627, 1998.

Erlandson, R. E., L. J. Zanetti, M. H. Acuña, A. I. Eriksson, L. Eliasson, M. H. Boehm, and L. G. Blomberg, Freja observations of electromagnetic ion cyclotron ELF waves and transverse oxygen ion acceleration on auroral field lines, *Geophys. Res. Lett.*, , *21*, 1855, 1994.

Gustafsson, G., M. André, L. Matson, and H. Koskinen, On waves below the local proton gyrofrequency in auroral acceleration regions, *J. Geophys. Res.*, , *95*, 5889, 1990.

Kintner, P. M., J. LaBelle, W. Scales, A. W. Yau, and B. A. Whalen, Observations of plasma waves within regions of perpendicular ion acceleration, *Geophys. Res. Lett.*, , *13*, 1113, 1986.

Knudsen, D. J., and J.-E. Wahlund, Core ion flux bursts within solitary kinetic Alfvén waves, *J. Geophys. Res.*, , *103*, 4157, 1998.

Knudsen, D. J., B. A. Whalen, T. Abe, and A. Yau, Temporal evolution and spatial dispersion of ion conics: Evidence for a polar cusp heating wall, in *Solar System Plasmas in Space and Time*, *Geophys. Monogr. Ser.*, vol. 84, edited by J. L. Burch and J. H. Waite, pp. 163–169, AGU, Washington, D. C., 1994.

Knudsen, D. J., J. H. Clemmons, and J.-E. Wahlund, Correlation between core ion energization, suprathermal electron bursts, and broadband ELF plasma waves, *J. Geophys. Res.*, , *103*, 4171, 1998.

Koepke, M. E., J. J. Carroll, and M. W. Zintl, Laboratory simulation of broadband ELF waves in the auroral ionosphere, *J. Geophys. Res.*, , *104*, 14,397, 1999.

Lund, E. J., E. Möbius, L. Tang, L. M. Kistler, M. A. Popecki, D. M. Klumpar, B. Klecker, M. Temerin, R. E. Ergun, J. P. McFadden, C. W. Carlson, and R. J. Strangeway, Waves that transversely accelerate ions at 2500–4000 km (abstract), *Eos Trans. AGU*, , *78*(46), Fall Meet. Suppl., F605, 1997.

Lund, E. J., et al., FAST observations of preferentially accelerated He^+ in association with auroral electromagnetic ion cyclotron waves, *Geophys. Res. Lett.*, , *25*, 2049, 1998.

Lund, E. J., E. Möbius, D. M. Klumpar, L. M. Kistler, M. A. Popecki, B. Klecker, R. E. Ergun, J. P. McFadden, C. W. Carlson, and R. J. Strangeway, Occurrence distribution of preferential heating events in the aurora, *Adv. Space Res.*, in press, 1999.

Lynch, K. A., R. L. Arnoldy, P. M. Kintner, and J. Bonnell, The AMICIST auroral sounding rocket: A comparison of transverse ion acceleration mechanisms, *Geophys. Res. Lett.*, , *23*, 3293, 1996.

Möbius, E., et al., The 3-D plasma distribution function analyzers with time-of-flight mass discrimination for Cluster, FAST, and Equator-S, in *Measurement Techniques in Space Plasmas: Particles*, *Geophys. Monogr. Ser.*, vol. 102, edited by R. F. Pfaff, J. E. Borovsky, and D. T. Young, p. 243, AGU, Washington, D. C., 1998.

Norqvist, P., M. André, L. Eliasson, A. I. Eriksson, L. Blomberg, H. Lühr, and J. H. Clemmons, Ion cyclotron heating in the dayside magnetosphere, *J. Geophys. Res.*, , *101*, 13,179, 1996.

Norqvist, P., M. André, and M. Tyrland, A statistical study of ion energization mechanisms in the auroral region, *J. Geophys. Res.*, , *103*, 23,459, 1998.

Roth, I., and M. Temerin, Enrichment of ^{3}He and heavy ions in impulsive solar flares, *Astrophys. J.*, , *477*, 940, 1997.

Saito, H., T. Yoshino, and N. Sato, Narrow-banded ELF emissions over the southern polar region, *Planet. Space Sci.*, *35*, 745, 1987.

Sharp, R. D., R. G. Johnson, and E. G. Shelley, Observation of an ionospheric acceleration mechanism producing energetic (keV) ions primarily normal to the geomagnetic field direction, *J. Geophys. Res.*, , *82*, 3324, 1977.

Temerin, M., and I. Roth, The production of ^{3}He and heavy ion enrichments in ^{3}He-rich flares by electromagnetic hydrogen cyclotron waves, *Astrophys. J.*, , *391*, L105, 1992.

Wahlund, J.-E., et al., Broadband ELF plasma emission during auroral energization 1. Slow ion acoustic waves, *J. Geophys. Res.*, , *103*, 4343, 1998.

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