GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 3, PAGES 487-490, FEBRUARY 1, 2001

Modeling Ionospheric Absorption Modified by Anomalous Heating During Substorms

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Abstract. Riometers monitor the changes in ionospheric conductivity by measuring the absorption of very high frequency radio noise of galactic origin passing through the ionosphere. In this Letter the absorption of radio signals by a thin layer of ionospheric plasma, produced by ionization due to energetic precipitating electrons, is modeled by taking into account strong turbulent heating caused by instabilities. The precipitating electron population is obtained from a global MHD simulation of the magnetosphere, along with the electric fields which excite the Farley-Buneman instability and lead to turbulent electron heating. A comparison, the first of its kind, of the data from polar and sub-auroral riometers for the magnetic cloud event of January 10, 1997 shows good agreement. The ionospheric conductance modified by turbulent electron heating can be used to improve the magnetosphere — ionosphere coupling in the current global MHD models.

Introduction

The coupled solar wind-magnetosphere-ionosphere system exhibits many dynamic changes over global and local scales during substorms. An extensive database of substorm activity is obtained from ground-based networks of various instruments. One of these is the riometer which measures changes in the absorption of very high frequency radio signals of galactic origin passing through the ionosphere [*Rosenberg et al.*, 1991]. The change in ionospheric conductivity is mainly due to the enhanced collisional ionization arising from energetic electrons precipitating during substorms. An important goal of space physics is to understand how the solar wind, which is monitored by upstream spacecraft such as WIND and ACE, drives the magnetosphere and the ionosphere to produce phenomena observed by means of ground measurements such as riometers.

Global MHD simulations, which use the solar wind data to drive the time evolution of the magnetosphere, provide a link between the solar wind and the ionosphere. The Lyon-Fedder-Mobarry (LFM) simulation model [*Fedder et al.*, 1995; *Lyon et al.*, 1998] has been used to examine several substorm events, and the results have shown that the code reproduces well the observed main sequence of events during substorms. The magnetospheric output obtained from simulations driven by actual solar wind data is then used as input into the ionosphere. This in turn is used to model the resultant ionospheric processes and to compare with ground based observations. In this Letter we present the first results from modeling the ionospheric absorption of galactic radio signals at several riometer locations using the precipitating electron population inferred from the LFM simulation model. The model results are compared with riometer network data for the January 10, 1997 event.

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Paper number 2000GL003823.
0094-8276/01/2000GL003823$05.00

Ionospheric Absorption: Basic Physics

The absorption of cosmic radio noise in the ionosphere depends on the height integrated electron density and temperature in the lower ionosphere and provides a measure of the ionospheric conductivity. Absorption in the auroral and polar cap region is measured by an array of imaging riometers developed at the University of Maryland [*Detrick and Rosenberg*, 1990]. A strong increase in auroral absorption during a substorm is often associated with the intensification of the auroral electrojet [*Hudson et al.*, 1999]. The radio signals used by riometers are typically of very high frequency (VHF), in the 20–50 MHz range. The total column integrated changes in the intensity of VHF waves due to the ionospheric absorption is given by

$$A = \frac{1}{2c\,(2\pi f)^2} \int \omega_{pe}^2\, \nu_{en} dz \qquad (1)$$

where f is the frequency of the VHF wave, ω_{pe} is the electron plasma frequency, and ν_{en} is the electron-neutral collision frequency. Note that the frequency of the radio waves used in riometers is much greater than both the electron gyrofrequency Ω_e and electron-neutral collision frequency ν_{en}, viz. $2\pi f >> \Omega_e, \nu_{en}$.

In the model below we consider the ionospheric absorption of VHF signals caused by a thin plasma layer, produced by ionization due to precipitating electrons. Furthermore, since the ionospheric absorption strongly depends on the bulk electron temperature, we include anomalous electron heating by strong turbulent electric fields developed at the same time, due to electrojet instabilities [*Ossakow et al.*, 1975; *Stauning*, 1984; *St-Maurice and Laher*, 1985]. Note that electron heating up to 2000–3000 K at the time of a substorm is often inferred by radar observations [*Schlegel and St-Maurice*, 1981; *Schlegel and Collis*, 1999].

The problem is solved in several sequential steps. First, using the characteristic energy ε and flux Φ of precipitating electrons from the LFM model we obtain the energy deposition height and total energy flux released by the precipitating electrons. Next, we compute the electron density inside the ionized layer along with the electron-neutral collision frequency for cold electrons. Using the electric fields E in the ionosphere obtained from the LFM model we estimate the temperature of the bulk of electrons due to turbulent heating. Finally, we compute the total VHF absorption taking into account the effect of electron heating on the electron-neutral collision frequency and electron density at several riometer locations, and compare the model predictions with the observations.

Computational Model

We consider for simplicity absorption by a uniform ionospheric layer with thickness Δz, electron density n_e, neutral density N_n, and electron temperature T_e, and apply eq. (1) with the effective electron-neutral collision frequency ν_{en} given by [*Gurevich*, 1978] as follows $\nu_{en}(s^{-1}) = 0.6\times10^{-8} N_n(cm^{-3})\,(T_e/300\,K)^{5/6}$. It takes into account the dependence of the cross section of electron-neutral inelastic collisions upon the electron temperature.

We obtain first the penetration altitude of the fast precipitating electrons, and then find the neutral density at this altitude. The energy balance of electrons moving downwards in the ionosphere is given by $d\varepsilon/dz = -\sigma_{ion}(\varepsilon)\,\varepsilon_{ion} N_n(z)$ where σ_{ion} is the ionization cross section, while ε_{ion} is the energy spent per ionization, which is usually taken as 35 eV [*Rees*, 1989]. In the exponential ionosphere $\left(N_n \sim e^{-z/H}\right)$ where H is the density scale we can obtain the penetration altitude z_p, and the neutral density corresponding to z_p by using $\sigma_{ion}(\varepsilon)$ given by *Gurevich et al.,* [1997]

$$N_n(z_p) = \frac{4\times10^9\text{cm}^{-3}}{(\text{H}/10\,\text{km})}\left(\frac{\varepsilon}{\varepsilon_m}\right)^{1.75}. \quad (2)$$

Using the U. S. Standard Atmosphere (1976) we found the penetration altitude for different electron energies and compared them with that found by using the formulas from *Rees* [1992]. This analysis reveals a consistency between these models at 1 keV $\leq \varepsilon \leq$ 20 keV with an accuracy of a few percent.

We next estimate the electron density in a thin ionized layer created by the absorption of fast electrons. Taking into account that the total energy of fast electrons is absorbed along the scale height H of the pressure gradient, we find that the energy flux $\varepsilon\Phi$ of fast electrons produces thermal electrons inside the column H with the ionization rate $q_{ion} = \varepsilon\Phi/\varepsilon_{ion}H$. The electron density balance equation gives $dn_e/dt = q_{ion} - \alpha\, n_e^2$ where $\alpha \simeq 2\times10^{-7}\,(300\text{K}/\text{T}_e)\,\text{cm}^3/\text{s}$ is the electron-ion recombination rate [*Gurevich*, 1978]. In a stationary case $\left(\frac{d}{dt}=0\right)$ the electron density becomes $n_e = (\varepsilon\Phi/\varepsilon_{ion}H\alpha)^{1/2}$. Finally, the absorption of the radio noise having frequency f can be found from eqs. (1), (2) taking into account that the thickness of the ionized layer is $\Delta z \simeq \text{H} \simeq 10\,\text{km}$. Thus we obtain

$$\text{A(dB)} = 6.9\left(\frac{\varepsilon}{1\,\text{keV}}\right)^{2.25}\left(\frac{1\,\text{MHz}}{\text{f}}\right)^2\left(\frac{\Phi}{\Phi_0}\right)^{1/2}\left(\frac{T_e}{300\text{K}}\right)^{4/3}. \quad (3)$$

Here Φ is given in electron/cm^2 s, while $\Phi_0 = 2\times10^9$ cm^{-2} s^{-1}. Equation (3) reveals that the absorption strongly depends upon the temperature of the bulk of electrons which increases during magnetic cloud events, as discussed in the next section.

Anomalous Electron Heating

It is known from numerous radar observations that electron temperature rises significantly in the polar electrojet during substorms [*Schlegel and St-Maurice*, 1981; *Jones et al.*, 1991; *Schlegel and Collis*, 1999]. Strong anomalous electron heating is predominantly caused by turbulent electric fields developing in the electrojet mostly as a result of the modified two-stream, or Farley-Buneman (F-B) instability driven by the convection electric field E_C. This mechanism was first suggested by *Schlegel and St-Maurice* [1981]; see also *St-Maurice and Laher* [1985] and *Jones et al.* [1991]. However, the existing approximate models cannot interpret satisfactorily the available radar data. In this paper we will give a simple and usable recipe for estimates of the temporally- and spatially-averaged electron temperature, based on physical reasonings and comparison with available radar observations of the heating.

To get the electron temperature under quasi-stationary conditions, equating the electron Joule heating by the total electric field, **jE**, to the cooling via inelastic electron-neutral collisions, $\delta_{en}\nu_{en}n_e k_B(T_e - T_0)$, where k_B is the Boltzmann's constant, and T_0 is the electron temperature approximately equal to the temperature of neutral particles in the cold (unperturbed) ionosphere while $\delta_{en}(T_e)$ is the average fraction of the electron energy lost in electron-neutral collision. As a result we obtain for the average temperature increment $\Delta T_e = T_e - T_0$

$$\frac{\Delta T_e}{T_0} \simeq \frac{2m_e}{m_i\delta_{en}}\left(1 + \frac{< E_{||}^2 > \Omega_e^2}{< E_\perp^2 > \nu_{en}^2}\right)\frac{< E_\perp^2 >}{E_{th0}^2} \quad (4)$$

where $E_{||,\perp}$ are the components of the total electric field parallel and perpendicular to the geomagnetic field B, respectively (the angular brackets mean time averaging). The normalization constant $E_{th0} \simeq 20\,mV/m$ represents the minimum F-B threshold field $E_{th}(T_e) = C_S B/c$ ($C_S = [k_B(T_e + T_i)/m_i]^{1/2}$ is the ion acoustic speed) taken for the 'cold' (i.e. unperturbed) ionosphere: $C_S = C_{S0} \approx (2k_B T_0/m_i)^{1/2}$.

Since the nonlinear theory of the F-B instability is still far from complete, here we estimate the electric field energy in the nonlinearly saturated turbulent state based on simple physical reasonings. For the driving field E_C well above the threshold value $E_{th}(T_e)$, it is natural to assume that the energy level of saturated turbulence is such that the major nonlinear term is of order of the largest linear terms in the appropriate equations. This yields for the turbulent electric field a simple estimate $< E^2 > \approx < E_\perp^2 > \sim E_C^2$, corresponding to several percent of the coupled plasma density perturbations. Strong electron heating is due to parallel turbulent electric field associated with finite parallel components of the wave-vectors $k_{||}$ [*St-Maurice and Laher*, 1985]. For potential F-B waves we have $E_{||}/E_\perp = k_{||}/k_\perp \approx \theta$, where $\theta << 1$ is the aspect angle.

We may anticipate that the bulk of saturated turbulence in the θ-space is spread over a broad range around the linear growth rate maximum, at least up to the boundary of the linearly unstable range, $\psi = \psi_\perp[1 + (\theta\,\Omega_e/\nu_{en})^2] \simeq E_C/E_{th}(T_e)$, where $\psi_\perp = \nu_{en}\nu_{in}/(\Omega_e\Omega_i)$. The F-B instability is effectively excited at the altitudes where $\psi_\perp << 1$. Taking $\psi \simeq 1$ as an effective value of ψ responsible for the main contribution to the Joule heating, we obtain $(\theta\,\Omega_e/\nu_{en})^2 \simeq 1/\psi_\perp >> 1$ and from eq (4)

$$\frac{\Delta T_e}{T_o} \simeq \frac{2\,m_e}{m_i\delta_{en}\psi_\perp}\left(\frac{E_C}{E_{th0}}\right)^2. \quad (5)$$

This is an implicit expression for T_e in terms of E_C since $\psi_\perp \propto \nu_{en}(T_e)$. In the range of interest $800\text{K} < T_e < 3,000\text{K}$, to a good accuracy, the temperature dependence of the electron cooling rate is given by $\delta_{en}(T_e)\,\nu_{en}(T_e) \propto T_e$ [Gurevich, 1978]. Thus for $T_e \simeq \Delta T_e >> T_0$ the estimated electron temperature is roughly proportional to the convection electric field.

Comparison of Model Results with Observations

In the present letter we compare our results with recent observations by *Schlegel and Collis* [1999], made by the EISCAT facility during the storm of January 10, 1997. The values of T_e and E_C presented in the paper were both measured over the EISCAT area. For proper comparison, we should average eq.

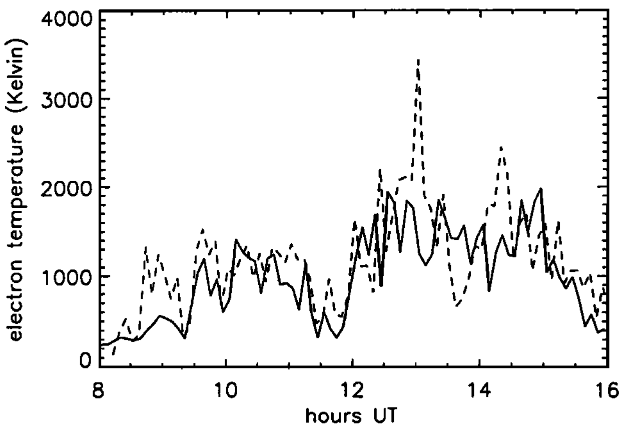

Figure 1. Temporal evolution of the modeled electron temperature (dashes) for the January 10, 1997 substorms along with the electron temperature directly measured by EISCAT (solid line).

(5) over the altitude range between 105 and 115 km within the electrojet. Assuming the exponential height dependence of the neutral atmosphere with the typical e-folding scale for these altitudes $H \simeq 10$ km, neglecting the spatial dependence of ion composition and E_C, B and T_0 within the range of interest, while adopting the values of δ_{en} from *Gurevich* [1978] we obtain from eq. (5) the average temperature

$$< T_e > \simeq 1.5 T_0 (E_C / E_{th0}). \quad (6)$$

Note that derivation of eqs. (5) and (6) required excitation of the F-B instability well above the threshold. The actual threshold electric field increases with temperature, $E_{th}(T_e) \propto C_S \propto (T_e + T_0)^{1/2}$. Thus a strong anomalous electron heating caused by nonlinearly developed turbulence might in principle break this condition. However, as seen from eq. (6), for $E_C >> E_{th0}$ the ratio $E_C/E_{th}(T_e) \sim (E_C/E_{th0})^{1/2}$, so that the required condition and, hence eq. (6) remain to be valid.

Figure 1 shows the temporal evolution of the modeled electron temperature $< T_e >$ (dashed curve), computed with equation (6) using the EISCAT measurements for the convective electric field E_C. This model result is plotted against the electron temperature directly measured by EISCAT (solid curve). We see that the linear dependence of $< T_e >$ upon E_C agrees reasonably with the observational data, except for the time around 1300 and 1430 UT when the strong heating cannot be described by the linear approximation applied. The radar observations [*Schlegel and St-Maurice*, 1981; *Jones et al.*, 1991] reveal that the electron temperature can be described by eq (6) with the numerical coefficient ranging between 0.9 and 2.3 for the altitudes 100–120 km. It increases with the altitude as the collisional losses reduce. Further details of the turbulent electron heating model will be published elsewhere. Meanwhile we will use a simple approximation (6) for the following estimates of the electron temperature.

The global MHD model has been used to estimate the population of precipitating electrons during a period of substorm activity on 10 January 1997. The precipitating flux and spectra are then used to model the electron heating due to the instabilities and consequently the ionospheric absorption in local cells (400 km × 400

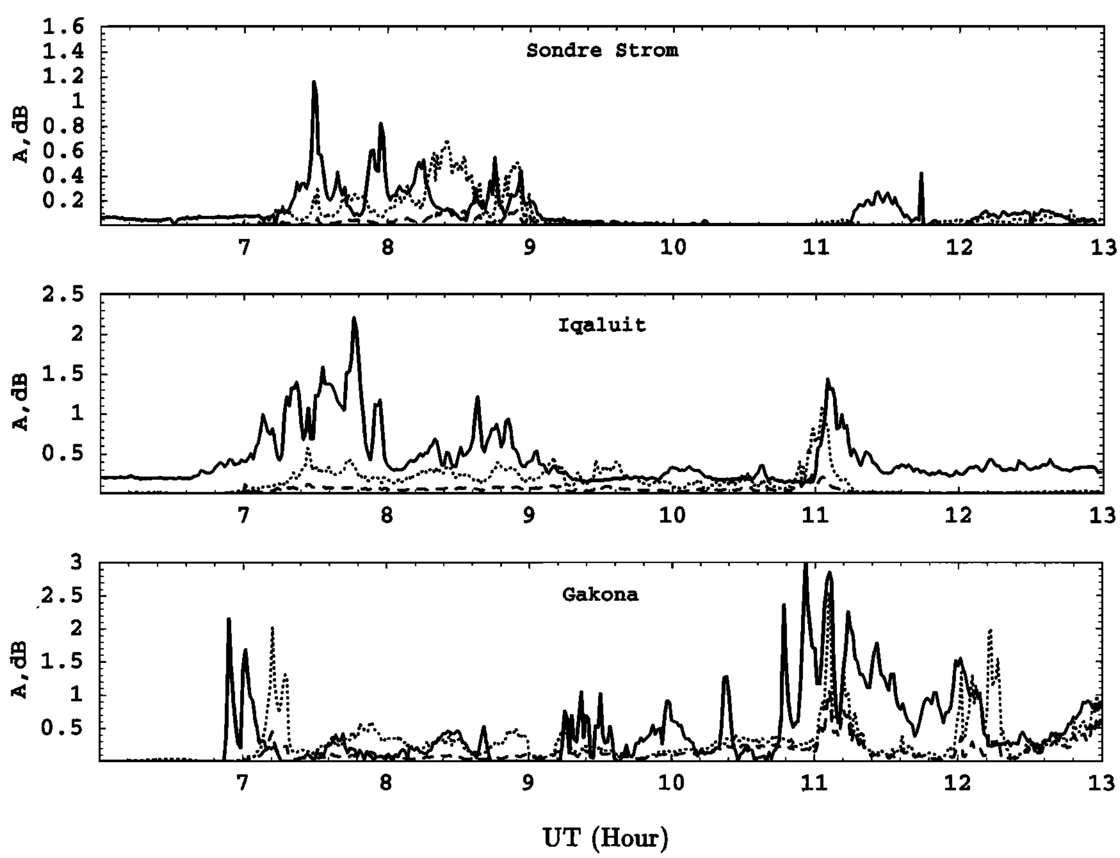

Figure 2. Temporal evolution of the VHF absorption for f = 38.2 MHz observed during January 10 event at the three locations of interest (solid line) along with computations made by (a) consider anomalous heating (dots); (b) keeping the electron temperature constant, T_e=350 K, (dashes).

km) at the three different riometers located at Sondrestrom (67N; 309E), Iqaluit (63.7N; 291.5E), and Gakona (62.4N; 214.8E).

Figure 2 shows the VHF absorption measured by the riometers at the above three locations during 10 January 1997 (solid line) along with the model results computed by taking into account the anomalous electron heating (dots), and by neglecting it and assuming constant electron temperature (dashes). The results show that the model is in total disagreement with the observations if anomalous heating is neglected. When anomalous heating is taken into consideration the agreement between the computed VHF absorption and observations improves considerably.

There are many features of the model that are responsible for the limited agreement of its results with the observations and some of these are as follows. Many of the observed details of the observations, such as at Gakona at 0915–1030 UT could be produced by a local arc, which cannot be obtained by the MHD model with 400 km spatial resolution. In the LFM model the energy of precipitating electrons does not exceed 20 keV, which corresponds to the penetration altitude in excess of 95 km. Thus the model neglects the changes in absorption which occur in the ionosphere below 95 km. This may lead to an underestimate of the total absorption, as is seen in the top two panels of Figure 2 corresponding to the higher latitude stations. Also some mismatch in the timing between the model and observations are apparent, especially for the low latitude Gakona case. The spatial resolution of 400 × 400 km in the model is equivalent to a temporal resolution of 15 min due to the rotation of the Earth, and thus a mismatch of this magnitude is inherent in the model. While the agreement between the model results and observations are not high enough to be usefully quantified in terms of correlation coefficients, it brings out new features such as the role of anomalous electron heating.

Conclusions

In conclusion the paper presents a first attempt to use the global MHD model to model ionospheric absorption and the results are compared with riometer measurements. The comparison shows the important role of anomalous electron heating and many features of the temporal variations of computed absorption are consistent with that measured by the riometers; the magnitude for VHF absorption are comparable between model and observations; and in many instances the model resolution cannot describe the fine structure of the high frequency radio wave absorption, which could be produced by patchy or arc-like structures of smaller scale.

Currently the MHD model neglects the effect of turbulent electron and collisional ion heating by the ionospheric electric field. However, the inclusion of the turbulent electron heating led to a much better agreement of the simulations with the actual values of integrated absorption at the three riometer locations. We expect that inclusion of anomalous collision frequency into the ionospheric conductance could improve the model by providing feedback between the model ionosphere, serving as a dynamic boundary condition, and the 3–D global magnetospheric simulations.

Acknowledgments. The research was supported by the ISTP program sponsored by NASA. One of the authors (YD) was supported by NSF grant ATM-9812679. The authors are very grateful to Dr. K. Schlegel for providing the EISCAT data.

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(Received May 26, 2000; revised November 1, 2000; accepted November 6, 2000.)