REVIEW OF RECENT GROUND-LEVEL OBSERVATIONS OF TERRESTRIAL AURORAL RADIO EMISSIONS

J. LaBelle*

Abstract

Recent observations have significantly extended knowledge about auroral radio emissions in the frequency range 0.1–5 MHz which are observed at ground level. These phenomena fall into three general classes: Auroral Roar, a relatively narrow band emission ($\delta f/f \sim 0.1$) that occurs near two and three times the ionospheric electron cyclotron frequency; Auroral MF-Burst, a broadband impulsive emission in the frequency range 1.4–4.4 MHz often characterized by a null at the electron cyclotron harmonic; and Auroral Hiss, an impulsive emission with peak power spectral density at VLF but which often extends above 1 MHz. (A second type of auroral hiss is continuous in nature but seldom extends above VLF.) Auroral Roar exhibits fine structure similar to that observed in auroral kilometric radiation. MF-Burst is strongly correlated with Auroral Hiss on time scales of seconds. All three emissions are observed at ground level during the expansion phase of substorms and are associated with optical aurora. A well-developed quantitative theory exists only for Auroral Hiss, which has been observed for decades. Even in the case of Auroral Hiss, there is evidence for a subset of cases which cannot be explained by the generally accepted theory. Theoretical work on Auroral Roar is not yet well developed, but two competing classes of mechanisms have been proposed: direct mechanisms such as the cyclotron maser instability, in which electron energy is directly converted to EM waves; and indirect mechanisms by which auroral electrons stimulate electrostatic waves which mode convert to escaping EM waves. No quantitative theory exists for the Auroral MF-Burst phenomenon, although it has been suggested that such bursts may result from Langmuir or upper hybrid waves excited over a range of altitudes by bursts of auroral electrons. Although these 0.1–5 MHz auroral radio emissions are much weaker than auroral kilometric radiation and probably do not play as significant a role in auroral dynamics, they remain an outstanding mystery of the terrestrial aurora, and the resolution of the mystery may lead to better understanding of auroral dynamics or better methods of detecting auroral processes with ground-based instruments.

*Department of Physics and Astronomy, Dartmouth College, Hanover, New Hampshire, USA

1 Introduction

The aurora has been recognized as a radio source ever since the first observations of auroral hiss at VLF (3–30 kHz) (see reviews by Helliwell, [1965]; Sazhin et al., [1993]). Later, auroral hiss was observed in the LF band (30–300 kHz) (e.g., Reber and Ellis, [1956]; Dowden, [1959]), and numerous ground-level measurements of higher frequency radio noise from aurora have been reported (reviews by Ellyett, [1969]; LaBelle, [1989]; LaBelle and Weatherwax, [1993]). These include reports of synchrotron radiation from the aurora (e.g., Parthasarathy and Berkey, [1964]) and observations of wideband noise (e.g., Benson and Desch, [1991]). Various theoretical predictions of LF/MF/HF auroral emissions have also appeared in the literature (e.g., Wang et al., [1971]; Yermakova and Trakhtengerts, [1981]; Wu et al., [1989]; Ziebell et al., [1991]). For the past several years, Dartmouth College researchers have deployed radio receivers in the Arctic and Antarctic to produce systematic long-term measurements of LF/MF/HF auroral radio emissions at multiple ground-based observatories. Three distinct types of emissions have been identified: auroral hiss, auroral roar, and medium frequency burst. The mechanisms responsible for these emissions will shed light on ionospheric plasma processes and provide a means of remote sensing ionospheric conditions. However, no satisfactory generation mechanism has been established for auroral roar or auroral MF-burst.

2 Review of Recent Results

At Dartmouth College, we have developed a computer-controlled radio receiver system which records 0.05-5.0 MHz spectra. The sensor is a 10 m^2 magnetic loop, and the dynamic range is 70 dB. Computer control of the experiment allows a large number of operational measurement modes to be programmed. (Sample rate, measured frequencies, and calibration signals can be varied according to a pre-programmed schedule.) Undergraduate and graduate students contribute to both the hardware and software components of the experiment.

The first Dartmouth radio receivers confirmed the existence of auroral roar, a narrowband radio emission near twice the ionospheric electron gyrofrequency ($2f_{ce}$) previously reported by Kellogg and Monson [1979; 1984]. Unexpectedly, we found that this narrow-band emission also occurs near *three* times the electron gyrofrequency [Weatherwax et al., 1993]. In addition, we discovered an entirely new bursty type of auroral radio emission called MF-burst, which occurs at frequencies 1.3–4.5 MHz during the expansion phase of substorms and is strongly correlated with auroral hiss [Weatherwax et al., 1994]. Explanations have been proposed for $2f_{ce}$ and $3f_{ce}$ auroral roar (e.g., Gough and Urban, [1983]; Weatherwax et al., 1995; Yoon et al., [1996]), and recently two possible mechanisms have been proposed to explain auroral MF-burst [Sotnikov et al., 1996; LaBelle et al., 1997].

Figure 1*a* shows a striking example of auroral radio emissions, recorded at the CANOPUS observatory at Arviat, NWT (71.4° invariant latitude). Frequency (0–4 MHz) is displayed on the vertical axis, time (40 minutes) is on the horizontal axis, and wave intensity is encoded into the gray scale, with white and black pixels corresponding to 4.0

and 100.0 nV/m$\sqrt{\text{Hz}}$, respectively. Dark horizontal lines represent fixed frequency transmissions, such as those occurring in the AM radio band at 550–1600 kHz. The prompt reduction in the intensity of most AM signals at 0651 UT is typical of substorm onset which was identified using data (not shown) from CANOPUS magnetometers and riometers. During the expansion phase of the substorm, auroral hiss occurs at frequencies up to 800 kHz; although the literature implies that auroral hiss is rarely observed above 500 kHz at ground level, our data show that such events are commonplace. Broadband bursty emissions in the frequency range 1.5–4.0 MHz also occur during the substorm expansion phase. These are named medium frequency burst (MF-burst); in Figure 1*a*, they occur in batches lasting 1–5 minutes and correlate well with similar batches of auroral hiss. The MF-bursts exhibit a null near 3 MHz, approximately $2f_{ce}$ at ionospheric altitudes. In addition to auroral hiss and MF-burst, narrow-band $2f_{ce}$ auroral roar at 2.8–3.0 MHz is observed for approximately 20 minutes prior to substorm onset (0651 UT) and intermittently thereafter. Auroral roar observed at ground level often becomes intermittent or ceases entirely during the break-up phase of the auroral substorm, an effect which has been attributed to screening by low-altitude ionization associated with auroral activity (e.g., Weatherwax et al., [1995]; LaBelle et al., [1994]). Figure 1*b* shows radio waves observed at Churchill (69.2° invariant latitude), 200 km south of Arviat. Auroral hiss, $2f_{ce}$ auroral roar, and MF-burst are also observed at Churchill and show features similar to those recorded at Arviat. However, after 0652 UT no MF-burst or auroral roar occurs above the instrument noise level at Churchill, even though these are observed 30-40 dB above the noise level at Arviat.

In addition to improvements made in swept frequency receiver measurements, Dartmouth College recently developed a receiver which translates an operator-selectable 10 kHz band to the audio range, thus allowing a high time- and frequency-resolution samples of the auroral radio emissions to be recorded on audio tapes. This instrument led to a significant discovery: much of the auroral roar is composed of many fine structures which have bandwidths as narrow as 10 Hz, and which shift up and down in frequency in complicated patterns [LaBelle et al., 1995]. To the ear, the roar emissions resemble VLF chorus or auroral kilometric radiation (AKR) (e.g., Gurnett and Anderson, [1981]). Possibly, processes offerred to explain AKR fine structure such as the cyclotron maser instability with feedback [Calvert, [1982] can be applied to auroral roar. In April, 1996, Dartmouth graduate student Simon Shepherd interactively operated the downconverting receiver at Churchill and recorded fine structure signals from dozens of auroral roar emissions [Shepherd et al., 1996]. These exhibit a bewildering variety of characteristics, including both falling and rising tones with frequency-time slopes ranging from zero to several hundred kHz/s both positive and negative. Negative slopes appear more common than positive slopes among those features with slopes exceeding 10 kHz/s. Many features drift alternately positive and negative, changing slope on approximately a 1-s time scale. As in AKR fine structure, multiplets are often observed, in which several narrowband tones separated by 100–1000 Hz drift up and down in frequency together. We are compiling an atlas of these fine structures to guide theoretical efforts, and we are building a digital downconverting receiver to make higher quality fine structure observations.

Deployment of radio receivers at multiple observatories for extended time periods has enabled the determination of latitude and seasonal dependences of auroral roar. Auroral

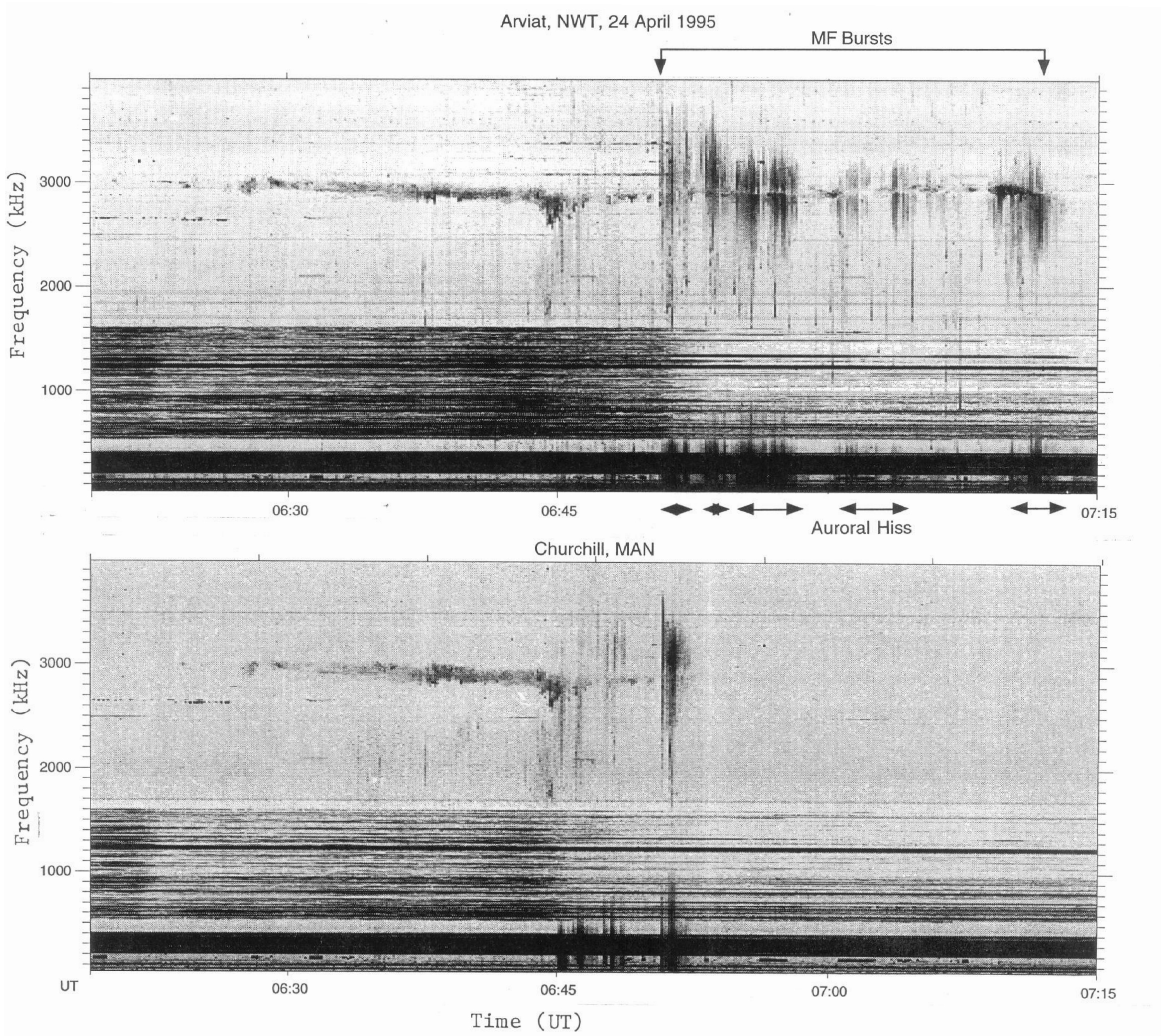

Figure 1: Wave data from (a) Arviat (71.3° invariant) and (b) Churchill (69.4° invariant) for a 55-minute interval around magnetic midnight (0635 UT) on April 24, 1995. Auroral roar, MF-bursts, auroral hiss, and substorm-induced fading of AM broadcast stations occur during this interval, as described in the text. During 0652-0712 UT, auroral radio emissions continue to be observed at Arviat more than 35 dB above the noise level even though no emissions are detected at Churchill, 200 km away.

roar and MF-burst emissions are most common during geomagnetically active periods, and their occurrence rate maximizes between 69° and 71° invariant latitude under present solar cycle conditions. As mentioned above, auroral MF-burst and impulsive LF auroral hiss usually occur simultaneously during substorm onset. Auroral roar is most commonly observed for periods of 10 minutes to an hour or more preceding substorm onset. Ground-level observations of auroral roar and MF-burst often cease shortly after substorm onset, an effect which has been attributed to ionospheric screening as mentioned above. Data from multiple ground stations show that the most common observed frequency of the auroral roar emission is proportional to the magnitude of the Earth's magnetic field at the station, and the constant of proportionality is that expected for generation at twice the electron gyrofrequency. These multiple-station data thus provide convincing evidence that the auroral roar emission is associated with electron gyrofrequency harmonics.

Of great importance is the correlation between data from ground-based receivers and satellite wave and particle data. We have identified 27 intervals in 1994–5 when the Freja satellite intersected field lines within 2.5 degrees of our receiving stations at the same times when auroral roar or MF-bursts occured. The Freja wave receivers detect waves up to 4 MHz, and when these receivers are operated in their high-gain mode, they may determine whether or not auroral roar occurs in the topside ionosphere. James et al. [1974] observed 2- and 4-MHz waves in the topside, but it is unknown whether these waves are identical with auroral roar seen at ground level. Operating the ground-based receivers during the International Solar Terrestrial Program (ISTP) will provide conjunctions with several satellites, including POLAR and FAST.

Turning to the MF-burst emissions, recent high-time resolution measurements show that these are composed of wave packets with duration 100-300 μs [LaBelle et al., 1997], two orders of magnitude shorter than the upper bound placed on the time scale by lower resolution observations [Weatherwax et al., 1994]. Sometimes the wave packets are periodic with periods in the range 1-1.5 ms, which is comparable to the proton gyroperiod at ionospheric altitudes. Coincidentally, the time scale of these MF-burst wave packets is identical to that of whistler solitary waves recently measured with the FAST satellite at much higher altitudes, and the whistler solitary waves are also sometimes periodic with the local ion gyroperiod [Ergun et al., 1996]. MF-burst is strongly correlated with auroral hiss, but it remains to be seen whether this correlation extends to the time scales of the individual wavepackets. There are at least two competing models of auroral MF-bursts: if the auroral electron beam has sufficient free energy at ionospheric altitudes, Langmuir waves might be destabilized in the F-region and could convert to an EM mode on the density gradient under the right conditions (e.g., LaBelle et al., [1997]). Sotnikov et al. [1996] propose an alternative mechanism in which the waves extract energy from the perpendicular part of the electron distribution function rather than the parallel part.

In August 1995 we deployed a receiver at Sondrestrom, Greenland, to take advantage of regular measurements of ionospheric structure by the VHF incoherent scatter radar and imaging riometer, digisonde, and VLF instrumentation. A large number of auroral roar and MF-burst events have been detected. During the 1995–6 winter, fourteen of these events occurred during times when the incoherent scatter radar was in operation. Simultaneous with several of these auroral roar observations, the radar detects F-region electron density cavities, similar to those reported by Doe et al. [1993], centered within 50–100 km of the radio observatory. In the cyclotron-maser model for auroral roar, electron density cavities play a key role by reflecting the wave through a source region many times before it escapes to the ground [Weatherwax et al., 1995; Yoon et al., 1996]. An alternative theory of auroral roar involves excitation of upper hybrid waves by auroral electrons, which occurs favorably where the upper hybrid frequency (f_{uh}) matches electron cyclotron harmonics [Kaufman, 1980], followed by conversion of the electrostatic waves to EM waves which propagate to the ground [Gough and Urban, 1983; Weatherwax et al., 1995]. Analysis of electron density profiles measured with the radar during times when auroral roar occurs shows that in eleven of fourteen cases, the matching condition ($f_{uh} = 2f_{ce}$ or $3f_{ce}$) is met somewhere in the F-region for the full range of observed auroral roar frequencies

[Shepherd et al., 1997]. Simultaneous incoherent scatter radar and auroral radio emission observations provide a promising means to test theories of auroral roar and MF-burst generation, but currently the radio observations do not include determination of the source location, which is critical in order to correlate the radio emission sources with features in the radar images. Dartmouth proposes to build at Sondrestrom a radio emission imaging interferometer which will bring to fruition the promise that this technique shows for determining the ionospheric plasma processes involved in these radio emissions.

3 Conclusion

Clearly, unexplained ionospheric plasma processes allow radio emissions generated in the ionosphere to be observed at ground level. Recent observations confirm the existence of $2f_{ce}$ auroral roar and reveal two new types of terrestrial auroral radio emissions: $3f_{ce}$ auroral roar and MF-bursts. The principal progress of the past two years towards characterizing and explaining these processes is summarized below:

1) It was discovered that auroral roar consists of many fine structures having bandwidths as small as 10 Hz, implying $f/\Delta f$ the order of 10^5 [LaBelle et al., 1995]. The fine structures exhibit a bewildering variety of patterns [Shepherd et al., 1996].

2) Receivers at multiple observatories covering invariant latitudes 67–79° reveal the latitude and seasonal dependence of the wave events. Freja satellite overflights during times of ground–level wave activity are under investigation. Data continue to be acquired as ISTP enters into full swing, with the FAST and POLAR satellites overflying the stations.

3) The time scale of the individual wave packets composing the MF-bursts has been determined to be far shorter than previously thought: the order of 100–300 μs [LaBelle et al., 1997].

4) Development of theoretical models for auroral roar and MF-burst is proceeding. For auroral roar, the cyclotron maser mechanism has been quantitatively explored [Weatherwax et al., 1995; Yoon et al., 1996]. Models for MF–burst are less well–developed, but two models have been suggested [LaBelle et al., 1997; Sotnikov et al., 1996].

5) For fourteen events so far, the ionospheric density structure has been measured with incoherent scatter radar at the same time that auroral roar and MF-bursts are observed with ground–based radio receivers. In some cases, auroral roar is associated with F–region density depletions; in most cases, the observed frequency of the auroral roar is consistent with the frequency range for which matching condition $f_{uh} = 2f_{ce}$ or $3f_{ce}$ is met in the F–region within the region probed by the radar. A proposed auroral radio emission imaging instrument will enable rigorous tests of proposed generation mechanisms of auroral roar and MF-burst.

Despite the importance of radio wave generation mechanisms in astrophysics, planetary physics, and in the Earth's magnetosphere and ionosphere, there exist radio waves generated a few hundred kilometers above the Earth's surface which are neither understood theoretically nor fully described observationally: auroral roar and MF-burst. Determining the unknown ionospheric plasma processes involved in these emissions requires a more thorough observational description of the waves, including radio-frequency imaging to locate their source in the sky at the same time when other imaging instruments detect ionospheric plasma structures and processes.