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# Detection of a meteor contrail and meteoric dust in the Earth's upper mesosphere

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**Abstract**—In 1983 a series of small rockets were launched from the Poker Flat Rocket Range near Fairbanks, Alaska to study what has come to be called Polar Mesospheric Summer Echoes (PMSE). We report here on a fortuitous simultaneous 50-MHz radar and rocket detection of what seems to be a meteor contrail produced over the Poker Flat Rocket Range. The two data sets are mutually consistent and taken together suggest some very interesting properties for the trails of large meteors. Most notable is the first evidence that the ablated material can coagulate into particles the order of 50 nm in radius. This estimate is based primarily on the fall speed deduced from both the Doppler shift of the VHG radar signal and the time rate of change of the target as it fell through the beam. In addition the very existence of the radar target, the extremely sharp edges of the trail, and the existence of electron density structures inside the trail more than an order of magnitude smaller than the Kolmogorov microscale, all require large charged aerosols and a very high Schmidt number. Curiously the environment leading to PMSE (the study of which was our primary mission), is very similar to the properties of a large meteor trail some minutes after it is formed. In the PMSE case ice particles grow and become charged by the plasma and, when more than half the charge is tied up on the ice, the plasma diffusion coefficient becomes so small that structure can be supported at VHF scattering scales. In the late-time meteor case large aerosols coagulate and tie up both natural charge in the plasma and the original meteor trail electrons. Following the work of Rosinski and Snow (1961) and Hunten *et al.* (1980) we conclude that the incident meteor was the order of 100 g and would have had a visual magnitude of about −5. This dust production process may resolve some open questions concerning long-lived meteor radar echoes. For example, in the event studied the electron density was well into the underdense condition and yet was detected for over 6 min. Classical meteor scatter theory has no explanation for such a long duration underdense event. 

## INTRODUCTION

In 1983 a series of small rockets were launched from the Poker Flat Rocket Range near Fairbanks, Alaska to study what has come to be called Polar Mesospheric Summer Echoes (PMSE). The term "echo" here refers to anomalous high VHF radar returns from the region first reported by Balsley and co-workers using the 50-MHz Poker Flat Radar [Ecklund and Balsley (1981)]. The purpose of the experiment was to understand the scattering mechanism and to this end simple nose tip Langmuir probes were flown on Super Arcas rockets during strong PMSE conditions.

The project was quite successful and indeed a new understanding did develop out of the analysis. In brief, the probes showed a characteristic extension of the electron density fluctuation spectrum to scales considerably smaller than the Kolmogorov microscale [Ulwick *et al.* (1988)] and a theory was developed to explain this via an enhanced Schmidt number (Kelley *et al.*, 1987; Kelley and Ulwick, 1988). The Schmidt number is the ratio of the neutral viscosity coefficient to the electron diffusion coefficient. This enhancement was later shown to be possible if about more than half of the charge in the plasma is tied up on microscopic particles, most likely the ice associated with the subvisible precursors to noctilucent clouds [Cho *et al.* (1992)]. The phenomenon of PMSE continues to provide interesting problems including new observations of enhanced UHF scatter and a number of rocket, radar and lidar studies continue (see review by Cho and Kelley (1993) for more details and references).

In this paper we report on a remarkable structure observed during one of the rocket flights. The event was detected immediately in the flight records from the rocket and verified as well in a review of the independent radar data set. Why then has thirteen years passed before reporting the observation? At the time, and in subsequent periodic reflections, it had seemed too far-fetched a result to publish. However, we feel now that we have a better understanding of charged

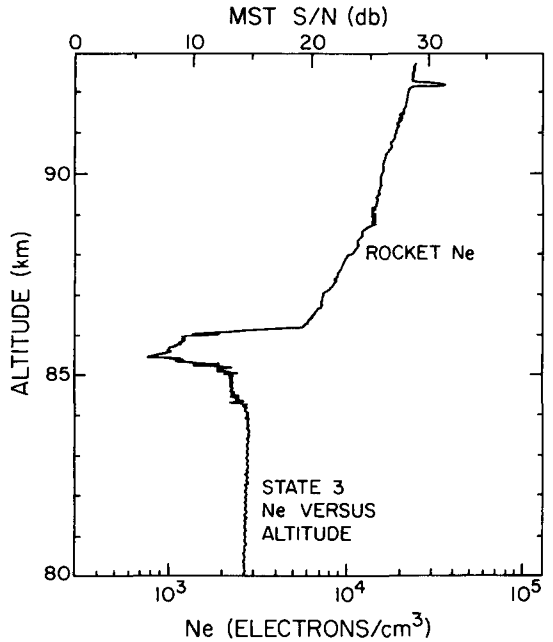


Fig. 1. Rocket electron density profile vs altitude for the event. The most intense Polar Mesospheric Summer Echo is associated with the electron density bite-out near 85 km and the radar echo of interest here with the enhancement near 92 km.

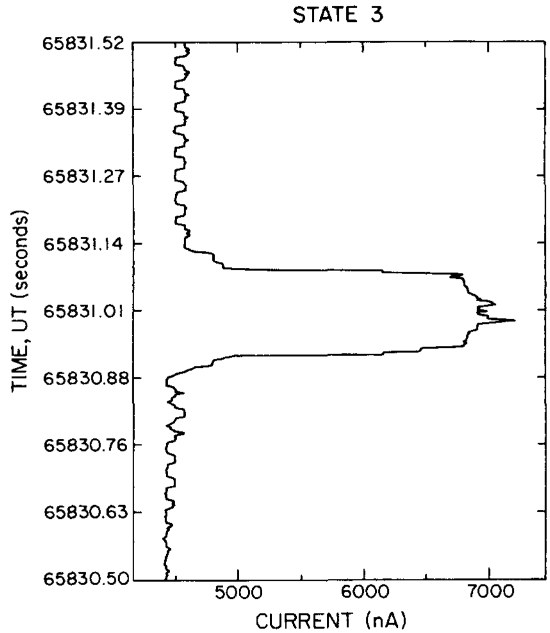


Fig. 2. A detailed plot of the electron density in the thin layer near 92 km. The rocket vertical velocity is such that each major tick mark corresponds to about 40 m. The regular modulation above and below the layer is due to a wake effect at the rocket spin rate.

dust and that data recently published in several other radar and lidar studies may be related to our observations. In the next section the results are presented along with a review of the other new data sets, which we feel might be related. A companion paper, for example, describes the potential for incoherent scatter radars to detect the Earth's dust layer [Cho *et al.* (1977)]. Some discussion and speculation follows.

## THE DATA

Three rockets were launched during moderate to strong PMSE in the campaign which had the acronym STATE (Structure and Atmospheric Turbulence Environment), the results of which were reported in several papers (Ulwick *et al.*, 1988; Kelley and Ulwick, 1988; Watkins *et al.*, 1988; Fritts *et al.*, 1988). The third, STATE 3, is of interest here and the upleg electron density profile is reproduced in Fig. 1. The structure of greatest interest to the project was the bite-out in electron density centered at about 85.5 km. This deep depletion is now thought to be associated with electron scavenging on ice (Reid, 1990; Klostermeyer, 1996) and is clearly associated with the enhanced average radar returns for the period encompassing the launch. Attention is drawn, however, to the extremely thin electron density enhancement detected at 92.3 km.

An expanded plot of this region is presented in Fig. 2 and shows its remarkable character. The entire layer is only 42 m thick and has remarkably sharp edges. The gradient on each edge is 1000 e/m, which if converted to an e-folding length corresponds to 1.2 m. The immediate and incredulous conclusion was that the rocket had penetrated a meter trail, an event so unlikely as to be embarrassing to report. In fact, it would not have been reported at all (and almost was not) had not the structure been verified by the radar.

Figure 3 shows the radar returns from all three beams. Receiver 2 is the most northerly beam (334° azimuth; 15° zenith) and is the one closest to the rocket trajectory. Receiver 3 is vertical while Receiver 1 has a 64° azimuth angle from true north and a 15° zenith angle. The range resolution was 300 m and the radar cycle time was 84 s. By combining the line-of-sight Doppler shifts the wind profile can be determined. This particular record was made 5 min after the rocket penetrated the thin layer. The first radar detection was made 3 min after the rocket data. This is consistent with the time required for a structure to drift from the uplet location of the rocket to the radar

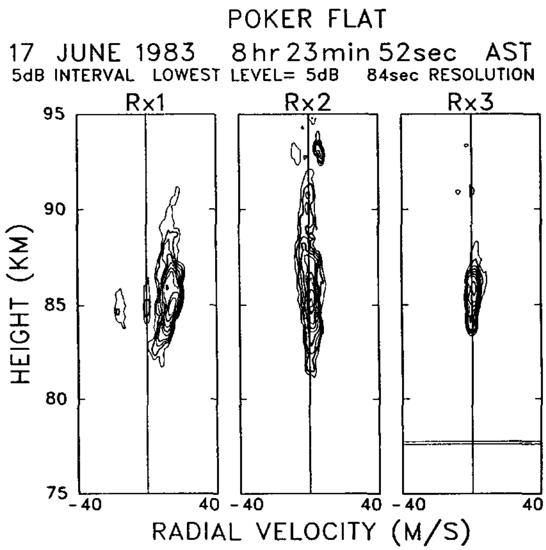


Fig. 3. Radar data closest in time to the rocket flight. The set of contours in the middle (R × 2) plot at 93 km and with a positive Doppler offset are of primary interest.

beam at the wind speed measured at the height of the event. There is clearly enhanced echo in the data centered at 93 km with a range spread of nearly 2 km. The Doppler shift indicates a $4.4 \pm 2$ m/s motion toward the radar. The Doppler width of the spectrum ($\pm 3$ m/s) is less than that of the simultaneously measured PMSE. This echo was not seen at all in the other beams. As evidenced by the progression of the echoing height through the range gates during the next four observing intervals shown in Fig. 4, the structure moved toward the radar with a mean projected velocity of $4.6 \pm 0.5$ m/s. (To be precise, the plots are converted to height instead of range but at such a small zenith angle there is only a 4% difference.) This value is in excellent agreement with the mean Doppler shift of the scatter. The echoing region fell from about 93 to 91.5 km during the period it was observed, moving in and through more than five range gates. The line-of-sight velocity of the background medium measured in this height range and in the north beam was small and of the opposite sense from the transient scatterer. If, as usual, we interpret this Doppler as due to horizontal wind component projected along the beam, a 17 m/s northward wind is found. If the scatterer is entrained in this same wind field, a vertical fall velocity of about 9 m/s is indicated. The more easterly beam (64° azimuth) shows a line-of-sight Doppler of almost 20 m/s at 91 km suggesting a total wind speed of about 80 m/s. At such a velocity a horizontally localized scatterer will leave a given beam in little more than a minute. Since the echo lasted quite a bit longer than this it seems that the scatterer could not have been so localized.

The echo strength was about 10 db above the noise and was about 15 db weaker than the signal registered at the normal PMSE height (85 km) for this period.

## THE SCATTERING MECHANISM

As mentioned in the Introduction, recently there has been a renewed interest in meteor radar studies using large aperture radars. In the 1960s Evans (1965) reported on measurements of this type using the Millstone Hill radar but until very recently there has been little additional work in this area. Chapin and Kudeki (1994a, 1994b) reported on some long lived echoes detected with the Jicamarca radar which they interpreted as due to plasma instabilities operating along a meteor trail when it has a suitable orientation. Pellinen-Wannberg and Wannberg (1994), using the EISCAT radar, reported the properties of head echoes as well as some long duration signals which they interpreted as due to incoherent scatter from meteor trails. Zhou *et al.* (1995) and Zhou and Kelley (1997) reported on unusual head echoes detected with the Arecibo radar and which seemed to have the largest cross-section for meteors travelling down the beam. This is quite the opposite of classical meteor radar scatter in which the strongest signal comes when the meteor is orthogonal to the beam. Zhou and Kelley (1997) calculated that a plasma instability seemed necessary to explain the data and speculated that high velocity negative ions or charged dust might play a role in generating ion acoustic waves. These authors also reported on long duration (several second long) echoes which did not seem to be due to incoherent scatter, and it is not at all clear whether the long duration Arecibo and EISCAT scattering mechanisms are the same or not. In addition to radar studies, a recent report on lidar detection of the atoms in an ablation trail from a meteor has been published by Kane and Gardner (1993). Interpretations of these new radar observations are not internally consistent and a variety of processes are most likely involved. The present data set may be related to some of the observations mentioned above and we have the unique advantage of two independent and quite different observing schemes.

The meteor literature is rich with studies of long duration meteors but nearly always in the case of overdense scattering. This term refers to conditions in which the plasma frequency exceeds the radar frequency and the wave energy cannot penetrate the trail.

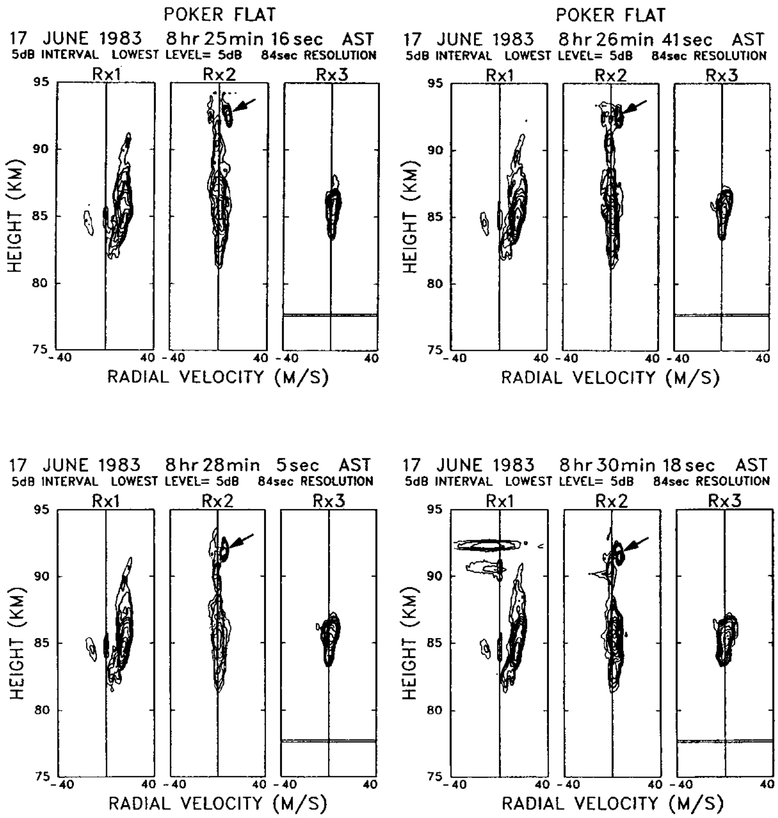


Fig. 4. Four radar sets subsequent to the one shown in Fig. 3. The set of contours shown in Fig. 3. The set of contours shown by the arrows remains present at about the same scattering strength while drifting downward from plot to plot. The signal bursts between 90–95 km in R × 1 (lower right) may be a normal meteor event.

Once the plasma density falls below the critical value the signal is lost due to constructive interference inside the smoothly (Gaussian) expanding cylinder. The decay time constant at this height and radar wavelength is about 100 ms, so more than three hundred e-folds would have occurred in the more than six minutes of observations. In fact, there was very little decay of the signal strength. A long duration overdense echo could last 6 min but the rocket data early in the event found an electron density nearly three orders of magnitude below the critical density. This model for long enduring echoes is very far from the characteristics of the present data set, although the length of time it was observed places it squarely in the category of a long enduring echo. Millman and McKinley (1948) reported on some unusual long-duration meteor echoes that accompanied head echoes and which may be related to the present results.

We know of no mechanism other than a meteor which could possibly create such a thin layer as that observed. A particle precipitation mechanism would have to be exceedingly monoenergetic, be of quite high energy, and be very localized in horizontal extent to create the structure. Wind shear mechanisms yield layers at least an order of magnitude thicker than this one, move vertically at a much slower rate, and also would have to be very localized horizontally not to be seen in all three beams. In addition, there was no null point in the wind speed as registered by the VHF radar nor is the Poker Flat Radar sensitive to incoherent scatter from such a layer. We will proceed with the notion therefore that a meteor trail is involved and see what problems arise.

First, the scattering mechanism must be clarified. The plasma density indicated by the Langmuir probe is far below that needed ($2.5 \times 10^{13}$ m$^{-3}$) to yield overdense scattering from the trail. Incoherent scatter is also impossible due to the low density, the small fraction of the beam encompassed and the low power-aperture product of the Poker Flat radar. Another possibility to investigate, of course, is that classic underdense meteor scatter was responsible for the

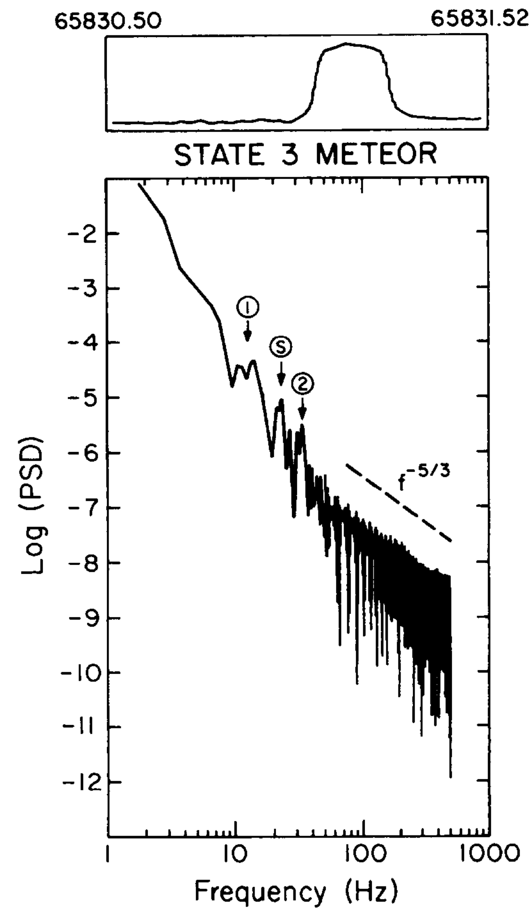


Fig. 5. The Fourier spectrum of the entire event.

event. This would require not only that the rocket pass through the trail but that it was oriented perpendicular to the radar beam which seems exceedingly unlikely. In addition, there is the problem that the trail is many wavelengths thick, a situation in which the scattering from a smooth, classically diffusing trail is reduced by an exponential term of the form exp-$(8\pi^2 r_0^2/\lambda^2\ s^2\theta)$, where $\lambda$ is the radar wavelength and $\theta$ is the angle off perpendicular. Even taking this angle to be zero yields a huge negative exponent and the scattering would be negligible. As already noted, the radar echo did not decay very fast, if at all, and certainly not with a 100-ms time constant.

This leaves turbulent, rough-trail scatter or partial reflection as the only viable processes.

A Fourier analysis of the rocket data has been performed and the results presented in Fig. 5. The lowest frequencies are suspect in this analysis for a variety of reasons. The relative peaks labeled 1 and 2 are due to the dominant structure and its harmonics. The feature labeled S is due to the spin of the rocket. At frequencies above about 40 Hz the spectrum displays a power law form. For reference a $-5/3$ law is superposed. From such a presentation we cannot be sure how much contamination is present due to the harmonics and how much is due to structure in the medium. In Fig. 6 the spectrum of just the high density portion of the probe response is presented. Here the steep edges are not present and the spin effect is much less as well since the latter is much more of an experimental problem at low plasma densities. The spectral density and power law form for frequencies above 40 Hz are essentially identical to those in Fig. 5. The fluctuation level inside the trail is elevated above the background level for all frequencies up to 300 Hz. Inspection of the raw data in Fig. 2 shows that this fine structure is indeed present in the signal at an rms level of about 1%, and that clear fluctuations are evident by eye at 3 m scale. What makes this small fluctuation level important is that it is at such a small scale size, a scale particularly suited for VHF scatter.

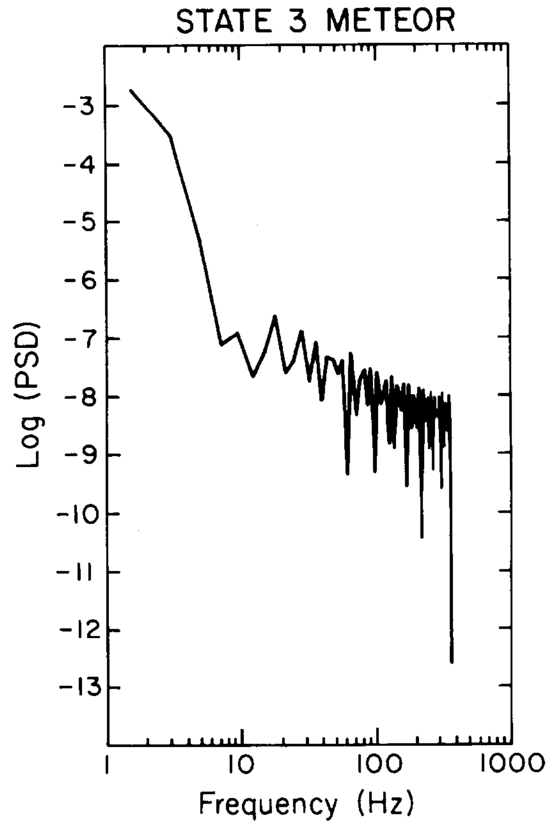


Fig. 6. The Fourier spectrum of a short data segment in the region near the peak in the layer density.

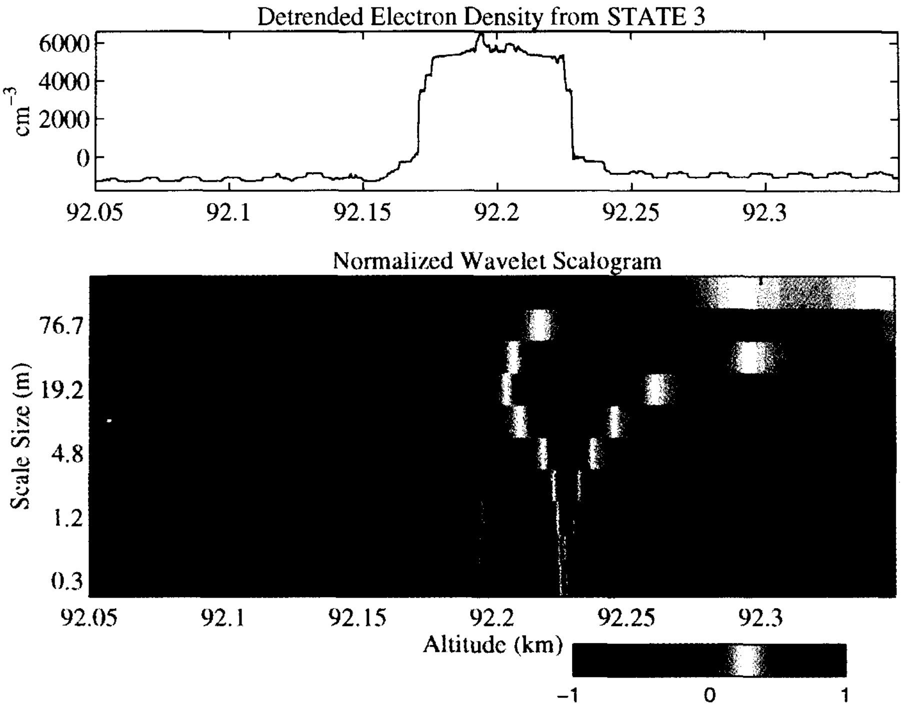


Fig. 7(a). Wavelet analysis. The upper plot is the original data set and the second panel is a color scalogram showing the wavelet coefficients.

Hagelberg and Gamage (1994) and others have developed wavelet-based analysis that allow the separation of steep coherent edges from noise-like features such as turbulence or instrument noise. We have applied such an analysis to the present data set with the results presented in Fig. 7(a) and 7(b). In Fig. 7(a) the rocket electron density data is presented in the upper panel along with a wavelet scalogram below. The latter is then used to locate the steep edges in the profile. Clearly, there are two very steep edges localized by the wavelets. We next decompose the original data into a truncated set of wavelets, which we deem to include the edge component. Our choice for this truncation is illustrated in panel (b) of Fig. 7(b) by showing the data reconstruction found by inverting the process. The wavelets do a very good job in locating and reproducing the edge component. Panel (c) is obtained by subtracting the reconstructed data from the original data, which reveals the turbulent component plus whatever instrument noise exists. The outer portions of this plot are dominated by the spin component, which only affects the data at low density. The portion of the difference data corresponding to the bar in the third panel has been Fourier analyzed with the results given on the right-hand side of the last panel. For reference, a dashed line shows a $k^{-1.5}$ spectral form. The full Fourier analysis at the left and the Fourier analysis of the reconstruction from the edge coefficients both show a much steeper power law, a typical result from the analysis of data sets dominated by a few sharp transitions. We think this analysis provides evidence that the internal part of the meteor trail was characterized by turbulent fluctuations with a classic spectral form near $k^{-5/3}$. It should be mentioned here that both the steepness of the edges and the existence of microstructure in turbulent fluctuations down to scales of 0.2 m is very surprising and requires a very small diffusion coefficient. This is discussed in more detail below.

The edge scattering cross section is very hard to estimate in this case, since we do not know what fractions of a Fresnel zone the trail encompasses. This wavelet partitioning of the spectrum into turbulent and coherent components is, we believe, the first example using mesospheric data. The technique has been applied previously in the boundary layer [Hagelberg and Gamage (1994)] and is being applied as well to other rocket data in the presence of the polar summer mesospheric echoes (Alcala, pers. comm.,

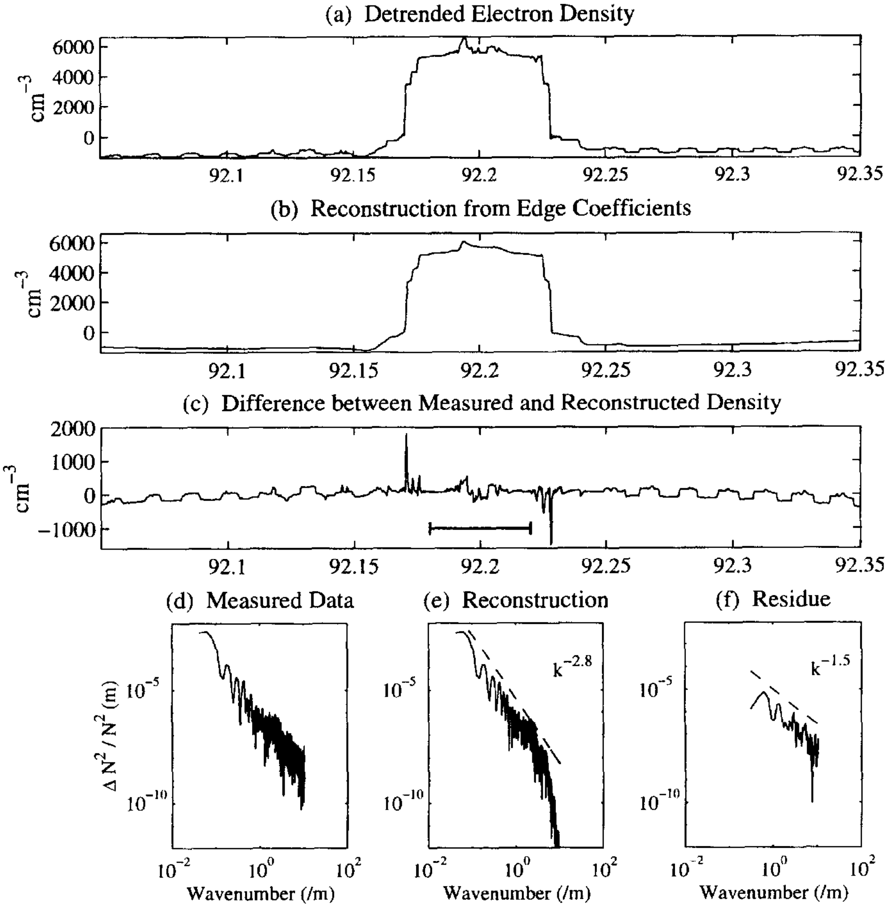


Fig. 7(b). The top panel is the same as the Fig. 7(a). Panel (b) shows the inversion of the wavelet series, which localizes the edges in the data set. The signal found by subtracting panel (b) from panel (a) is given in panel (c). The three FFT's plotted below in panels (d)–(f) correspond (left to right) to the Fourier analysis of the original data and the two partitions.

1997). Both components can contribute to the radar backscatter. Below we explore the expected scattering due to the turbulent component but it is important to realize that both can be important in the PMSE environment and perhaps as well in the dusty meteor case.

The relevant spectral density for a scattering estimate is that near the frequency corresponding to the 3-m radar backscatter wave number ($\mathbf{k}_s$), abut 170 Hz at a rocket velocity of 500 m/s. Ulwick *et al.* (1988) have already analyzed both the STATE 1 and STATE 3 rocket data and compared the results to the radar S/N with good results so we have some confidence in this approach. In Table 1 we present the measured S/N for the mesospheric layers studied in the two flights (PMSE), along with the properties of the event reported here. In each case the electron density and the fluctuation power spectral density are presented.

Table 1. Scattering properties of the PMSE and meteor trail event

| Data | Electron density $cm^{-3}$ | Spectral density $Hz^{-1}$ | S/N Measured DB |
|---|---|---|---|
| STATE 1 | 10,000 | $4\times10^{-8}$ PMSE | 38 |
| STATE 3 | 1000 | $5\times10^{-8}$ PMSE | 22 |
| STATE 3 | 40,000 | $4\times10^{-9}$ Meteor event | 18 |

These are needed since the radar cross-section per unit volume for a structured medium is given by the expression:

$$\sigma = 4\pi r_e^2 \Delta N^2(\mathbf{k}_s) m^{-1} \quad (1)$$

where $r_e$ is the classical electron radius and $\Delta N$ is the absolute electron density fluctuation strength. We assume that the meteor trail fills one of the horizontal dimensions of the radar volume but is smaller by the ratios 50/300 m and 50/1400 m in the other two dimensions. Then we can predict the measured signal-to-noise (S/N) ratio for the meteor event by multiplying the corresponding PMSE signal-to-noise ratios by these two factors, by the ratio of the power spectral densities and by the square of the electron density ratios. When we scale STATE 1 in this manner we obtain a prediction of 18 db for the meteor contrail and when we scale STATE 3 in this manner we obtain 21 db. These values are in good agreement with the observed 18-db signal.

The scattering calculation is thus consistent with a turbulence-like scatter. Rough trail scattering mechanisms have been discussed by Zhou and Kelley (1997) with regard to the Arecibo data set. They concluded that for the initial head echoes detected by Arecibo for very weak meteors (magnitude 15) turbulence induced by the meteor entry could not explain the echoes and that some sort of plasma instability was needed to get echoes at 0.35 m wavelength (430 MHz). But the turbulence model they presented may well be valid for the late time trail observations such as the one here. This possible relationship is discussed in the next section.

## THE DUSTY TRAIL HYPOTHESIS

Although the rocket data seem to clearly show that the layer was highly structured at small scales, this is not so easy to understand. Classic diffusion theory suggests that a given macro-structure, e.g. the meteor trail itself after it is formed, will expand according to the well known $t^2$ law,

$$r = r_0(1+4Dt)^2 \tag{2}$$

As noted above, by the time a meteor trail expanded to 50-m diameter with a Gaussian shape it would be invisible to a 50-MHz radar unless the electron density were very high (overdense). The electron line density suggested by the rocket data is only the order of $8\times10^{13}$ m$^{-1}$, so the initial meteor could have been overdense but almost immediately it would have become underdense. For example, according to eqn (2) starting with an initial radius of 0.3 m and using a diffusion coefficient of 4 m$^2$/s, within 0.2 s the trail would have expanded to a radius equal to the radar wavelength and become invisible to it.

Similarly, fine structure which is not driven by some structuring mechanism such as turbulence, will decay according to the decay rate formula,

$$\gamma = (k^2D) \tag{3}$$

For a 3-m wavelength and typical diffusion coefficient of 4 m$^2$/s at 93 km, eqn (3) yields a time constant for decay of 0.06 s. Since the echoes lasted for many minutes this classical decay cannot be occurring. The rocket data show that even before entering the radar beam the trail was underdense so the usual overdense enduring trail model is inappropriate.

The event was observed below the turbopause so there is the possibility of turbulent structuring. However, even a simple turbulent model has problems since the 3-m scale is well below the Kolmogorov microscale. Hocking (1985), for example, calculated the spectral cut-off for turbulent structure at 93 km to be in the range of 20 m. However, a complicating feature of the Polar Summer Mesopause region where these data were obtained deals exactly with this same issue: how is it that PMSE occurs at all if the radar wavelength is into the cut-off regime? In the latter case, and as revealed clearly by the STATE project itself and verified in later rocket flights, the electron density fluctuation spectrum exhibits a different inner scale than the neutrals, one that is extended as the square root of the Schmidt number (Kelley and Ulwick, 1988; Lübken *et al.*, 1993). Both the STATE 1 and STATE 3 PMSE spectra exhibit a cutoff in the fluctuation spectrum around 5 m with a $-5/3$ power law at larger scales and a $-5$ or steeper spectrum at smaller scales. The event spectrum reported here displays as $-5/3$ law as well but shows no break in the spectrum even out to 1 m where the noise level is reached. The implication is that the Schmidt number is even larger in the meteor trail than in the aerosol rich summer polar mesopause region. In the limit of high aerosol charging the ambipolar diffusion coefficient approaches the very low aerosol diffusion rate [Cho *et al.* (1992)] and the electrons and aerosols are bound together.

Rosinski and Snow (1961) (hereafter referred to as R&S) and Hunten *et al.* (1980) have explored the rate at which meteor trails form dust in the mesosphere and find that it is quite rapid. Unfortunately there seems to be a consistent mislabeling in the R&S calculation (see their Table 2) such that their 48-g meteor actually corresponds to a 6.0-g meteor, etc. The accumulation of matter in their Case V thus is appropriate for a 6.0-g meteor that is of visual magnitude of about $-2$ [Hughes (1978)]. They calculate that in 70 s the meteor trail material will consist of $8\pm4$ nm diameter particles with a density of $2.7\times10^{13}$ cm$^{-3}$. We argue below that the particles in our case were probably larger than this but even for this case the effect on scattering would be substantial. For example, Cho *et al.* (1992) showed that if half of the charge in a region was tied up on aerosol particles the plasma diffusion coefficient would be drastically reduced. Particles of the size quoted above can accommodate one electron on average but the predicted densities of particulates is higher than the background electron density, so indeed most of the charge would be on the aerosols. In the limit of high percentage charging, the plasma will diffuse at the rate of the aerosols, which is quite slow.

For classic meteor observations in this late time period the conventional wisdom is that eddy diffusion takes over and the trails become distorted. Since the perpendicular condition is crucial for such scatter, this drastically reduced the scattering cross-section. But for the rough trail high Schmidt number scattering this response to atmospheric turbulence only serves to maintain the scattering. Following the approach described by Kelley and Ulwick (1988) and Cho *et al.* (1992), we can find a lower limit to the Schmidt number ($S_c$) using the fact that the $-5/3$ spectrum indicated in Fig. 7 extends at least to 0.3 m. Since this value is 100 times the cut-off predicted for the background neutral turbulence, $S_c$ must be more than $10^4$. Using the Cho *et al.* (1992) expression for the aerosol diffusion coefficient and typical mesospheric viscosity values ($\sim 1$ m$^2$/s), we find aerosol radii the order of 10 nm or larger are required.

We can get a better estimate of the size using the fall velocity. For mesospheric heights a terminal velocity of 4 m/s corresponds to a radius of 50 nm for meteoric material. This is determined using the hard sphere interaction model, which is appropriate for particle radii smaller than the near free path. A detailed discussion of this regime is found in Cho *et al.* (1993). This is a surprisingly large radius but is not inconsistent with the other parameters calculated here and we find the agreement of the Doppler shift and time rate of change of the scattering center to be compelling evidence for falling matter and for the conclusion that the material is in this size range.

The long observation time also argues for very large aerosols. Using a value of 50-nm radius, in the ten-minute time period following the rocket observations, the trail would have expanded classically to only 58 m, thereby maintaining a high signal to noise ratio for radar scatter. If the particles were 5 nm in radius, the diffusion would lead to a trail size with nearly a 7-km radius.

Unfortunately, the 6.0-g calculation by R&S just barely entered the large aerosol regime. The latter was in the slow diffusion range which allows a rapid growth of the particle radius. The median diameter had grown to 8-nm radius with a density of $3 \times 10^{13}$ m$^{-3}$ within 70 s. Extrapolation their curve yields at 21-nm diameter after about 200 s.

We can estimate the mass of our meteor as follows. Using the radius estimate from the fall speed, the average charge is about 3 e$^{-1}$ for polar mesospheric conditions [Jensen and Thomas, (1991)]. Cho finds that for 50-nm radii that the Schmidt number easily can exceed 1000 so the extension of the inner scale is explained. To exceed the nominal 50% charged tie-up on aerosols given the observed electron density of $4 \times 10^{10}$ m$^{-3}$ inside the trail, then implies a number density of aerosols equal to $4.4 \times 10^9$ m$^{-3}$. The total mass then is calculable using the nominal trail parameters of Hunten *et al.* (1980) most notably the 10-km trail length and density of 2 g cm$^{-3}$, which for the 42-m diameter trail yields a mass of about 100 gm. This result is certainly consistent with R&S, who comment that 30 nm and even larger particles should form in the wakes of very bright meteors. Such a meteor would have a visual magnitude of about $-5$.

## SUMMARY

We report here on a fortuitous simultaneous radar and rocket detection of what seems to be a meteor contrail produced over the Poker Flat Rocket Range. The two data sets are mutually consistent and taken together suggest some very interesting properties for the trails of large meteors.

Most notable is the evidence that the ablated material has coagulated into particles the order of 50 nm in radius. This estimate is based primarily on the fall speed deduced from both the Doppler shift of the VHF radar signal and the time rate of change of the target as it fell through the beam. In addition the very existence of the radar target, the extremely sharp edges of the trail, and the existence of electron density structures more than an order of magnitude smaller than the Kolmogorov microscale all require large charged aerosols and a very high Schmidt number. Following the work of Rosinski and Snow (1961) and Hunten *et al.* (1980) we conclude that the incident meteor was the order of 100 g and would have had a visual magnitude of about $-5$. Such a meteor is not common and it is remarkable indeed to have had the opportunity to study its evolution with radar and particularly with the rocket instrumentation.

These data may represent one of the first observations of meteor dust or smoke particles. The only other experimental data, as far as we can ascertain, is that of Schulte and Arnold (1992) who reported detection of smoke particles. Many reports of self-luminous long-enduring meteor contrails exist in the literature, although their discussion has centered about atomic and molecular processes (Trowbridge, 1907; Millman, 1950). One of us (M. C. Kelley) observed a meteor contrail for five minutes on 17 November 1996 during the Leonid shower over Puerto Rico. In this period the trail was clearly distorted by gravity wave activity.

Since properties of this trail are comparable to those of noctilucent clouds it seems they should be detectable optically or with lidar since the clouds themselves are observable. At twilight, particularly near dawn when the meteor flux is highest, a radar based meteor head echo system could be used to detect large meteors [Jones and Webster (1991)] and optical systems trained on the area to detect the aerosols in scattered sunlight. Alternatively, all-sky CCD imagers could be used to detect bright meteors and metallic atom resonant lidars used to study the initial atomic species and the subsequent aerosol development. The background dust may also be measurable with an incoherent scatter radar using the technique described in the companion paper (Cho *et al.*, this issue). We suggest that the anticipated brightening of the Leonid meteor showers be used as a catalyst for further studies of meteor contrails through the remainder of this century. In particular, the eddy diffusivity of molecular and dusty species could be determined.

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