CURRENT PUZZLES IN MIDDLE ATMOSPHERIC RADAR SCATTERING AND REFLECTION

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Despite the proliferation of MST radars in recent years, by no means do we completely understand all the signals that we receive back from the atmosphere. Here I highlight three types of radar scattering and reflection encountered in the middle atmosphere that are still puzzles to us.

Meteor Observations by Large-aperture Radars

Meteor observation by radar has had a history as long as radar itself, and until recently had been considered mature and "old hat" in many respects. The field seemed to have passed on a long time ago from the inquiry of basic issues to that of application and operational use. For atmospheric science, VHF meteor radars had proliferated around the globe for taking routine measurements of upper mesospheric and lower thermospheric winds. However, in the last few years unexpected results from the world's biggest VHF and UHF radars—Arecibo, Jicamarca, and EISCAT—have shown that we are still far from figuring out all there is to know about radar scattering from meteors.

Meteor echoes are usually categorized as (1) coming from the head, i.e., spatially localized and moving along with the meteoroid, (2) reflecting from an overdense trail, or (3) scattering from an underdense trail.

Although the overdense and underdense trail echoes have well-established theories of scattering, head echoes have always been difficult to explain. The meteoroid itself is too small a physical target for Rayleigh scattering. A ball of ionization much larger than the meteroid has been suggested, but unlike trail echoes, head echoes have no appreciable duration, so it is hard to explain the near-instant disappearance of the ionization after the meteroid passage. Also what might create the ionization at a distance away from the meteroid is unknown. Shock waves and ultraviolet light have been suggested, but criticized on various grounds. I think we can safely state that there is no generally accepted explanation for head echoes at this time. (See *McKinley* [1961] for classical theories of meteor scattering and reflection.)

While VHF meteor radars with their wide beams mainly detect perpendicular trail echoes, narrow-beam MST radars observe a much larger fraction of down-the-beam head echoes [*Zhou et al.*, 1998]. Simple geometric considerations of the antenna beams cannot explain it, since both types should be sampled equally less for a narrower-beam radar. At first it was thought that the higher power of the MST radar made head echoes more "visible," but recent results show that even the low-power wind profilers detect more head echoes than do meteor radars [*Valentic et al.*, 1996].

Down-the-beam head echoes are also much more prevalent for UHF ISRs [*Pellinen-Wannberg and Wannberg*, 1994; *Zhou et al.*, 1995; *Zhou and Kelley*, 1997]. Simultaneous UHF/VHF observations have yielded very different wavelength dependences of the head echo scattering cross section. The EISCAT results show higher cross sections at shorter wavelengths (like Rayleigh scattering) [*Wannberg et al.*, 1996], while the Arecibo results indicate higher cross sections at longer wavelengths [*Zhou et al.*, 1998]. This is a very fundamental disagreement that is currently under investigation.

Another puzzle is the time gap often seen between the head echo and its corresponding trail echo. In this case, as the meteoroid was traveling down the beam, the trail could not have been perpendicular. The trail also does not necessarily exhibit a smooth decay with time. In this case it cannot be a classic perpendicular underdense trail. Perhaps it could be a trail that gets deformed by turbulence and wind shear so that parts of the "cylinder" surface became momentarily perpendicular to the radar beam. (This idea is known as the "glint" theory.) However, it seems implausible that such deformation could take place within tens of milliseconds as is necessary to explain the observations.

At the magnetic equator, the Jicamarca VHF radar has been used to observe long duration (2 s to 3 minutes) meteor echoes whose Doppler spectral skewness is clearly correlated with the direction of the E-region zonal electric field, indicating the dependence of the meteor scattering process on plasma electrodynamics [*Chapin and Kudeki*, 1994*b*; *Chapin and Kudeki*, 1994*a*]. The investigators concluded that meteor trails deposited within the equatorial electrojet must carry intense discharge currents that excite two-stream and/or gradient-drift instabilities. The direction of electron motion responsible for the discharge current then agrees with the Doppler shift of the high-frequency components in the meteor echoes.

Finally, in an incredibly fortuitous coincidence, a sounding rocket with an electron density probe happened to fly through a meteor trail that was simultaneously detected with the Poker Flat MST radar [*Kelley et al.*, 1998]. The trail as measured by the rocket was at 92 km in altitude, 42 m thick with a peak electron density of 40,000 cm^{-3}, which was 50% above the ambient density, and the edges were extremely sharp with an e-folding length of 1.2 m. A Fourier analysis of the density fluctuations inside the trail showed a turbulence-like spectrum that extended down through the 3-m Bragg scale of the radar, while a wavelet scalogram also showed that the edge gradients also had considerable power at the Bragg scale. The radar echo persisted for several cycles of the radar Doppler beam swinging, had a downward Doppler velocity of about 4 m/s and a spectral width of about 6 m/s. The low electron density ruled out overdense echoing, while the thickness of the trail ruled out classic underdense scattering. The authors proposed that a charged-dust mechanism for lowering the electron diffusivity analogous to PMSE (see next section), was responsible for the maintenance of electron density structures at such small scales. In a companion paper, a technique for the detection of such charged meteoric dust using an ISR was outlined [*Cho et al.*, 1998].

In summary, meteor radar research is far from dead. As we have seen, there are fundamental problems that need to be solved. And MST/ISR systems have been instrumental in bringing about a renaissance to the field. Furthermore, in the next several years the annual Leonid meteor shower is expected to reach a peak in activity. Plans should be laid ahead of time for radar observations of these events.

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Polar Mesosphere Summer Echoes (PMSEs)

There is something about the high-latitude summer mesopause (the coldest region of our atmosphere) that generates a number of interesting phenomena: noctilucent clouds, electron density bite-outs, and anomalously strong radar scattering, especially at VHF. Evidence has been mounting in recent years that all of these phenomena are intimately related. Various theories have been proposed to explain the generation of PMSE, but the viable ones all depend on the existence of large charged particles, such as ice, dust, and cluster ions. However, because enhancement of radar scattering is observed at frequencies ranging from MF to UHF, it is likely that different mechanisms operate at different length scales. Due to the space limitation and the existence of review articles on this topic, I refer the reader to *Cho and Röttger* [1997] for a discussion of VHF PMSE theories and to *Cho and Kelley* [1993] for proposed UHF mechanisms. MF [*Bremer et al.*, 1996] and HF [*Karashtin et al.*, 1997; *Tsunoda et al.*, 1998] observations are quite recent, and no quantitative theory has yet been outlined.

Stratospheric Thin Layers

It is often the case with nature that as instrumental resolution improves, one discovers finer and finer structures. This has been the case with MST radars, especially in the stratosphere where scatterers as thin or thinner than $\sim$ 20 m have been observed [*Ierkic et al.*, 1990; *Cho et al.*, 1996] as better vertical resolution capabilities were developed. In situ balloon measurements have revealed even thinner (meter-scale) "sheets" in the temperature field [*Dalaudier et al.*, 1994]. Assuming that radar scatter and reflection result from density inhomogeneities associated with these temperature structures, considerable success has been achieved in comparing these temperature measurements with VHF radar observations [*Luce et al.*, 1996; *Luce et al.*, 1997]. However, the S-band radar observations with 20-m resolution mentioned above requires the Bragg length to be in the centimeter scale, so finer temperature measurements are required for comparison. Conventional wisdom would also say that Fresnel scatter at such short length scales should be negligible, which means that turbulent layers less than 20 m thick ought to exist in the stratosphere. (Note that *Muschinski and Wode* [1998] have observed temperature and humidity sheets at sub-meter scales using a helicopter-borne probe in the lower free troposphere. They also saw evidence of turbulent layers at these scales.)

The question of what produces such thin layers of temperature discontinuity and turbulence remains unanswered. Viscosity waves are a candidate [*Hocking et al.*, 1991]. A simple differential advection model has been proposed at this workshop by Muschinski et al. Further comparisons between radar and in situ measurements are necessary to advance our understanding in this area.

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