A BRIEF REVIEW OF PMSE SCATTERING MECHANISMS

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The remarkably strong radar echoes from the summer arctic mesopause region, coined PMSE (polar mesosphere summer echoes), have been an enigma to atmospheric and radar scientists since their discovery more than a decade ago [*Ecklund and Balsley*, 1981]. Since then, more sophisticated radar experiments and in situ rocket measurements have shed some light on the underlying physics and chemistry, and theories have been formulated to explain the generation of the intense radar backscatter and the remarkable physical conditions associated with it.

Mesospheric radar echoes from non-summer seasons and non-polar latitudes are orders of magnitude smaller than the summer polar case and can be explained by electron density inhomogeneities created by neutral gas turbulence which in turn is generated by breaking gravity waves [*Balsley et al.*, 1983; *Røyrvik and Smith*, 1984]. The same explanation cannot be directly applied to PMSE because, at the higher altitudes from which they originate, the viscous cutoff scale of the neutral air turbulence is much larger than the radar Bragg lengths. This means that the turbulent energy would have been dissipated by viscosity without creating significant structures at the radar scattering scales of 3 m or less. Clearly there must be something extraordinary happening in the summer polar mesosphere that drastically enhances the radar scattering process.

We list below the pertinent observations:

(1) In the polar summer mesosphere, the 50-MHz radar cross sections are enormously enhanced relative to those in other seasons and latitudes [*Ecklund and Balsley*, 1981].

(2) Rocket measurements show that, in the PMSE layers, the electron density has structures well below the viscous cutoff length scale of the neutral gas [*Kelley and Ulwick*, 1988; *Kelley et al.*, 1990].

(3) The range of occurrence of PMSE in space and time corresponds well to the cold summer mesopause [*Balsley et al.*, 1983]. In the same region, large water cluster ions and aerosols form due to the uniquely low temperatures.

(4) Very steep gradients and "bite-outs" in the electron density are often observed in PMSE regions by rocket probes and the EISCAT UHF radar [*Ulwick et al.*, 1988; *Inhester et al.*, 1990; *Röttger et al.*, 1990].

(5) A simultaneous observation of noctilucent clouds by rocket-borne instruments and PMSE by a 50-MHz radar showed that the PMSE layer was ~ 1 km above the optical cloud layer [*Wälchli et al.*, 1993].

(6) Semi-diurnal periodicities in PMSE strength are apparent, and *Fritts et al.* [1988] have observed a case in which regions of maximum echo power corresponded to an unstable phase of tidal modes and long-period gravity waves.

(7) PMSE at 50 MHz are often aspect sensitive with respect to the vertical [*Czechowsky et al.*, 1988].

(8) At VHF, the Doppler spectral widths are often not positively correlated with backscat-

tered power [*Czechowsky et al.*, 1989; *Röttger and La Hoz*, 1990; *Thomas et al.*, 1992].

(9) At 50 MHz, a two-layer PMSE was observed in which the neutral gas was turbulent in the upper layer and not turbulent in the lower layer [*Cho et al.*, 1993; *Lübken et al.*, 1993; *Ulwick et al.*, 1993].

(10) The radar cross sections are highly frequency dependent, but their temporal evolution and spatial morphology at 50 and 224 MHz are very similar [*Hall*, 1991; *Kirkwood et al.*, 1993] and can most likely be explained by the same process [*Cho et al.*, 1992*a*]. PMSE at 933 MHz and 1.29 GHz are much rarer and weaker, but nonetheless much stronger than reasonable extrapolations of the VHF echoes could account for, and the very narrow spectra preclude incoherent scatter as an explanation [*Röttger et al.*, 1990; *Cho et al.*, 1992*b*].

Observation (2) is the direct explanation for (1). Thus, recent theories have been trying to account for the existence of the small-scale electron density fluctuations. Most of the theories also revolve around item (3) which may also have a role in explaining (4). If the presence of ice aerosols are responsible for producing PMSE as the theories propose, then (5) suggests that it is the smaller, sub-visible particles which play the dominant role, rather than the occasionally occurring noctilucent clouds. Item (6) suggests that turbulence does exist in the summer mesosphere and sometimes modulates the generation of PMSE; however, (7), (8), and (9) imply that neutral gas turbulence is only one of the mechanisms which generate electron density fluctuations which lead to PMSE. Observation (10) hints that PMSE at UHF may be fundamentally different from PMSE at VHF. For a more complete review of PMSE see *Cho and Kelley* [1993].

The existence of electron density structures can be thought of as a continuous struggle between their generation and their diffusive dissipation. Diffusion acts preferentially on shorter length scales, so in general it is harder to maintain smaller structures. Hence, the central problem of PMSE: what anomaly allows the maintenance of electron density inhomogeneities at smaller scales (i.e., the radar Bragg scales) than are normally possible in the mesosphere? The short answer is that either (1) the generation of structures is enhanced or (2) the electron diffusivity is reduced, or possibly both.

From the observational evidence, we can conclude that neutral gas turbulence is certainly one of the generation mechanisms in the VHF regime. However, the type of VHF PMSE that have extremely narrow spectral widths and are very aspect sensitive could not have been generated by turbulence. Other generation mechanisms have been discussed [*Röttger and La Hoz*, 1990; *Havnes et al.*, 1992], but they remain speculative.

No matter what the generation mechanisms are, however, a reduction in electron diffusivity will certainly enhance the radar scatter. Following the lead of *Kelley et al.* [1987], *Cho et al.* [1992*a*] showed that the presence of subvisible charged ice particles with intrinsically low diffusivities will significantly reduce the electron diffusivity through ambipolar electric fields. They calculated that the presence of ice aerosols and neutral gas turbulence with reasonable parameters could account for the strongest PMSE observed with the VHF radars. Note that this theory also conveniently accounts for the correlation of PMSE occurrence with the very low temperatures of the summer mesopause.

However, at the shorter Bragg scales of the radars operating near 1 GHz, it is difficult to produce an echo enhancement above the ambient incoherent scatter level even with the reduction of electron diffusion. As it turns out, charged aerosols can also enhance radar scatter by introducing inhomogeneities in the ambient ionization solely due to their own charge. Historically, this phenomenon was first discussed in the context of plasma waves in dusty plasma and was called "transition scattering" [*Tsytovich et al.*, 1989]. It was then extended to the case of electromagnetic wave scatter [*Bingham et al.*, 1991] and was proposed as a mechanism for PMSE by *Havnes et al.* [1990]. *Hagfors* [1992] and *La Hoz* [1992] developed a parallel theory using the Debye-Huckel "dressed particle" approach which was one of the bases for the development of incoherent scatter theory. For lack of an established nomenclature, we shall call this scattering mechanism "dressed aerosol scatter." Because of its limited capacity to enhance radar scatter above the incoherent scatter level and its non-dependence on radar wavelength, dressed aerosol scatter is only relevant for UHF radars.

The idea is as follows: statistically, 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 plasma Debye length, λ_D. If $\lambda_D \ll \lambda_R$, the radar wavelength, then the Debye sphere will respond in phase, therefore leading to an increase in the scattered power per aerosol over that of incoherent scatter by a factor of roughly $|Z|^2$, where Z is the charge number per aerosol. Thus, for an electron density that is held constant, the resultant scattering increases roughly by $\sim |Z|$ over incoherent scatter. A more quantitative result depends crucially on the ratio of the average distance between aerosols to the plasma Debye length [*de Angelis et al.*, 1992; *La Hoz*, 1992]. If the ratio is large compared to one, then the aerosols can be considered independent and the resulting enhancement of radar scatter can become large. However, if the ratio is smaller than one, then the mutual interactions between the aerosols weaken the enhancement. *Hagfors* [1992] has shown that, in the latter case, radar scatter from charged aerosols is not likely to rise above incoherent scatter levels. Thus, the mechanism favors a small number of highly charged aerosols over a large number of particles with low charge.

Also, *Cho et al.* [1992*a*] showed that the resulting spectral width of dressed aerosol scatter from charged aerosols decreases sharply with the particle radius. The very narrow PMSE spectra observed by the EISCAT UHF radar [*Röttger et al.*, 1990] could thus be interpreted as an effect of dressed aerosol scatter.

However, to account for the observed radar cross sections, dressed aerosol scatter requires the presence of aerosols that are not thought to be reasonable, i.e., individual aerosols with a high degree of charging. But this belief itself is based on very scant knowledge of the nature of the summer mesopause aerosols; clearly, more investigations need to be conducted in this area.

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