GEOPHYSICAL RESEARCH LETTERS, VOL. 19, NO. 11, PAGES 1097-1100, JUNE 2, 1992

ENHANCEMENT OF THOMSON SCATTER BY CHARGED AEROSOLS IN THE POLAR MESOSPHERE: MEASUREMENTS WITH A 1.29-GHZ RADAR

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Abstract. The summer polar mesosphere was observed with the Sondrestrom 1.29-GHz radar with a new high-resolution data acquisition mode. On one occasion, a spatially narrow enhancement in the backscattered power was seen near an altitude of 88 km. We discuss possible explanations and propose that this layer may be the first example of polar mesosphere summer echoes (PMSE) detected above 1 GHz. Specifically, we suggest that these echoes are enhanced Thomson scatter from a layer of charged aerosols, and we speculate upon the size and charge state.

Introduction

The summer polar mesosphere has fascinated atmospheric radar scientists since *Ecklund and Balsley* [1981] observed 50-MHz radar backscatter cross-sections much larger than could be explained by existing theories. Mesospheric echo powers from non-summer seasons and non-polar latitudes are several orders of magnitude smaller and can be explained by electron density inhomogeneities created by neutral atmospheric turbulence which is generated by breaking or saturating gravity waves [*Balsley et al.*, 1983]. The same explanation cannot be directly applied to polar mesosphere summer echoes (PMSE) because, at the higher altitudes at which they occur, the viscous cutoff scale of the neutral air turbulence is much larger than the radar scattering length, which means that the turbulent energy would have been dissipated by viscosity without creating significant structures at the radar scattering scales. *Kelley et al.* [1987] proposed that the presence of heavy hydrated protons in the region would slow down the diffusion of electrons and move the diffusive cutoff to shorter wavelengths, thereby facilitating the creation of inhomogeneities at the radar scattering length. They went on to predict that PMSE might also be seen at even shorter scattering lengths, which was confirmed by *Hoppe et al.* [1988] at 224 MHz and *Röttger et al.* [1990] at 933 MHz. *Cho et al.* [1992] have shown that charged aerosols (perhaps in the form of dust from meteors and ice crystals from subvisible or visible noctilucent clouds) are even better than hydrated ions at retarding electron diffusivity, which could explain the extension of the turbulence-driven scattering regime to the VHF radar frequencies. They also showed, however, that it is exceedingly difficult to extend the turbulent mixing/high Schmidt number concept to explain gigahertz backscatter.

Havnes et al. [1990] proposed an alternate PMSE mechanism which invokes the idea that a "cloud" of charge surrounding a multiply charged aerosol will respond to radio waves in phase such that the scattered power will be greater than that of normal Thomson scatter from the same number of electrons. Contrary to *Havnes et al.* [1990], *Cho et al.* [1992] pointed out that this mechanism is only plausible for the higher frequency radars and not for VHF since the PMSE cross sections are extremely frequency dependent, whereas this theory predicts an essentially constant cross section with respect to frequency. Thus, if this mechanism is responsible for the 933-MHz PMSE, then it should also work at 1.29 GHz as long as the scattering length is above the Debye length cutoff. The turbulent mixing theory, on the other hand, predicts that the cross section at 1.29 GHz should be at least 15 dB down from the signal at 933 MHz.

Therefore, in light of these conflicting theories, it was a natural step to search for PMSE with the Sondrestrom 1.29-GHz radar.

Experimental Set-Up

The Sondrestrom radar is situated at geographic 67° N which is similar in latitude to the other radars which have observed PMSE. (The European incoherent scatter (EISCAT) radars are at 69° N (as was the Cornell University portable radar interferometer (CUPRI)), the Poker Flat radar was at 65° N, and the mobile sounding system (SOUSY) radar was at 69° N.) The peak transmission power is 4 MW, the effective antenna aperture is 403 m^2, antenna gain is 49.9 dB, and system noise temperature is 110 K. Other details of the radar are given by *Kelly* [1983].

A new mode was created for mesospheric observations, since the usual modes used by the Sondrestrom radar were designed for high-altitude incoherent scatter measurements. We used a Barker-coded single pulse designed for fine height resolution while maintaining a high signal-to-noise ratio (SNR). A 13-baud code with 4-μs bauds was employed, which resulted in a 600-m resolution. The primary drawback with the single pulse scheme was the lack of auto-correlation function (ACF) data, thus precluding knowledge of Doppler spectra. A Barker-coded multipulse scheme was also tried in order to gain spectral data at the expense of SNR, but the spectral resolution of 1.6 kHz was too coarse to get any meaningful information from the mesosphere. Integration times of 10- and 30-s were used on-line at different times.

Paper number 92GL01155
0094-8534/92/92GL-01155$03.00

Observations

Under our operating modes, electron density levels in the mesosphere were such that it was difficult to get a radar return below ~ 90 km without an enhancement caused by a particle precipitation event. Although geomagnetic activity was low during the periods of observation, one such event did occur on July 14, 1990, starting at 10:00 am local time. The local riometer indicated an absorption event, and the digisonde traces vanished at this time as well, providing further evidence and implying that particle precipitation penetrated at least as low as the upper D region.

The first three panels in Figure 1 show 5-minute averaged electron density profiles obtained during this active period. The dotted line is an average from a quiet day. In the first three panels, particle precipitation increased the electron density in the upper mesosphere thus making the region below 90 km "visible" to the radar. The electron density at 90 km, for example, is roughly an order of magnitude above the extrapolated quiet day curve. This enhancement is a necessary condition for PMSE detection since they occur almost exclusively below 90 km. The peak in the signal near 88 km is shaded and often persists from one 5-minute integration to the next. The narrow layer of enhanced radar scatter shown in Figures 1*a* and 1*b* is difficult to explain with known mechanisms of electron production or gathering mechanisms. On the other hand the data are quite reminiscent of the narrow peak in 933-MHz echo strength reported by *Röttger et al.* [1990] which was coexistent with a strong, classic PMSE echo at 50 MHz. Figure 1*d* shows an example late in the event when the layer was no longer present and the electron density was returning to normal solar induced levels.

Discussion

What could be causing such a thin scattering layer to form? First consider the possibility of a sporadic E formation. Periodic wind shears in a gravity wave can create, through drag and magnetic forces on the plasma, regions of increased plasma density which are transported downward with the phase propagation of the wave [*Whitehead*, 1961]. This mechanism, however, operates only down to altitudes where the magnetic field effect on the ions are dominant over that of collisions with the neutral gas. The relevant parameter is κ_i, the ratio of the ion gyrofrequency to the ion-neutral collision frequency, which must be a significant fraction of unity. At 90 km in the polar summer $\kappa_i \sim 2 \times 10^{-3}$, so this mechanism cannot explain the existence of a layer at these heights.

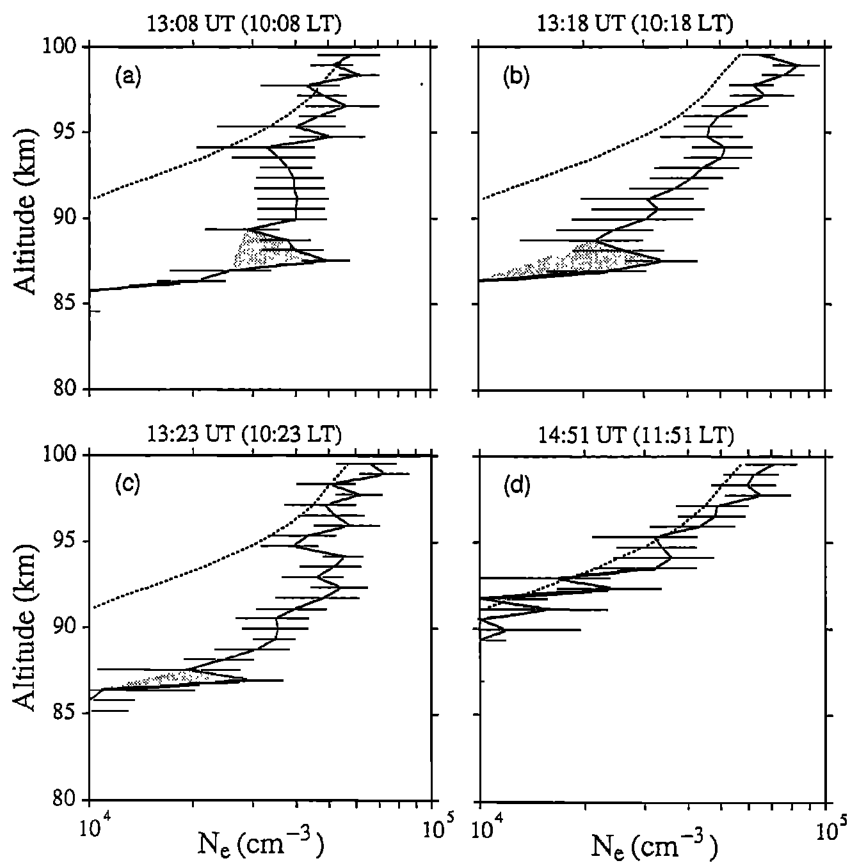

Fig. 1. Examples of range-corrected signal-to-noise ratio plotted vs. height for July 14, 1990. The abscissa is calibrated for normal Thomson scatter such that the values give a reasonable estimate of the electron density. The solid line is a 5-minute average, while the dotted line is a 2-hour mean taken on a geomagnetically quiet day. The altitude resolution is 600 m. The first three frames show profiles during a period of electron precipitation, such that the region below 90 km is observable. Note the persistence of a peak at ~ 88 km. The last frame is from a much later time when the ambient electron density level had gone back down.

Sugiyama [1988] considered the effect of gravity waves on electron density through changes in chemical reaction rates. This approach can only produce layers with thickness on the order of the vertical wavelength of the wave itself ($\sim$ 5–15 km), thus it is not a candidate for producing the layer in question.

Since we observe the layer during periods of electron precipitation, one might ask whether it is simply a result of an unusual spectral distribution in the energy of precipitating electrons. However, to produce a narrow layer below 90 km requires a physically implausible energy distribution as shown by *Collis and Kirkwood* [1990]. Moreover, the layer that they were trying to reproduce was more than 10 km wide; we are interested in something that is on the order of 600 m, which is even harder to produce. Also, such a narrow layer of electrons would tend to diffuse away rapidly unless there was an accompanying stratus of positively charged macroscopic particles that inhibited the motion through ambipolar electric fields.

Finally we examine the possibility that the layer might be a manifestation of PMSE. Two distinct mechanisms have been proposed so far for the generation of PMSE: (1) coherent scatter resulting from turbulence (and steep electron density gradients) with the addition of a viscous-convective subrange through a raised Schmidt number and (2) enhanced Thomson scatter from charged aerosols.

The highest radar volume reflectivity, η, recorded during the event reported here was $\approx 2.5 \times 10^{-18}$ m^{-1}. For reference the ambient electron density extrapolated from nearby heights above and below the layer was $N_e \approx 2.7 \times 10^4$ cm^{-3}. (The largest PMSE η observed at 933 MHz is $\approx 4 \times 10^{-18}$ m^{-1} with $N_e \approx 8 \times 10^3$ cm^{-3} [*Röttger et al.*, 1990].) Since we do not have a measure for the turbulent energy dissipation rate ϵ, it is difficult to compare the observed η with that derived from turbulent scattering theory. Using ϵ = 0.1 W/kg [*Watkins et al.*, 1988] in the turbulence model of *Driscoll and Kennedy* [1985], we find that $Sc \sim 5000$ is required to yield the observed η. (Sc is the Schmidt number defined as the ratio of the neutral gas viscosity to the electron diffusion coefficient.) In turn, this requires the presence of charged aerosols with radii of at least 0.07μm such that their total charge accounts for at least 60 % of the plasma charge [*Cho et al.*, 1992]. Such large aerosols can only be noctilucent cloud particles which are usually found at a lower height ($\sim$ 83 km [*Gadsden and Schröder*, 1989]), although they have been detected as high as 89 km [*Witt et al.*, 1976]. Another difficulty with such large particles is that they must be limited in number. The largest observationally inferred number density N_a for cloud aerosols of radius 0.07μm is 150 cm^{-3} [*Thomas*, 1984]. Since N_e was $\approx 2.7 \times 10^4$ cm^{-3}, this would require an average charge of at least $Z \approx 100$. Such high values are implausible for pure ice particles whose charging is expected to be dominated by collection of electrons; photoemission has little influence due to the high work function for ice. Model calculations by *Jensen and Thomas* [1991] yield an average value of $Z \approx$ -5 for particles of radius 0.1 μm. However, *Havnes et al.* [1990] have pointed out that the cloud particles may be a mixture of ice and metallic substances from meteor ablation which could significantly lower the work function, thus leading to high positive charges.

Havnes et al. [1990] also proposed the enhancement of Thomson (or incoherent) scatter by multiply charged aerosols as an alternative explanation for PMSE. The idea is that a charged aerosol would be surrounded by a "sphere" of surplus or deficit (corresponding to a positively or negatively charged particle) of electrons with a characteristic length scale given by the Debye length, λ_D. If $\lambda_D \ll \lambda_R$, the radar wavelength, then the Debye sphere will respond in phase, thus leading to an increase in the scattered power per particle by a factor of $|Z|^2$ [*Bingham et al.*, 1990]. (However, as mentioned earlier, the scattered power is independent of radar frequency for $\lambda_D \ll \lambda_R$, so this mechanism can only be applied to the higher frequency regime where the coherent scatter power is expected to decay rapidly.) To compare with our data, first we check the Debye length criterion. Near the observed layer we calculate $\lambda_D \approx 6$ mm (using N_e = 20,000 cm^{-3} and T = 130 K) which is much smaller than the radar wavelength of 23 cm, so enhanced scatter can take place. A rough estimate of the backscattered power is proportional to $Z^2 N_a$ plus the electron density not associated with the Debye spheres around the aerosols. Using the estimates of N_e and N_a used earlier we get $|Z| \approx 10$ in order to explain the observed layer. Since the calculation for coherent scatter with raised Sc required $Z > 100$, clearly the enhanced Thomson scatter will dominate in this case. Moreover, unlike the turbulence case, the backscattered power is not dependent on the aerosol size; therefore, particles smaller than noctilucent cloud droplets can be responsible, which raises the ceiling on available number density and lowers the required charge per aerosol. This, in turn, is more consistent with the observed height of the layer, because larger particles are expected to reside at lower altitudes due to sedimentation.

Summary

Observation of the polar summer mesosphere with the Sondrestrom 1.29-GHz radar revealed a narrow peak in the backscattered power profiles. It is most likely due to the presence of a thin layer of charged aerosols which enhances the Thomson scatter, i.e, a form of PMSE. We estimated that for N_a = 150 cm^{-3}, the average charge state of the aerosols must be ≈ 10 to produce the enhancement.

However, this scenario would be more convincing if we had obtained Doppler spectral data showing the characteristic narrow spectra as calculated by *Cho et al.* [1992], or simultaneous 50-MHz echoes showing an obvious PMSE. (*Röttger et al.* [1990] have shown that the PMSE observed by the EISCAT UHF radar had spectral widths much too narrow for normal Thomson scatter.) The spectral resolution of the radar mode, which was wider than the normal incoherent scatter spectral width for these heights, prevented us from making this comparison. Also, a higher SNR would make reliable measurements possible down to 80 km without the help of precipitation events. Therefore, the development of new radar modes with these points in mind is suggested as future work.

Acknowledgments. We would like to thank Peter Stauning of the Danish Meteorological Institute for providing the riometer data and Geoff Crowley of the University of Lowell for sharing the digisonde data. JYNC would like to thank the site crew at Sondrestrom, Terri Dabbs, Annette and John Jørgenson, and Tom Lovelace, for their cooperation and hospitality. We also appreciate Don Farley's helpful comments. This work was funded by a National Science Foundation contract, ATM-8913153. Also, one of us (JYNC) was supported by a NASA Space Grant Fellowship.

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(Received March 16, 1992;
accepted April 29, 1992.)