ORDERED FINE STRUCTURE IN THE RADIO EMISSION OBSERVED BY CASSINI, CLUSTER AND POLAR

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Abstract

Cassini has observed ordered fine structure in the Saturn kilometric radiation (SKR) data that bears a strong resemblance to similar features observed by Polar and Cluster in the terrestrial auroral kilometric radiation (AKR) data. We investigate the possible role of electromagnetic ion cyclotron (EMIC) waves in stimulating the growth of AKR and producing the ordered fine structure observed at Earth. We believe this same mechanism may be applicable to the ordered fine structure observed in SKR by Cassini, and should indicate the presence of EMIC waves in the Saturnian auroral magnetosphere.

1 Introduction

Kurth et al. [2005] have recently reported observations at high time resolution of Saturn kilometric radiation (SKR). These observations clearly show a fine structure to the SKR that is strikingly similar to observations of terrestrial auroral kilometric radiation (AKR) as has been reported in the past by Gurnett et al. [1979] and Gurnett and Anderson [1981], for instance, using ISEE data. As in the case of AKR, the SKR fine structure show discrete bursts lasting only a few seconds or less.

The AKR fine structure provides an insight into the linear and nonlinear mechanisms responsible for the generation of AKR. Menietti et al. [1996; 1997] have identified an ordered fine structure in the terrestrial AKR which has been called striations or "rain" by Mutel et al. [2004]. An example of this special type of fine structure observed in the Polar plasma wave instrument data is shown in Figure 1. These structures indicate a systematic drifting in frequency that implies a physically drifting source region travelling up the magnetic field line at typically a few hundred km/sec.

The observations of ordered fine structure at Saturn reported by Kurth et al. [2005] imply that the source mechanisms for these signatures are similar to or the same as

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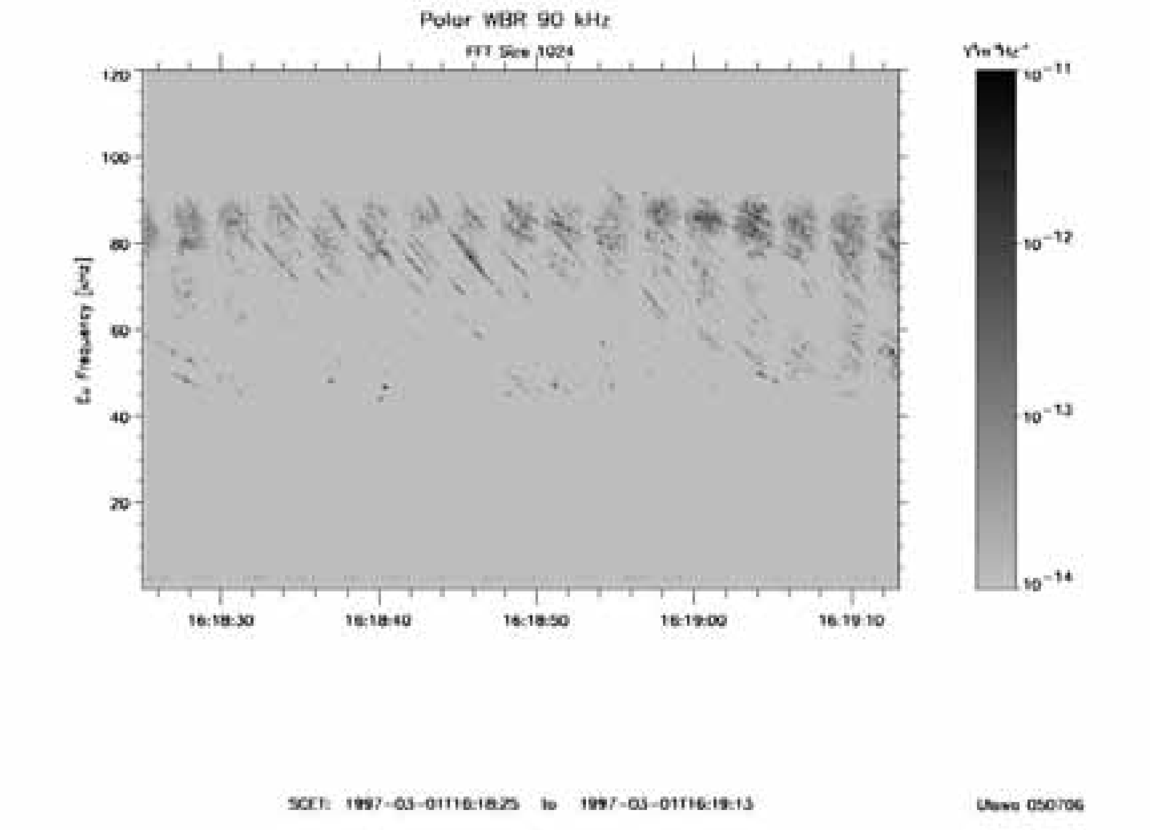

Figure 1: A 48-s frequency-time spectrogram obtained by the wideband receiver of the plasma wave instrument on board the Polar spacecraft on March 1, 1997, starting at 16:18:25 UT. At this time the spacecraft is located over the polar cap, well above the auroral kilometric radiation (AKR) source region. The negative frequency-drifting signatures all with about the same slope are striations or "rain". In some cases the slope decreases at the lowest frequencies.

those observed at Earth. Menietti et al. [1996; 1997] suggested that EMIC waves which are commonly observed in the AKR source region may be responsible for stimulating the growth of AKR. Field-aligned electrons that have served to satisfy the resonance condition for the growth of AKR also serve as a free-energy source for the growth of EMIC waves near the lower part of the auroral acceleration region. These waves are generated by inverse Landau resonance as described in Chaston et al. [2002]. Menietti et al. [2006] have investigated the role of EMIC waves in the possible stimulation of auroral kilometric radiation. The authors used a conjunction pass of Polar (in the AKR source region) and Cluster (above the source region) to show that observed electron beams within the AKR source region could generate EMIC waves that may propagate in the AKR source region to stimulate AKR fine structure (rain). The EMIC waves are found to have group velocities along the magnetic field line with magnitudes of several hundred km/sec, consistent with observed frequency drift rates.

In this paper we compare the data obtained at Earth (AKR) to that at Saturn (SKR).

Based on modeling results for terrestrial AKR ordered fine structure we form some conclusions about the possible plasma conditions within the SKR source regions.

2 SKR Observations

An example of the data obtained by Cassini is shown in Figure 2, obtained by the wideband instrument (WBR), part of the plasma wave instrument. The frequency range is from 4 to 11 kHz and the time interval is 77 seconds. The data were obtained for day 69 of 2005 when the spacecraft was located at a distance of near 16 R_s, latitude of 0.11 degrees and a local time of 4.74 hours. We note negative frequency-drifting signatures all with about the same slope, but the slope decreases at the lowest frequencies. Another example shown in Figure 3 is from the same day about 15 minutes later. Here we see the striations are observed at slightly higher frequency, and show almost a constant frequency drift, with no clear indication of decreasing slope at the lowest frequency.

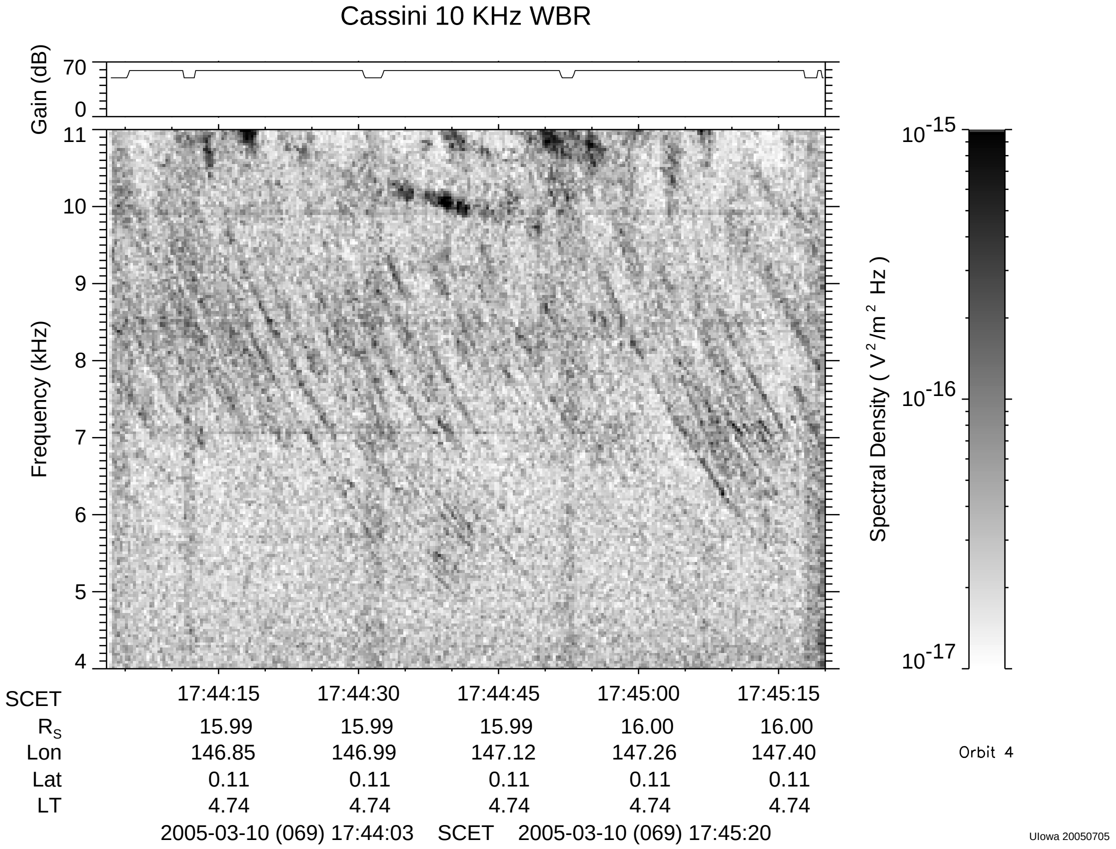

Figure 2: A frequency-time spectrogram obtained by the WBR on board Cassini. The frequency range is from 4 to 11 kHz and the time interval is 77 seconds. The data were obtained for day 69 of 2005 when the spacecraft was located at a distance of near 16 R_s, latitude of 0.11 degrees and a local time of 4.74 hours. The negative frequency-drifting signatures all have similar slope, which decreases at the lowest frequencies.

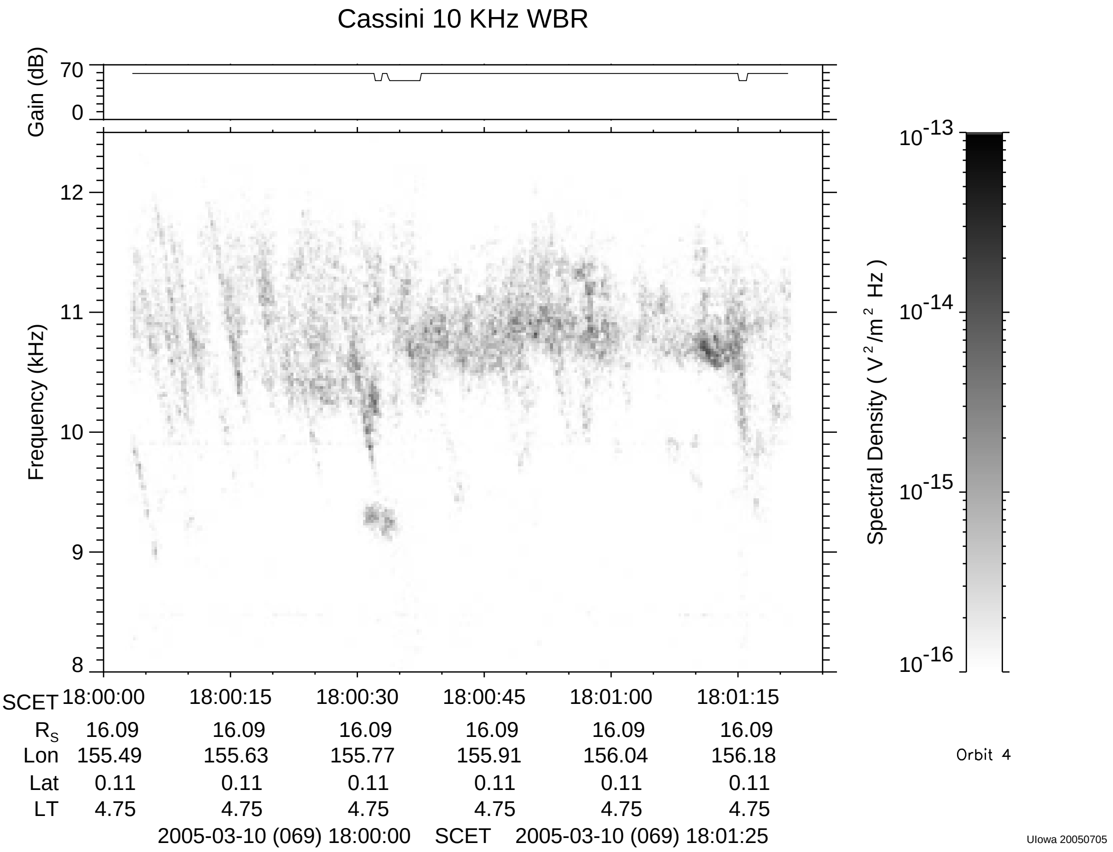

Figure 3: A spectrogram of Cassini WBR data obtained less than 15 minutes after the time of Figure 2. The striations are observed at slightly higher frequency, and show almost a constant frequency drift, with no clear indication of decreasing slope at the lowest frequency.

Ordered fine structure in the SKR data has also been observed at higher frequencies. Due to space limitations we do not show wave data taken by WBR for July 12, 2005, from 20:33 to 20:55 SCET. Cassini was located at a radial distance of about 21.7 R_s, latitude of -20.4 degrees and a local time of about 9.6 hours. During this time, striations similar to those observed in Figures 2 and 3 are observed while the instrument is operating with an 80 kHz bandwidth. The negative frequency drifting signatures exist over a frequency range from 80 kHz (and probably higher) down to less than 20 kHz. It is perhaps significant that these observations are made in the southern hemisphere.

These observations are strikingly similar to those of the terrestrial AKR. A notable difference is the frequency range. While SKR is observed at frequencies of several hundred kilohertz, it can also be observed at only a few kilohertz. The ordered fine structure to date observed in SKR appears most frequently at the lowest frequencies. While terrestrial AKR is observed usually at frequencies above 40 kHz or higher, it is also true that observations of AKR ordered fine structure occur most frequently at the lowest frequencies.

3 Discussion

The systematic (ordered) nature of the fine structure features, all with negative slope and occurring in semi-regular fashion over a limited frequency range, is a common feature of the striations observed in terrestrial AKR as well as the SKR. A theory for the generation of the terrestrial striations proposed by Menietti et al. [1996; 1997; 2006] suggests that EMIC waves travelling up (away from the planet) act to stimulate the growth of AKR (SKR). The process of wave stimulation may be the result of a plasma that is in marginal stability and the electric fields of the EMIC waves generate a locally unstable environment through a change in local plasma density or in pitch angle anisotropy.

As pointed out by Gurnett and Anderson [1981], to explain a drifting frequency signature of cyclotron maser emission would require that the source drift along the field line at a velocity given by

$$\frac{dR}{dt} = -R_E \frac{df}{dt} \frac{f_{ce}^{1/3}}{3f^{4/3}} \tag{1}$$

For the case of terrestrial AKR, the typical frequency range is 40kHz $< f <$ 500kHz, with excursions up to 800 kHz rarely. In the past, Warwick et al. [1981] have reported observations of SKR from the lowest frequency channel of the Planetary Radio Astronomy instrument (20 kHz) ranging to about 1.2 MHz, with the peak intensities occurring typically from 200 to 400 kHz. Gurnett et al. [2005] report peak intensities of SKR over a similar frequency range from 100 to 400 kHz, but SKR does extend to frequencies even less than 10 kHz [cf. Kurth et al., 2005].

For AKR, Menietti et al. [2000] have reported striations are predominantly found in the 40 kHz to 215 kHz frequency range. If we select parameters from the terrestrial data of Figure 1, assuming $f_{ce} = 80$ kHz and $df/dt = -4.2$ kHz/sec, equation 1 gives $dR/dt = 302$ km/sec away from Earth.

We obtain an approximate frequency drift rate of -0.25 kHz/s for the SKR data of Figure 2. However, the local cyclotron frequency is much lower. For $f_{ce} = 8$ kHz (ion cyclotron frequency, $f_H = 4.3$ Hz) equation 1 gives us 2590 km/sec as a source drift rate away from the planet. Figure 3 is easier to measure because of the lack of changing slope. We obtain $df/dt = -0.45$ kHz/s. For $f_{ce} = 11$ kHz we obtain $dR/dt = 3049$ km/sec away from the planet. These values are about an order of magnitude larger than those observed for terrestrial AKR, due to the much larger value of the radius of Saturn. No *in situ* plasma measurements within the SKR source region are yet available to provide estimates of the group velocity of EMIC waves.

4 Summary and Conclusions

Based on the model of Menietti et al. [2006], one should expect to observe EMIC waves propagating along the magnetic field lines containing the AKR/SKR source region. These waves are commonly observed in the terrestrial auroral region and can modulate electron particle fluxes [cf. Temerin et al., 1986; Chaston et al., 1998] and energy [McFadden et al., 1998]. McFadden et al., [1998] clearly show how intense EMIC waves modulate the electron energy within the terrestrial AKR source region. Chaston et al. [1998] further state that these same waves have Poynting fluxes usually directed upwards out of the auroral acceleration region. It is not difficult to imagine how this modulation of particle energy directly impacts the AKR growth rate by changing the cyclotron resonance condition and the electron distribution function from marginal stability to instability. As pointed out in Kurth et al. [2005], future Cassini trajectories will allow the spacecraft to traverse field lines within five Saturnian radii, and these likely will include auroral field lines. It will be important to our understanding of the generation of AKR and SKR to carefully identify the particle distributions and the local wave fields within and near the auroral field lines. Given the abundance of H^+ and O^+ ions in the Saturnian magnetosphere, it is likely that EMIC waves are present in the low-altitude auroral region, generated by electron and ion beams.

We have considered the stimulation of AKR and SKR by EMIC waves as a possible explanation of ordered fine structure. There are still outstanding questions regarding the EMIC waves that must be answered. It is clearly observed that striations are predominantly observed with negative frequency drifts. EMIC waves are observed in terrestrial auroral regions that propagate both upward and downward along the magnetic field lines. Why would such waves only propagating upward stimulate the growth of AKR/SKR? Perhaps it is because the EMIC waves in the upward direction are not in inverse Landau resonance and do not extract energy from the electron beams. Perhaps it is because the EMIC waves that are generated are below the AKR/SKR source region and must be reflected or propagate initially upward to stimulate AKR/SKR growth. Another possibility is that EMIC waves are generated by the upward drifting ion beams near the top of the upward current region, as discussed by Bergmann [1984]. In the latter case, predominately upward travelling EMIC waves should result.

Berthomier et al. [1998] and Pottelette et al. [2003] have shown that nonlinear ion acoustic hole structures evolve into electric potential ramps or weak double layers and density rarefactions. Further they have argued these electrostatic shocks with finite net potential drop across the structures may be responsible for providing the potential of the upward current region within the AKR source region. Pottelette et al. [2003] have suggested that AKR fine structure shows evidence of such electrostatic shock layers.

As reported by Bounds et al. [1999] ion holes within the terrestrial upward current region are observed with predominately upward velocities in the range $75\text{km/sec} < V < 300\text{km/sec}$ which are consistent with the frequency drifts observed for ordered fine structure. It is possible that ion holes accelerate the electrons producing small density depletions and localized electron beams. Ion holes thus provide another intriguing alternative for the production of ordered fine structure. Unfortunately, *in situ* measurements of ion holes within the SKR source region cannot be made. However, observations of shock-like impulses have been made in the magnetosphere of Jupiter [Kurth et al., 2001]. The effectiveness of the possible stimulation of AKR/SKR by EMIC waves and/or by ion holes is a topic of ongoing research.

Acknowledgements

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References

Bergmann, R., Electrostatic ion (hydrogen) cyclotron and ion acoustic wave instabilities in regions of upward field-aligned current and upward ion beams, *J. Geophys. Res.*, **89**, A2, 953-968, 1984.

Berthomier, M., R. Pottelette, and M. Malingre, Solitary waves and weak double layers in the two-electron-temperature auroral plasma, *J. Geophys. Res.*, **103**, 4261–4270, 1998.

Bounds, S. R., R. F. Pfaff, S. F. Knowlton, F. S. Mozer, M. A. Temerin, and C. A. Kletzing, Solitary potential structures associated with ion and electron beams near 1 R_E altitude, *J. Geophys. Res.*, **104**, A12, 28 709–28 717, 1999.

Chaston, C. C., R. E. Ergun, G. T. Delory, W. Peria, M. Temerin, C. Cattell, R. Strangeway, J. P. McFadden, C. W. Carlson, R. C. Elphic, D. M. Klumpar, W. K. Peterson, E. Moebius, R. Pfaff, Characteristics of electromagnetic proton cyclotron waves along auroral field lines observed by FAST in regions of upward current, *Geophys. Res. Lett.*, **25**, 2057–2060, 1998.

Chaston, C. C., J. W. Bonnell, J. P. McFadden, R. E. Ergun, and C. W. Carlson, Electromagnetic ion cyclotron waves at proton cyclotron harmonics, *J. Geophys. Res.*, **107**, 1351, doi:10.1029/2001JA900141, 2002.

Gurnett, D. A., R. R. Anderson, F. L. Scarf, R. W. Fredericks, and E. J. Smith, Initial results from the ISEE 1 and 2 plasma wave investigation, *Space Sci. Rev.,* **23,** 103–122, 1979.

Gurnett, D. A., and R. R. Anderson, The kilometric radio emission spectrum: Relationship to auroral acceleration processes, in *Physics of Auroral Arc Formation, Geophysical Monograph Series, Vol.*, **25**, edited by S.-I. Akasofu and J. R. Kan, American Geophysical Union, 341–350, 1981.

Gurnett, D. A., W. S. Kurth, G. B. Hospodarsky, A. M. Persoon, T. F. Averkamp, B. Cecconi, A. Lecacheux, P. Zarka, P. Canu, N. Cornilleau-Wehrlin, P. Galopeau, A. Roux, C. Harvey, P. Louarn, R. Boström, G. Gustafsson, J.-E. Wahlund, M. D. Desch, W. M. Farrell, M. L. Kaiser, K. Goetz, P. J. Kellogg, G. Fischer, H.-P. Ladreiter, H. Rucker, H. Alleyne, and A. Pedersen, Radio and plasma wave observations at Saturn from Cassini's approach and first orbit, *Science*, **307**, 1255–1259, 2005.

Kurth, W. S., D. A. Gurnett, A. M. Persoon, A. Roux, S. J. Bolton, and C. J. Alexander, The plasma wave environment of Europa, *Planet. Space Sci.,* **49**, 345–363, 2001.

Kurth, W. S., G. B. Hospodarsky, D. A. Gurnett, B. Cecconi, P. Louarn, A. Lecacheux, P. Zarka, H. O. Rucker, M. Boudjada, and M. L. Kaiser, High spectral and temporal resolution observations of Saturn Kilometric Radiation, *Geophys. Res. Lett.*, **32**, 20ff., doi: 10.1029/2005GL022648, 2005.

McFadden, J. P., C. W. Carlson, R. E. Ergun, C. C. Chaston, R. S. Mozer, M. Temerin, D. M. Klumpar, E. G. Shelley, W. K. Peterson, E. Moebius, L. Kistler, R. Elphic. R. Strangeway, C. Cattell, R. Pfaff, Electron modulation and ion cyclotron waves observed by FAST, *Geophys. Res. Lett.*, **25**, 2045–2048, 1998.

Menietti, J. D., H. K. Wong, W. S. Kurth, D. A. Gurnett, L. J. Granroth, and J. B. Groene, Discrete stimulated auroral kilometric radiation observed in the Galileo and DE 1 wideband data, *J. Geophys. Res.,* **101,** 10 673–10 680, 1996.

Menietti, J. D., H. K. Wong, W. S. Kurth, D. A. Gurnett, L. J. Granroth, and J. B. Groene, Possible stimulated AKR observed in Galileo, DE 1, and Polar wideband data, in *Planetary Radio Emissions IV*, H. O. Rucker, S. J. Bauer, and A. Lecacheux (eds.), Austrian Academy of Sciences Press, Vienna, 259–273, 1997.

Menietti, J. D., A. M. Persoon, J. S. Pickett, and D. A. Gurnett, Statistical study of auroral kilometric radiation fine-structure striations observed by Polar, *J. Geophys. Res.*, **105**, 18 857–18 866, 2000.

Menietti, J. D., R. L. Mutel, O. Santolik, J. D. Scudder, I. W. Christopher, and J. M. Cook, Striated drifting AKR bursts: Possible stimulation by upward traveling EMIC waves, *J. Geophys. Res.*, **111 (A4)**, 4214, doi: 10.1029/2005JA011339, 2006.

Mutel, R. L., D. Menietti, and I. Christopher, Cluster observations of banded fine structure in AKR source regions, Abstract of paper presented at the Fall Meeting of the American Geophysical Union, SM72D-05, 2004.

Pottelette, R., R. A. Treumann, M. Berthomier, and J. Jasperse, Electrostatic shock properties inferred from AKR fine structure, *Nonlinear Processes in Geophysics*, **10**, 87–92, 2003.

Temerin, M., J. McFadden, M. Boehm, C. W. Carlson, and W. Lotko, Production of flickering aurora and field-aligned electron flux by electromagnetic ion cyclotron waves, *J. Geophys. Res.,* **91,** 5769–5792, 1986.

Warwick, J. W., J. B. Pearce, D. R. Evans, T. D. Carr, J. J. Schauble, J. K. Alexander, M. L. Kaiser, M. D. Desch, B. M. Pedersen, A. Lecacheux, G. Daigne, A. Boischot, and C. H. Barrow, Planetary radio astronomy observations from Voyager 1 near Saturn, *Science*, **212**, 239–243, 1981.