

Simultaneous Observations of E -Region Coherent Backscatter and Electric Field Amplitude at F -Region Heights with the Millstone Hill UHF Radar

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Abstract

A combined coherent backscatter - incoherent scatter experiment was performed with the Millstone Hill UHF radar during strongly disturbed conditions on August 27, 1998 which provided simultaneous observations of electric field magnitude and coherent backscatter parameters on the same L shell. A carefully-designed geometry used sidelobe coherent contamination from two-stream irregularities at 110-km altitude, appearing at ranges corresponding to F -region altitudes in the main beam, in conjunction with simultaneous uncontaminated F -region observations of the $\mathbf{E} \times \mathbf{B}$ drift velocity in adjacent range gates. Three hours of such observations with 20-s temporal resolution were analyzed during varying conditions in which $|\mathbf{E}|$ varied [30, 80 mV/m]. We find a clear linear relationship between both logarithmic coherent power and the magnitude of the coherent phase velocity with $|\mathbf{E}|$. The results reported here are the first such observation of the relationship of coherent parameters to electric field magnitude made at 440 MHz and with the radar $\mathbf{k} \sim$ parallel to \mathbf{V}_{ph} . With the assumption that the coherent phase velocity is approximately the perturbed ion sound speed in the heated E region, we find an excellent agreement between the electron temperature derived from V_{ph} and previous incoherent-scatter results relating E -region T_e to $|\mathbf{E}|$. This confirms that heating by two-stream waves is the mechanism responsible for electric field-dependent electron temperature enhancements in the absence of energetic electron precipitation. A maximum value of $\sim 3100^\circ$ K has been found for such wave-induced E -region heating.

Introduction

The Millstone UHF radar is extremely sensitive to coherent backscatter because of its design as an incoherent backscatter system with 2 - 5 MW peak transmit power and a sensitive (44-dB one-way gain), narrow beam (1° full width at -3 dB) steerable antenna. The Millstone Hill 440-MHz UHF radar receives intense backscatter from 30 cm irregularities when viewing E region heights to the north at aspect angles near perpendicular to the magnetic field. For ionospheric electric field strength $|\mathbf{E}| > 15$ mV/m [Moorcroft, 1979, 1980], two-stream (Farley-Buneman) irregularities form near 110 km altitude as electrons are driven by the $\mathbf{E} \times \mathbf{B}$ force through the collisional ions [Farley, 1963, Buneman, 1963]. When the relative electron-ion velocity exceeds the local ion sound speed (~ 350 m/s) turbulence builds rapidly resulting in strong, coherent backscatter of radar signals directed near perpendicular to \mathbf{B} .

The coherent backscatter radar cross section is very large, such that off-beam (sidelobe) coherent returns can dominate the main-beam incoherent scatter signal at any range at which the E -region irregularities can be viewed at a favorable magnetic aspect angle. A narrow spectrum characterizes coherent contamination, whose intensity is decreased by a strong magnetic aspect angle dependence (-15 dB/deg) and the off-axis antenna sensitivity function. Past studies at Millstone Hill [Foster and Tetenbaum, 1991] investigated the temporal variation of power, finding a maximum calibrated volumetric cross section of $\sim 10^{-9}$ m $^{-1}$ (some 90 dB above the incoherent scat-

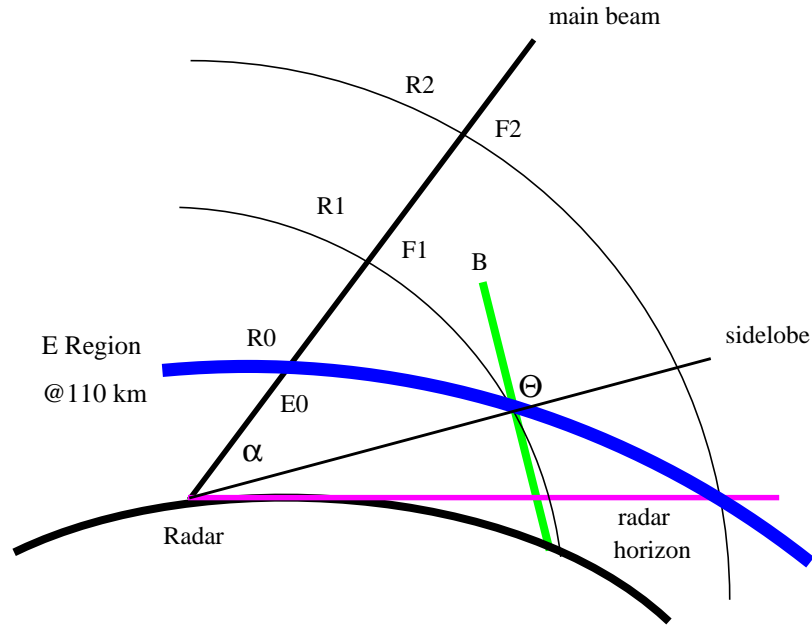


Figure 1. Schematic diagram of sidelobe coherent returns. Coherent backscatter is observed at range R_0 where the main beam penetrates the irregularity layer at E -region heights. Strong sidelobe contamination is seen at each range (e.g. R_1) at which the line of sight from the radar intersects the E layer at a favorable magnetic aspect angle, Θ . Beyond R_2 , E -region visibility is shielded by the limb of the earth, and only main-beam incoherent scatter is observed. At these ranges ($R > R_2$), an uncontaminated measure of plasma drift (electric field) is obtained.

ter background). A linear relationship between logarithmic power and coherent phase velocity was found over the range [350,700] m/s for V_{ph} and 30 dB dynamic range, but direct observations of the driving electric field were not made. The objective of the experiment reported here is to investigate simultaneously the characteristics of E -Region irregularities and the causative electric field.

Experiment Design

The geometry for observing coherent echoes from Millstone Hill and the intensity of the coherent returns present a challenge in simultaneously observing coherent power and the causative electric field with the monostatic MHR system. When the electric field is greatly expanded during disturbed conditions (e.g. *Foster et al.* [1986]), it is possible to observe coherent echoes while the radar beam (\mathbf{k}) is directed approximately parallel to $\mathbf{E} \times \mathbf{B}$ and with \mathbf{k} aligned along constant L shell (magnetic latitude). Since the principal gradients in \mathbf{E} are in the cross- L direction (i.e. latitude gradients), in this pointing configuration it is expected that adjacent sampling gates experience very-similar values of electric field and that a measurement of \mathbf{E} made at one range (gate) can be applied in nearby gates.

The Millstone Hill UHF radar is sized and configured for the detection of a very weak incoherent scatter signal, and therefore it is an extremely sensitive detector of coherent returns. *St-Maurice et al.* [1989] and *del Pozo et al.* [1993] identified composite coherent/incoherent scatter spectra during Millstone Hill operations in which weak sidelobe echoes from E -region irregularities viewed near perpendicular to \mathbf{B} contaminate incoherent scatter spectra from within the main beam at the same range. Figure 1 presents a schematic view of the geometry involved in a coherent/

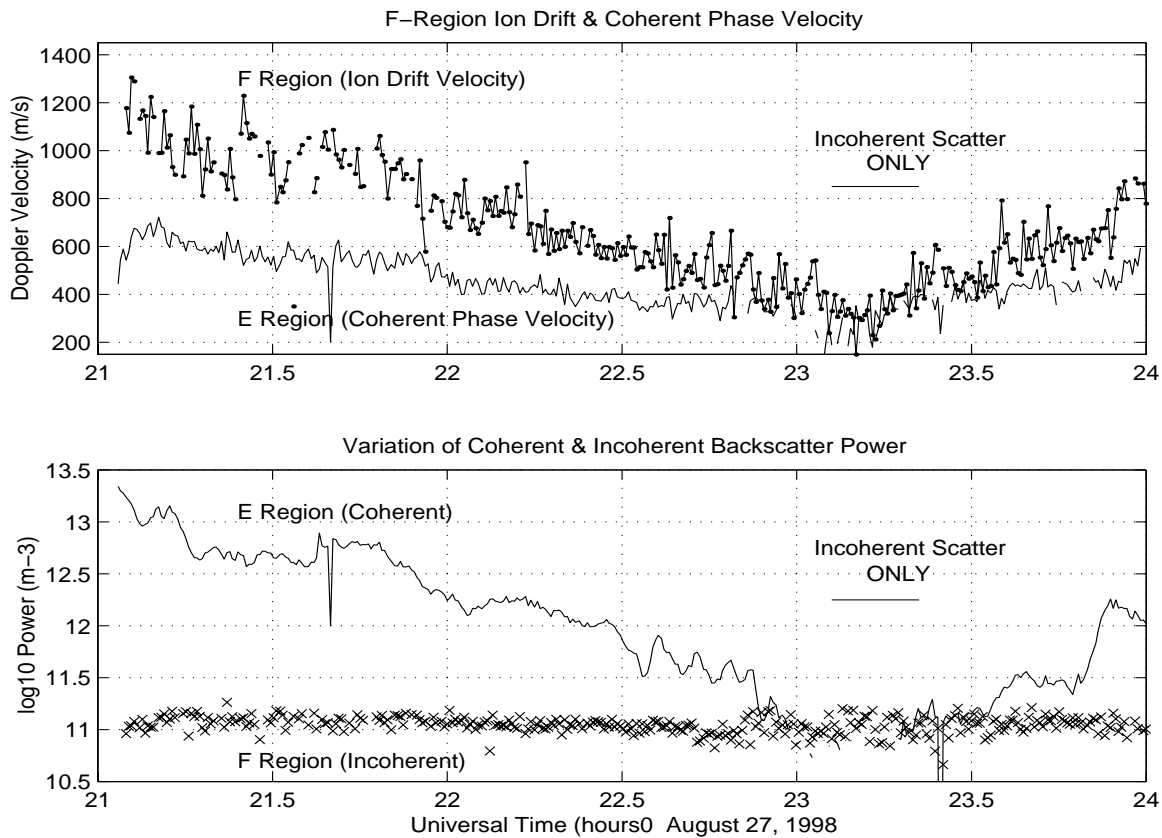


Figure 2. August 27, 1998 observations of *F*-region plasma parameters and *E*-Region two-stream irregularities with the Millstone Hill UHF radar. Doppler velocity and spectral parameters observed at 295-km altitude were uncontaminated by sidelobe coherent returns and provide a measurement of $\mathbf{V} \sim \mathbf{E} \times \mathbf{B}$ at $58^\circ \Lambda$. *E*-Region phase velocity is derived from narrow coherent spectra at ~ 980 km range, appearing in the main-beam altitude gate at 170 km.

incoherent experiment, including the effects of sidelobe coherent contamination. Coherent two-stream irregularities are confined to a limited altitude extent near 110 km and only occur in regions where the electric field strength in the *E* region exceeds threshold. For a uniform layer of irregularities, intense coherent backscatter is observed at ranges where the main beam penetrates the irregularity layer at *E*-region heights (R_0), while strong sidelobe contamination is seen at each range at which the unobstructed line of sight from the radar intersects the *E* layer at a favorable magnetic aspect angle (e.g. R_1). The intensity of the sidelobe contamination is reduced by the off-beam antenna attenuation factor (squared, since both transmit and receive paths are affected). Beyond ~ 1300 km range, radar samples are shielded by the limb of the earth from any *E*-region visibility, and only main-beam incoherent scatter is observed. At these ranges ($R > R_2$), an uncontaminated measure of ionospheric parameters and plasma drift (electric field) is obtained. By orienting the antenna such that the last sidelobe-contaminated gate ($R < R_2$) and the first clean gate are on the same *L* shell, a simultaneous observation of electric field magnitude and coherent backscatter parameters is obtained.

During two occasions in 1998 such an experiment was performed successfully with the narrow-beam MHR giving direct, simultaneous observations of $\mathbf{k} \cdot \mathbf{V}$ and $\mathbf{k} \cdot \mathbf{V}_{ph}$ at the same latitude. Several hours of simultaneous observations with 20-s integration were obtained on Aug 27 1998 when $|\mathbf{V}| \sim [300, 1200]$ m/s. *Nielsen and Schlegel* [1985] examined the relationship between coherent phase velocity observed with the 140 MHz STARE radar and electron drift velocity measured

on the same field line at F -region heights with EISCAT. They found V_{ph} to be limited to a value near the ion acoustic velocity and also found that this limiting velocity was a strongly increasing function of the electron drift velocity magnitude (electric field). We find a clear linear relationship between both the logarithmic power and the magnitude of the coherent phase velocity with $|\mathbf{E}|$. The results reported here are the first such observation of the relationship of coherent parameters to electric field magnitude made at 440 MHz and with the radar $\mathbf{k} \sim$ parallel to \mathbf{V}_{ph} .

August 1998 Experiment

In mid 1998, magnetic cloud events produced conditions with strong solar wind/magnetosphere coupling due to increased SW density, high SW velocity and magnetic field strength, and strongly southward IMF B_z . In response to such conditions, greatly enhanced and expanded ionospheric convection ($\mathbf{V}=\mathbf{E} \times \mathbf{B}$) can result as the magnetosphere and ionosphere are strongly driven in a convection bay. On August 27, 1998, real time monitoring of the ACE spacecraft, whose observations of the solar wind at the L1 point are available on the Internet, identified the occurrence of strong, steady negative IMF B_z (< -12 nT) for > 6 hours.

In response to this interval of sustained negative IMF B_z , the Millstone Hill UHF radar began operations shortly after local noon (17 UT) in a fixed-position mode designed to obtain simultaneous F -region convection velocity observations and E -region coherent parameters while looking parallel to $\mathbf{E} \times \mathbf{B}$. Intense sunward convection > 2500 ms^{-1} ($|\mathbf{E}| \sim 125$ mV/m) was observed. Radar azimuth was chosen to parallel $\mathbf{E} \times \mathbf{B}$ along the equatorward edge of the enhanced convection, according to statistical models of the 2-cell convection pattern (e.g. *Foster et al.* [1986]). As the region of strong electric field expanded to lower latitudes during the event, the MISA steerable antenna was rotated to be L -shell aligned at $\sim 58^\circ$ invariant latitude. Data were acquired during varying conditions in which $|\mathbf{E}|$ varied [30, 80 mV/m].

Overflights of the DMSP satellites of the post-noon convection at this time show the pronounced double-peaked sunward convection characteristic of the formation of a sub-auroral polarization jet during disturbed conditions [*Yeh et al.*, 1991]. A DMSP F13 overflight of the Millstone Hill longitude at 22:10 UT (not shown) shows close agreement between the radar F -region Doppler velocity and the drift meter observations. This confirms that the radar was looking parallel to \mathbf{V} and that the radar line-of-sight observations provided a good measure of the total electron drift vector and $|\mathbf{E}|$. *Erickson and Foster* [unpublished manuscript, 2000] examine the temporal and range-extent variability of the coherent scatter observed in a similar experiment in November 1998 and find that the electric field can exhibit small-scale variability in the region of the polarization jet.

Backscatter Model

The power/range distribution observed in these fixed beam experiments depends on the convolution of the antenna beam pattern with the latitude and altitude distribution of the irregularities. Given the radar pointing information, detailed beam shape, and an assumed spatially uniform layer of irregularities centered at a given altitude, the distribution of radar backscattered power as a function of range can be calculated. *Foster and Tetenbaum* [1991] have described such a model for the Millstone Hill system in which the aspect angle sensitivity, the altitude of the irregularities, the thickness of the layer, and the latitude extent of the layer can be varied. The current version of this model calculates the relative backscattered power at each range by determining the intersection of a specified irregularity layer with the antenna beam pattern at that range and then performing a discrete element integration over the beam pattern out to a 10° angle off the main beam direction. The beam pattern for the Millstone Hill 46-m steerable antenna has been presented by *St. Maurice et*

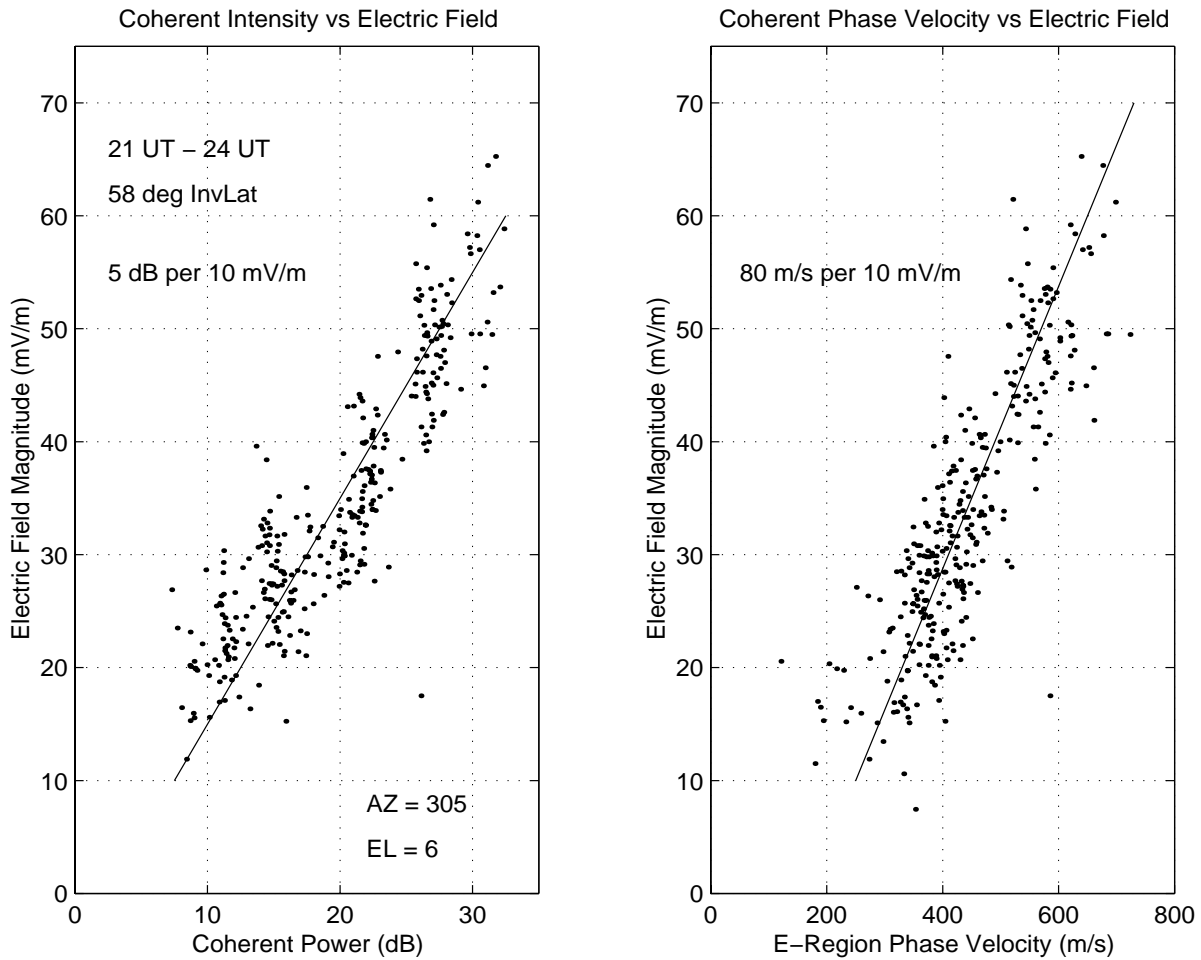


Figure 3. Electric field dependence of logarithmic coherent power and phase velocity derived from simultaneous measurements. A linear relationship is found for both parameters.

al. [1989] and the off-beam two-way attenuation factor is -80 dB for angles $> 3^\circ$. The IGRF97 magnetic field model is used to determine aspect angle at each integration element. *Foster et al.* [1992] found that the 440-MHz magnetic aspect angle sensitivity is -15 dB deg^{-1} for aspect angles between 0° and 3° , and -10 dB deg^{-1} for aspect angles between 3° and 6° from perpendicular. Model studies reveal that the dominant contribution to the received power comes from the center of the beam when the main beam intersects the irregularity layer. Since the aspect angle varies by only a degree or two within the region covered by the radar beam and its near side lobes, the fall-off of power with range away from this point is dominated by the antenna beam shape function. Model analyses of the experiment reported here were used to determine the antenna-pointing position employed and to confirm that the sidelobe *E*-region and the incoherent scatter *F*-region observations were made at the same invariant latitude.

Observations

During the three-hour interval 21 UT - 24 UT on August 27, 1998, while $K_p = 6+$, coherent scatter and incoherent scatter observations were obtained with the L-shell aligned experiment described above (23 UT = 18 LT). Overflights of the DMSP satellite confirm that the Millstone Hill coherent/incoherent scatter observations were made within and on the equatorward extent of a region of strong sunward (westward) plasma convection associated with the polarization jet or SAID [Yeh et al., 1991]. Figure 2 presents the Doppler velocity and backscattered power observations. Doppler velocity and spectral parameters observed at 295-km altitude (labeled F region) were uncontaminated by sidelobe coherent returns and provide a measurement of $V \sim \mathbf{E} \times \mathbf{B}$ at 58° Λ . For main-beam altitudes < 265 km, the E region at ~ 110 km is visible from Millstone Hill and sidelobe coherent returns dominate the spectra. The signal received in these sidelobe gates (labeled E region) provides a direct measure of the coherent phase velocity at the same invariant latitude as the F -region observations. Both E -region phase velocity and coherent power decrease as the magnitude of the F -region ion velocity decreases.

Whereas previous Millstone Hill experiments have shown a linear relationship between log power and phase velocity for the E -region coherent returns [e.g. *Foster and Tetenbaum, 1992*], those studies could not simultaneously determine the causative electric field. Assuming that the radar was aligned with $V = \mathbf{E} \times \mathbf{B}$, the F -region Doppler velocities yield $|\mathbf{E}|$ directly. Scatter plots of logarithmic coherent power (in dB) and two-stream phase velocity vs electric field magnitude for the observations shown in Figure 2 are presented in Figure 3. For electric field varying in the range [15,65] mV/m, we find a clear linear relationship between the magnitude of the coherent phase velocity and $|\mathbf{E}|$, with slope 10 ms^{-1} per 10 mV/m. Logarithmic coherent power also increases linearly with $|\mathbf{E}|$, with slope 5 dB per 10 mV/m. These are the first direct observations of the variations of coherent power and phase velocity with the magnitude of the ionospheric electric field obtained at 440 MHz from Millstone Hill. *Nielsen and Schlegel* [1985] investigated coherent phase velocity observed by STARE at 140 MHz with ion drift velocity observed on the same field line by the EISCAT radars. Our relationship between these parameters is considerably steeper than that reported in this earlier work.

Discussion

At high latitudes the two-stream phase velocity is found to be limited to the ion sound speed, C_s , at the E -region height of the irregularities [*Nielsen and Schlegel, 1983*]. Ion sound speed increases as the square root of the ambient electron temperature and it has been noted by those authors that this limiting velocity is a strongly increasing function of electron drift velocity magnitude. *Schlegel and St-Maurice* [1981] first reported elevated electron temperatures in the auroral E region from Chatanika radar observations and attributed this to heating by two-stream waves. *Williams et al.* [1992] performed an extensive investigation of E -region heating as a function of F -region electric field observed on the same field line with the EISCAT radars, finding a linear dependence of T_e on $|\mathbf{E}|$.

With the assumption that our observations of the two-stream phase velocity constitute an observation of perturbed C_s in the heated E region, we can interpret the increase in V_{ph} with $|\mathbf{E}|$ as an increase in E -region electron temperature. Figure 4 presents our observation of the electric field variation of T_e at 110 km, derived from the two-stream V_{ph} observations of Figure 3. Also shown are the direct incoherent scatter radar observations of E -region electron temperature and F -region electric field made at Chatanika [*Schlegel and St-Maurice, 1981*] and EISCAT [*Williams et al., 1992*]. The excellent agreement between the temperature derived from the coherent phase velocity

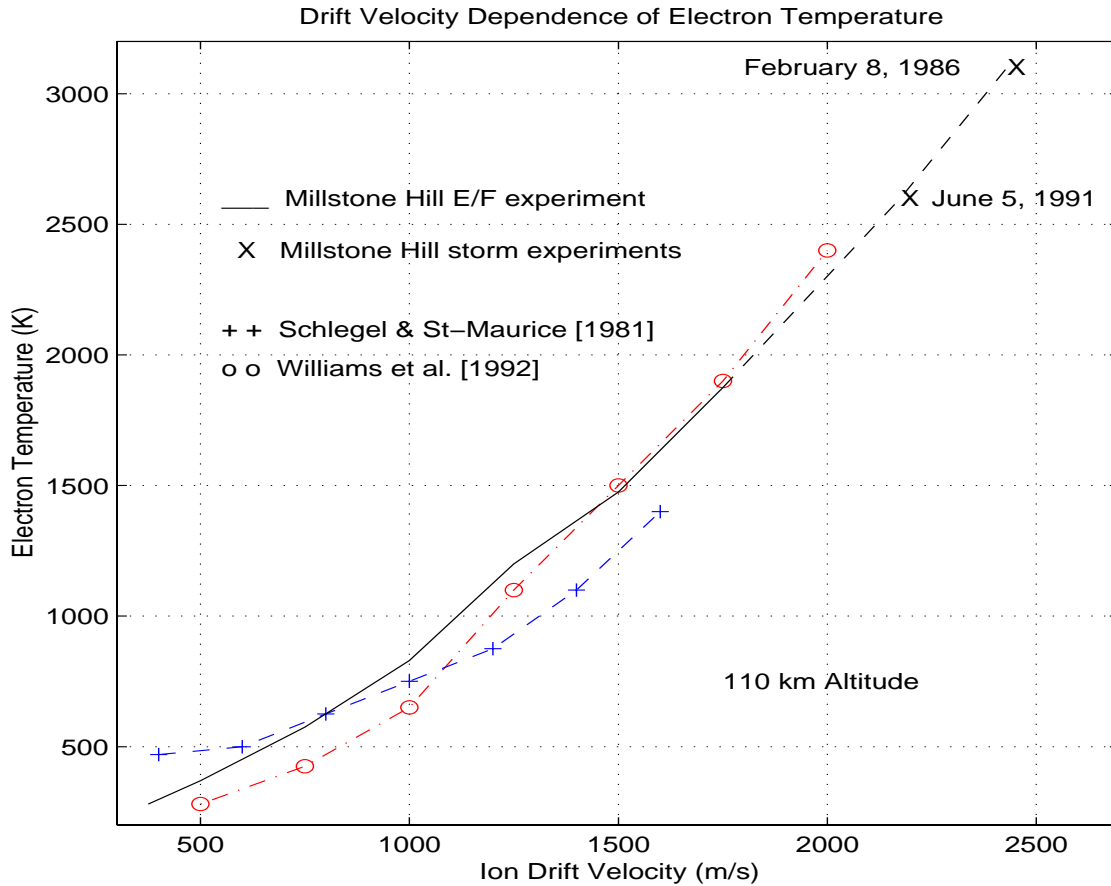


Figure 4. E-region electron temperature calculated from coherent phase velocity for $V_{ph} = C_s$ plotted versus $\mathbf{E} \times \mathbf{B}$ drift velocity. Results of the Millstone Hill E/F experiment are in close agreement with the relationships derived from Chatanika (Schlegel and St-Maurice [1981]) and EISCAT (Williams et al., [1992]). Greatly elevated T_e (3100° K) was found during the large geomagnetic storm of February, 1986.

and the incoherent-scatter results confirms that heating by two-stream waves is the mechanism responsible for the electric field-dependent electron temperature enhancements. Unlike the observations at auroral latitudes, the Millstone Hill observations are associated with polarization jet electric fields at sub-auroral latitudes and are not subject to particle-precipitation *E*-region heating effects.

It is important to identify if there is a limit to the wave-induced *E*-region heating. We have examined Millstone Hill coherent backscatter experiments to find the upper limit on observations of V_{ph} . The vast majority of observations of coherent V_{ph} from Millstone Hill fall in the range [350, 750] ms^{-1} , corresponding to T_e of [350, 2000] K. During the June 5, 1991 ($K_p = 8$) and February 8, 1986 ($K_p = 9$) magnetic storms, convection electric fields as great as 200 mV/m were observed at *F*-region heights (cf. Yeh *et al.*, [1991]), beyond the range of our sensitivity to coherent returns. At lower latitudes ($58^\circ \Lambda$), coincident with our coherent phase velocity observations, electric fields exceeded 100 mV/m and $V_{ph} > 930 \text{ ms}^{-1}$ was observed during the 1986 event, corresponding to an *E*-region electron temperature of ~ 3100 K. Data points (X) from these great storms are included in Figure 4 and constitute the first observations of such greatly elevated T_e at

E-region heights not associated with energetic electron precipitation.

Acknowledgements

Observations and analysis were supported by the National Science Foundation through a Cooperative Agreement with the Massachusetts Institute of Technology. We thank E. Mishin and B. Fejer for helpful comments, and the members of the Atmospheric Sciences Group at the Millstone Hill Observatory for their support and encouragement.

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