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Long duration meteor echoes characterized by Doppler spectrum bifurcation

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[1] We report on a new category of long lasting meteor echoes observed occasionally with HF and VHF radars. These meteoric returns, which have lifetimes from many seconds to a few minutes, are characterized by a distinct Doppler spectral signature showing a pronounced Doppler bifurcation which includes narrow bands of discrete Doppler velocities, often of opposite polarity. The large signal to noise ratios and the narrowness of the spectra imply that coherent or Bragg scattering is not of relevance here, therefore these echoes do not associate with the long living meteor-induced backscatter (MIB) from the lower *E* region. A reasonable interpretation needs to explain both the Doppler spectrum bifurcation and the long echo duration. As such, we propose the idea of a structured vertical wind shear in the lower *E* region which traps different fragments of a meteor trail plasma in the same way that sporadic *E* layers form. These trail parts inside the shear-related wind profile may act as relatively long-lasting meteoric reflectors moving with different Doppler velocities, also of opposite polarity.

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1. Introduction

[2] As micrometeoroids enter the earth's atmosphere they form ionized trails which are orders of magnitude more dense than the surrounding ionospheric plasma, and thus can cause specular reflections of radio waves that impinge upon them perpendicularly. These trails form mostly at altitudes between 80 and 110 km, where the plasma is attached to the neutrals by collisions, thus they act during their lifetime as tracers of atmospheric winds. The great majority of meteor radar echoes are classified as "underdense", meaning that the radio waves are only partially reflected from the ionized trails. Underdense echoes last for a fraction of a second. On the other hand, many meteor echoes can be "overdense", which implies a total reflection from the trail because its plasma frequency exceeds the radio wave frequency. Overdense echoes have lifetimes ranging from fractions of a second up to a few seconds. For a review on the radio science and theory of meteoric echoes see *McKinley* [1961].

[3] In addition to the short-lasting and well understood underdense and overdense meteors, there are reports on long lasting meteor echoes with lifetimes ranging from many seconds to several minutes. For example, *Kelley et al.* [1998] reported on a VHF meteor lasting over 10 minutes. Such long enduring meteor events are exceptional and constitute a mystery. A more common category of meteor echoes with lifetimes ranging from a few seconds to a few minutes, has been identified the last years with VHF coherent backscatter radars at middle, low and equatorial magnetic latitudes [e.g., *Haldoupis and Schlegel*, 1993; *Chapin and Kudeki*, 1994; *Reddi and Nair*, 1998; *Zhou et al.*, 2001]. These are magnetic aspect sensitive echoes having broad Doppler spectra similar to those obtained when the *E* region plasma becomes unstable to the gradient drift and the modified two stream instabilities. These are non-specular echoes that have been attributed to meteor-induced backscatter (MIB) from the lower *E* region, caused by Bragg scattering from field-aligned, meter-scale electrostatic plasma waves. The MIB hypothesis has been tested by *Oppenheim et al.* [2000] who simulated meteor induced instabilities in the equatorial electrojet, whereas more recently *Oppenheim et al.* [2003] developed a linear theory of meteor trail plasma instabilities.

[4] Here we report on a category of long lasting meteor echoes seen at 15 MHz and 50 MHz, which have a distinct Doppler spectrum signature never reported before. Although these do not classify as MIB, one cannot exclude a relation to some of the long duration meteor echoes reported occasionally in the literature for which, however, the Doppler spectrum details were not available.

2. HF Radar Observations

[5] A low power HF radar was deployed in Puerto Rico in March 1998 for *E* region backscatter studies. The radar system provided a 3 km range resolution and good resolution Doppler spectra. A Yagi antenna was used for transmission at 14.5 MHz with a 2 kW peak power. The receiving antenna was an east-west linear array comprised of 16 active magnetic loops which provided a northward pointing beam with an 8° beamwidth at 3 dB. In this setup, northward aspect sensitive backscatter from 110 km altitude would appear at a range of about 130 km. The objective was to observe sporadic *E* layer plasma instabilities but, unfortunately, sporadic *E* backscatter was not seen during a 10 day experiment and the only signals detected were meteor echoes. Among the numerous short lived meteor echoes recorded, there were sixteen long lasting ones with lifetimes ranging from about 20 to 120 s.

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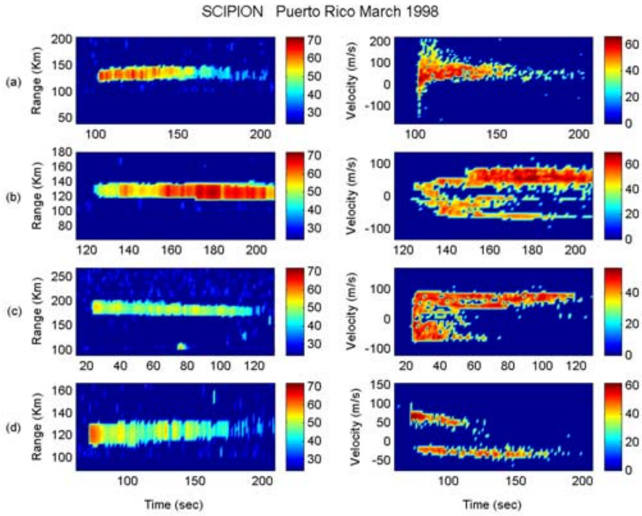

Figure 1. (a) A meteor-induced backscatter echo followed by (b–d) three typical examples of meteor echoes characterized by a bifurcated Doppler spectrum, all observed with a 15 MHz radar. These echoes have long lifetimes ranging from many seconds to a few minutes.

[6] Figure 1 shows four examples of long-lasting HF meteor echoes. Shown for every example are the range time intensity plot (left panel) and the Doppler velocity spectrogram at a range inside the meteor echo (right panel). Figure 1a shows a long lasting echo similar to the VHF MIB observations reported by *Haldoupis and Schlegel* [1993] and *Chapin and Kudeki* [1994]. This meteor echo occurred on day 86 at 0944 UT (0544 LT) and lasted about 100 seconds. The Doppler spectrogram is at the range of 129 km and shows a very broad spectrum at the echo onset (spectral width >200 m/s) and then both the width and power decrease gradually to zero. This is the only case of MIB observed during the 10 day radar campaign. The rest of the long lasting meteor echoes are different as shown by the rest of the cases in Figure 1.

[7] Figure 1b is a typical example of a long lasting meteor characterized by a bifurcated Doppler spectrum as observed on day 90 at 1204 UT (0804 LT). The echo lasted at least 100 seconds but since the file was closed before its end, its duration must have been longer. The Doppler spectrogram, which corresponds to the 126 km range, shows several interesting features: (i) there is a well defined onset but not as sharp as that in Figure 1a, (ii) about 10 seconds after onset, the Doppler spectrum exhibits a bifurcation with narrow band striations forming at both positive and negative Doppler shifts, (iii) the structures that appear during the echo duration stay at relatively constant Doppler velocity, (iv) the spectral width of these Doppler spectral bands is very narrow (a few tens of m/s), in sharp contrast with the broad MIB spectra shown in Figure 1a. As seen, 40 s after onset there are at least 4 discrete structures with different Doppler velocities between about −60 m/s and +80 m/s.

[8] Another similar echo, observed on day 85 at 1024 UT (0624 LT) and at 185 km range, is shown in Figure 1c. The Doppler spectrogram shows a fast bifurcation with two narrow Doppler bands forming at positive and negative velocities. Again, there are at least four Doppler striations at rather constant velocities between −60 m/s and +80 m/s. Finally, the example in Figure 1d illustrates an echo recorded on day 86 at 0832 UT (0432 LT) at the near range of 120 km. In this case the Doppler spectrogram exhibits only two Doppler bands at positive (~50 m/s) and negative (~−30 m/s) velocities. The positive spectral component lasted about 60 seconds whereas the negative one lived for about two times as much.

3. VHF Radar Observations

[9] The VHF meteor observations to be shown here were made with SESCAT (Sporadic *E* Scatter Experiment), a continuous wave Doppler radar operating at 50.52 MHz that was designed for midlatitude *E* region coherent backscatter studies [*Haldoupis and Schlegel*, 1993]. SESCAT is a bistatic system located in Crete, beaming northward towards a region perpendicular to the earth's magnetic field at *E* region altitudes and having the advantage of providing excellent time and Doppler spectrum resolution, but only approximate range information. During routine operation, the system records in real time a Doppler spectrum every 0.8192 s with a Doppler velocity resolution of 3.80 m/s.

[10] Besides the numerous short lived underdense meteor echoes, SESCAT detects also longer duration meteor events with lifetimes ranging from several seconds to a few minutes. The overwhelming majority of these are classified as being due to meteor-induced backscatter (MIB), as shown by *Haldoupis and Schlegel* [1993]. MIB echoes have an abrupt onset, accompanied by large Doppler spectrum broadening and occasionally large Doppler velocities, usually with only one polarity. The half power spectrum widths near onset are large ranging from about 150 to 350 m/s. As mentioned, the Doppler spectrum is reminiscent of backscatter from field-aligned plasma irregularities during unstable *E* region conditions.

[11] A very small subset of the long lasting SESCAT meteors do not classify as MIB, having a distinct Doppler spectrum signature similar to the HF observations presented previously. Figure 2 introduces the VHF Doppler spectra of the long lasting meteor echo under consideration. This event, which has a well defined but not sharp onset, lasted for about 30 seconds (tick marks are 6 s apart). The spectrogram is strongly bifurcated and striated, that is, the

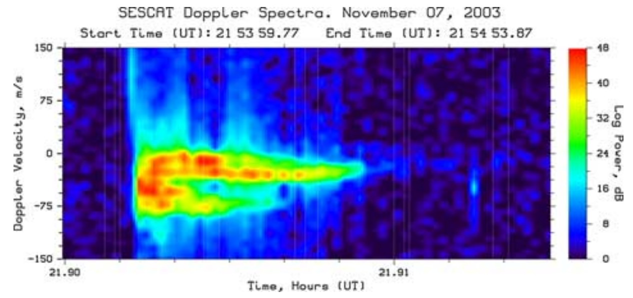

Figure 2. A Very High Frequency (50 MHz) Doppler spectrogram of an unusual meteor echo whose Doppler spectrum is bifurcated and composed of distinct Doppler bands of fast and slow line-of-sight velocities. The echo lasted for about 30 seconds.

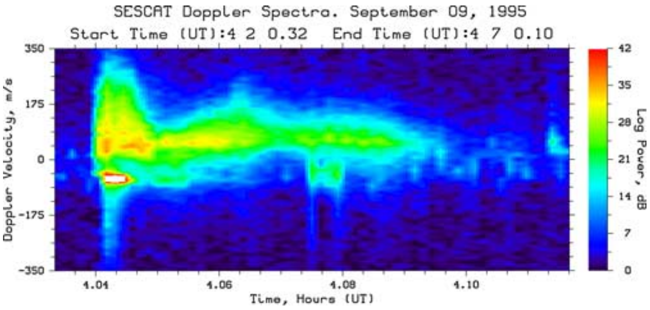

Figure 3. Another example showing a meteor echo whose spectrum is dominated by two narrow Doppler bands at about ±50 m/s. It lasted for about 3.5 minutes.

spectra are well structured having narrow Doppler velocity bands corresponding to discrete, fast and slow, motions in the viewing volume. The Doppler striations, or discrete bands, are extremely narrow and correspond to strong signals with signal to noise ratios ranging between about 20 to 50 dB. In addition, they appear to be amplitude modulated with periods of a few seconds. These properties are in sharp contrast with the broad and unstructured MIB Doppler spectra which are indicative of *E* region short scale plasma turbulence due to plasma instabilities. Finally, the similarity between the VHF spectrum in Figure 2 and the HF spectrum in Figure 1b is striking.

[12] Figure 3 presents another example of a similar event which lasted for about 3.5 minutes. Again the spectrogram is structured and dominated by two Doppler bands which appear to be symmetric about zero Doppler shift at ±50 m/s. The spectrogram is asymmetric with the positively shifted Doppler band being more continuous and lasting longer. The strong narrow peak at −50 m/s, which reached 49 dB above noise and lasted for about 20 s, can only be due to a specular reflection from a part of the trail that moves with the wind away from the radar. The VHF spectral signature in Figure 3 resembles well the HF spectrograms shown in Figures 1c and 1d, although some non-specular returns of MIB may also be present during the first minute or so of the echo.

4. Discussion and Speculation

[13] The spectral evidence is suggestive of strong specular meteoric reflections, either underdense and/or overdense, most likely coming from parts of a distorted trail following the neutral wind motions. This reminds us of suggestions made in the past [e.g., see *McKinley*, 1961], that vertical shears in the horizontal MLT winds distort the ionization trail so that portions of it become perpendicular to the incoming radar beam, acting therefore as specular reflectors. These trail fragments are expected to move at different velocities, also of opposite polarity, therefore this scenario could account at least for some of the characteristics seen in the Doppler spectrograms at both HF and VHF. As for the relatively large Doppler velocities observed in the present study which are up to about ±100 m/s, these are easily attainable during times of vertical wind shears of large horizontal winds, which, as shown by *Larsen* [2002], are frequently present in the MLT region.

[14] But why these fragmented meteor trails last so long? There is no easy answer to this question, as long duration meteors have remained a mystery for many years. Recently, and in an effort to explain an exceptional VHF meteor that lasted 10 minutes, *Kelley* [2004] relied on radar and rocket data to propose that underdense charged dust particles left behind a large ablating meteor undergo gravitational sedimentation which in turn reduces the electron diffusivity and thus it sustains the meteor trail for long time. Although the observations of *Kelley* [2004] showed a featureless single peak Doppler spectrum near zero Doppler shift, his idea of slowly diffusing meteoric dust plasma cannot be excluded as applying also to the present observations.

[15] Next, we speculate briefly on a different process which could account for both the bifurcated Doppler spectra and the long duration of the meteor echoes under consideration. This involves a strongly structured wind shear which can trap parts of the meteoric trail plasma in a way similar to the process responsible for the formation of sporadic *E* layers. According to the windshear theory (e.g., see review by *Mathews* [1998]), vertical shears in the horizontal wind can cause, by the combined action of ion-neutral collisional coupling and geomagnetic Lorentz forcing, parts of the meteoric trail ion plasma to move vertically, thus plasma structures may form that live relatively longer because diffusion is now counteracted by wind shear convergence. Next these structures may act as meteoric reflectors moving with different velocities depending on their positioning relative to the shear wind profile, therefore they can easily produce reflected signals having bifurcated/structured Doppler spectra. This scenario could also involve Kelvin-Helmholtz instability effects. These, as shown in the simulations of *Bernhardt* [2002], can cause the meteor plasma to be structured in altitude which then can lead to Doppler spectrum bifurcations. Note that the wind shear mechanism applies for altitudes higher than about 95 km and that at the lower *E* region heights it requires vertical shears in the zonal wind with a westward wind above and an eastward wind below. Finally we need to mention that the proposed scenario of sheared flows is further supported by our HF data as the Doppler spectrograms of consecutive ranges show indeed systematic changes.

[16] Although the proposed wind shear mechanism is speculative, it certainly deserves further study. On the other hand, it is interesting to note that there is already some experimental evidence in support of this option, provided by *Maruyama et al.* [2003], who analyzed rapid-run ionosonde data during the 2001 November 17–19 Leonid meteor shower. They found that certain meteors can lead to a spontaneous sporadic *E* like echoes that last for many minutes and characterized by a decaying critical (top) frequency. These ionosonde signals were attributed to specular reflections from meteor-induced sporadic *E* patches. We believe this topic deserves more attention.

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