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Day to night variation in meteor trail measurements: Evidence for a new theory of plasma trail evolution

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[1] A recent theory of meteor trail plasma diffusion made the prediction that meteors will generate more and longer lasting non-specular echoes at night than during the day. This letter presents the first evidence of a dramatic day to night difference in non-specular meteor trail occurrence rates and their duration. These observations were made by the 50MHz radar at the Jicamarca Radio Observatory (JRO) in Peru. In one 20 minute period starting 95 minutes before sunrise, this radar detected 1288 head echoes and 341 trails while a similar time after dawn, it measured 1240 head echoes but only 50 trails. Also, the duration of the nighttime trails greatly exceeded the daytime ones. This pattern was confirmed by a second experiment in July 2007. This data provides strong evidence that it is necessary to account for the effect of the ionospheric plasma density to explain meteor diffusion. **Citation:** Oppenheim, M. M., G. Sugar, E. Bass, Y. S. Dimant, and J. Chau (2008), Day to night variation in meteor trail measurements: Evidence for a new theory of plasma trail evolution, *Geophys. Res. Lett.*, *35*, L03102, doi:10.1029/2007GL032347.

1. Introduction

[2] Tens of millions of detectable meteors strike the Earth's upper atmosphere each second, creating plasma trails which persist for minutes before dissipating into the background ionosphere [*Ceplecha et al.*, 1998]. In the process of diffusing across the Earth's geomagnetic field ($\mathbf{B}_0$), large electric fields develop because of the complex interplay between highly mobile but magnetized electrons and the heavier but collisionally demagnetized ions. As is typical in plasmas, these fields point mostly perpendicular to $\mathbf{B}_0$ and change slowly along $\mathbf{B}_0$. Three recent papers [*Dimant and Oppenheim*, 2006a, 2006b; *Oppenheim and Dimant*, 2006] described the underlying physics of these fields, the resulting diffusive processes, and simulations to validate it. In this paper, we present compelling observational evidence that two predictions of this new model are valid: (1) that non-specular meteor trails are far more common during the night than day and (2) the daytime trails last for far less time than the night-time ones.

2. Background

2.1. Observational Background

[3] Non-specular meteor trails were first reported by *McKinley and Millman* [1949] and were first described as field-aligned irregularities by *Heritage et al.* [1962] and, more thoroughly, by *Chapin and Kudeki* [1994]. *Oppenheim et al.* [2003a, 2003b] showed how these irregularities arise from instabilities driven by the plasma gradient and ambipolar electric fields generated by the meteor. While an external E-region electric field or, equivalently, neutral winds can strengthen these instabilities, they are not essential. These instabilities create field-aligned irregularities which allow radars to observe them as non-specular echoes.

[4] Non-specular trails have now been observed by most high-power large-aperture (HPLA) VHF radars capable of pointing nearly perpendicular to the geomagnetic field, $\mathbf{B}_0$ [*Zhou et al.*, 2001; S. Close et al., The dependence of radar signal strength on frequency and aspect angle of non-specular meteor trails, submitted to *Journal of Geophysical Research.*, 2007]. When using a short pulse, HPLA radars receive signals with range-time signals similar to Figure 1 (left). The first and most common indication that a meteor has passed through a radar's beam is the isolated diagonal line with the high SNR called the head echo. The strong range and time extended signal to the right of the head echo is the non-specular trail.

[5] When the trail echo exists it almost always follows the head echo after a gap of greatly reduced signal strength. *Dyrud et al.* [2002] attributed this gap to the time necessary for plasma instabilities to generate sufficiently large amplitude turbulence which enables trail measurement. In a sample of 205 meteors from the current data set, a clear and continuous gap appears in 84% of all the head-trail pairs. In 8.3% of this sample we see an odd narrow trail spanning less than a kilometer emerging from some part of the head echo, often without a gap. In another 6.8% of the trails the gap does not exist or does not extend over the entire length of the trail. Only the JRO has collected data sets with thousands of trail observations. This large data set allows extensive analysis of meteor trail patterns as described in this letter.

2.2. Meteor Fields and Diffusion

[6] All existing models of meteor produced fields and diffusion have some fundamental simplifications, limiting their applicability to realistic meteor trails [*Kaiser et al.*, 1969; *Pickering*, 1973; *Lyatskaya and Klimov*, 1988; *Dyrud et al.*, 2001]. A notable study by *Jones* [1991] developed a 2D solution of meteor trail diffusion, assuming the background plasma had no effect. *Dimant and Oppenheim* [2006a, 2006b] show that the background plasma plays an essential role in meteor diffusion unless the peak meteor density exceeds the background density by more than approximately 3 orders of magnitude. These papers describe simulations and theory of diffusion which includes the

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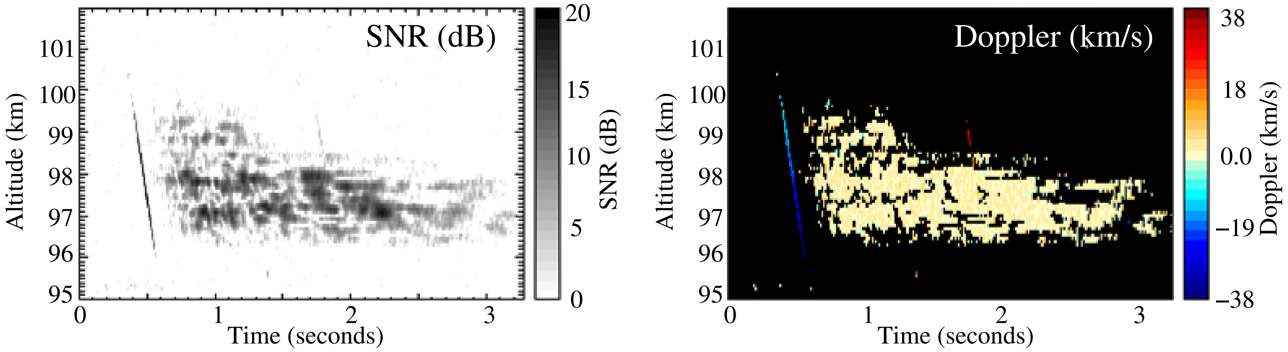

Figure 1. Processed data from the Jicamarca Radio Observatory 50 MHz large array on July, 12, 2005 at 3:43 (LT). A head and non-specular trail combination appears between 96 and 101 km altitude. A second head echo can be seen at between 1.5 s and 2.0 s and 98.5 and 99.5 km with no obvious trail following it. The SNR is the signal to noise ratio in dB from all three channels. The Doppler image shows an average of the phase shift from all three channels. It measures the velocity only within a 7 km/s range before aliasing the information. However, one can obtain unaliased (but lower accuracy) velocities from the range-time information of the head-echoes. All images have had a threshold applied to them such that the signal to noise ratio (SNR) must exceed the noise by 6 dB or no data is displayed.

effects of this background. One prediction was that trail diffusion would occur at two distinctly different rates. Initially, when the trail density is high, the cross-field diffusion rate is small. Later, when the meteor density falls to only a few orders of magnitude above the background density, currents flowing in the background plasma along $\mathbf{B}_0$ become sufficiently large to cause the meteor to diffuse as if it were unmagnetized. When this happens, its ambipolar field weakens which means that the driver for instabilities diminishes. During daytime the background plasma density exceeds the nighttime density by as much as a factor of 100. Therefore, we expect the period of strong ambipolar fields and, hence, trails, to be far shorter during the day. Further, the presence of a gap between the head and trail indicates that it generally takes some time for instabilities and turbulence to develop a sufficient amplitude to allow radar detection. During the day, the instability driver often will not persist long enough to allow this to happen.

3. Observational Technique

[7] Data for this experiment was collected by the primary antenna array at the Jicamarca Radio Observatory located near the geomagnetic equator (11.95 S, 76.87 W, 1° dip angle) in 2 sessions. Details about meteor observations with this enormously sensitive HPLA radar is given by *Chau and Woodman* [2004]. These experiments were unusual in that we used only a short uncoded pulse of 1 μs and an interpulse period spanning 60 km. This approach avoids mixing of the head and trail signals which occurs when using long coded pulses. We transmitted with the entire array and received the return signal with 3 quarter sections of the array enabling us to use interferometry to find a meteor's position within the beam.

[8] The primary difference between the '05 and '07 experiments was the pointing direction of the antenna array. In '05, we pointed the array 1.9° degrees off the zenith in order to align one of the nulls in the beam pattern with the direction perpendicular to $\mathbf{B}_0$. This reduces the sensitivity to strongly field-aligned irregularities such as type 1 and 2 radar echoes. This alignment does not completely eliminate these echoes because it only reduces sensitivity to electrojet signals by ~30 dB. We still expected to observe meteor trail echoes because spatially localized irregularities should produce signals over a broader range of aspect angles than the highly aspect-aligned electrojet waves (the aspect angle is the angle between perpendicular to $\mathbf{B}_0$ and the radar pointing direction). In '07, we performed the roughly same experiment with the array pointing to maximize sensitivity to field-aligned instabilities. These experiments also received signals from different altitude ranges: the '05 experiment spanned 90 to 119 km while the '07 covered 80–130 km.

[9] Figure 1 shows a typical head-trail pair from the early nighttime of the '05 data. One can see a second head penetrates the trail at $t = 2$ s. We can tell that this trail is not an echo of the primary trail because its Doppler information is distinct from those of the previous head. This data set also contains interferometric information which allows us to determine that these two head echoes do not come from the same location within the beam. We would count this second meteor as a head without a trail even though an indiscernible trail may exist within the earlier and stronger trail.

[10] To find heads we developed software that allows us to rapidly scan through the SNR at moderate resolution. If we saw a coherent line of echoes, we would zoom in and identify the beginning and end of the head. The smallest head echo identified spanned 7 pixels while the average head echo spanned 89 pixels. We also used the high Doppler shift and cross-channel phase correlations to identify heads.

[11] To identify a trail echo, we examine the SNR and phase correlations. To determine the length, we would place a line in the gap between the head and trail. We would then estimate the end point of the trail when it becomes indistinguishable from the local background noise. This proved difficult when one trail ran into another on or into electrojet turbulence. The duration of the trail is from the beginning

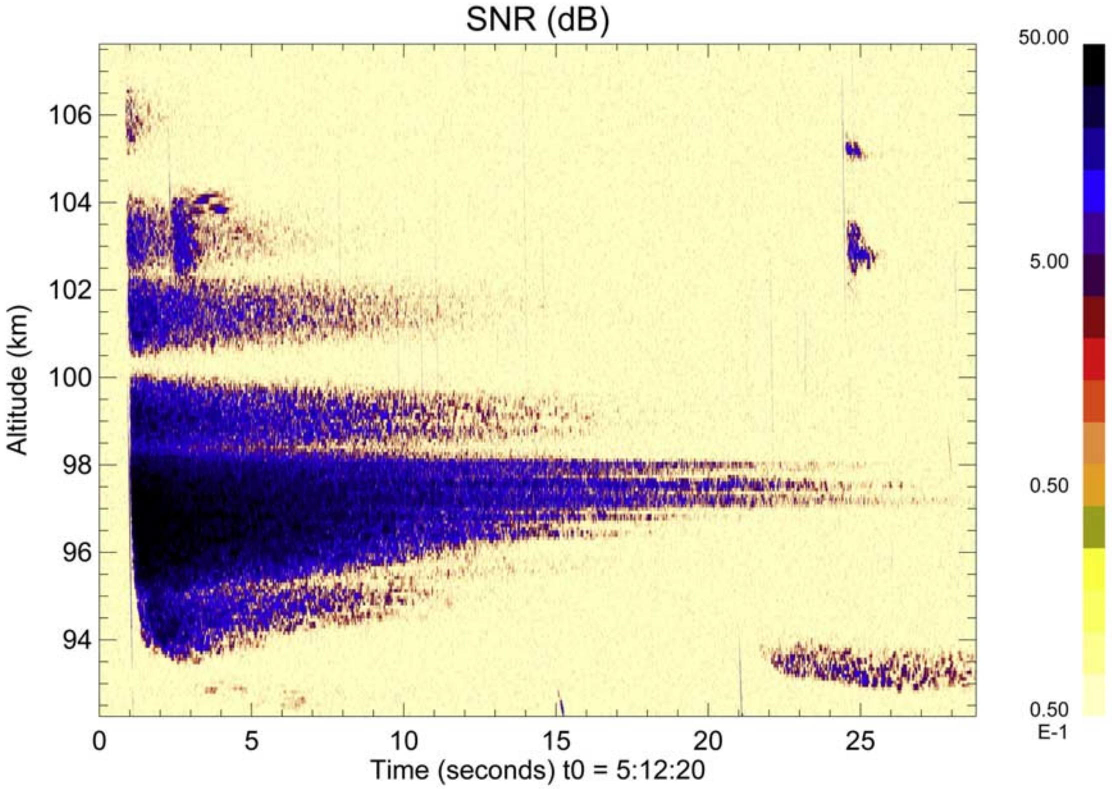

Figure 2. Section of data containing a long trail from ’05 data set. The head echo of the long trail was judged to extend from 103.5 km to 90.82 km while its trail echo extended for 25.43 seconds. Three other head/trail pairs were also found in this image and 19 additional heads without trails were found, though they only can be found at higher resolution.

time of the line in the gap until the end of the trail. One difficulty arose when heads and trails formed within or near previously generated long trails. Figure 2 shows an example of such a trail. To determine whether a head, embedded in a previously formed trail, had its own trail or we were just seeing a continuation of the previous trail, we would rely on a combination of signal strength and phase correlation. Nevertheless, this adds a certain bias to both the number of trails and the duration of the trails.

[12] Another problem arose when we attempted to extract head/trail data contaminated by electrojet signals as happened for the entire nighttime period in ’07. Figure 3 shows such a time. We only attempted to do this for weak electrojet contamination, because times of strong electrojet signal made extracting heads and trails nearly impossible. The count rate in this contaminated data dropped by over a factor of two per minute. Nevertheless, the ratio between heads and trails remained similar as discussed below.

4. Results

[13] The first experiment was conducted July 12, 2005 from 03:42 (local time) until 08:50. During most of the night time (until the 6:23 sunrise) there were only a few periods where electrojet signals interfered with meteor collection, while all but 20 minutes of the day time had some interference. We manually examined that quiet daytime data (from 8:01 to 8:21) to estimate the numbers of heads and trails. In that period we had 1240 heads and 50 trails. This data started 95 minutes after sunrise, so we also examined 20 minutes of data from 85 minutes before sunrise (from 4:58 to 5:18am). In this period we counted 1288 head echoes and 341 trails. This shows a dramatic

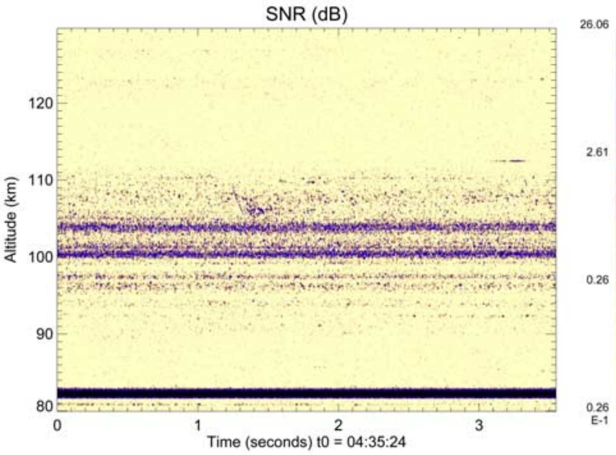

Figure 3. Head and trail data from the nighttime ’07 data set. The interfering electrojet contamination makes it difficult to observe weak heads and trails. For this data segment, we only detected the one head/trail combination starting after 1.2 s. The interference probably causes us to record a reduced trail length.

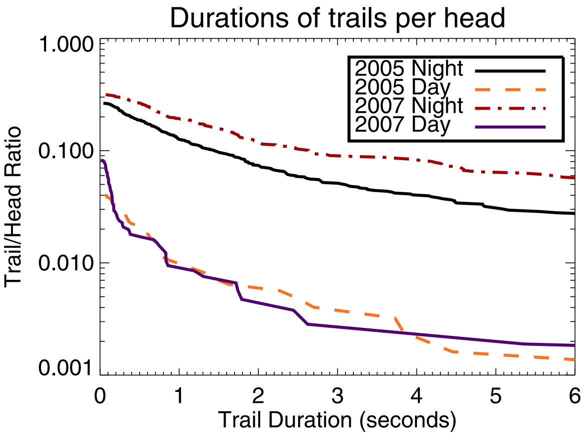

Figure 4. Fraction of head echoes having a trail persisting for a given time from four data sets. The "trail/head ratio" is the cumulative number of trails that last for at least the time indicated. Note that at night there were 35 trails persisting longer than 6 s in 2005 and 33 in 2007 but none during the day times.

increase at night of almost 6.6 times as many trail echoes per head echo.

[14] Not only do fewer trails form during the day than at night, those that form last for a far shorter period. In the two '05 quiet periods, the average nighttime trails persist for an average of 2.46 s with a median duration of 0.96 s. The daytime trails persist for an average of 1.05 s with a median of 0.52. Figure 4 shows the relative duration of trails in the day and night for both our 2005 and 2007 data sets. The higher fraction of trails seen in 2007 at night results from the favorable pointing direction of the antenna at this time. The steeper slope of the daytime lines, particularly for trails shorter than 1 s, shows that a relatively larger fraction of daytime trails decay more quickly than the nighttime trails.

[15] From this figure, one might argue that the 2007 nighttime data shows a change in slope at 2.5 s, indicating that there is a change in the nature of longer lasting non-specular trails. However, the 2005 data does not show this; instead the slope appears to change quite smoothly. This analysis does not show a particular duration at which a sharp change in the behavior of meteors occurs.

[16] The July 17, 2007 data showed similar results. In 30 minutes of daytime data, from 7:01 to 7:31, we observed 1057 heads and 87 trails. This ~90% higher rate in the number of trails per head probably reflects the change in pointing direction of the radar. In 30 minutes of nighttime data, between 4:01 to 4:36, we counted 401 heads and 185 trails. The low count rate results from the reduced sensitivity because the heads and trails signals lay within a weak electrojet background. This interference effectively makes low signal strength heads and trails invisible. Figure 3 shows an example of a head and trail within a background electrojet typical of this nighttime sample. The ratio of the number of trails to heads drops by roughly a factor of 6 from night to day. As in the 2005 data set, the daytime trails typically persist for shorter periods than at night. Figure 4 shows the same pattern as did the 2005 data. Unfortunately, these observations are not equidistant from dawn. In both day and night, the '07 data set shows a ~50% increase in the number of trails formed per head when compared to the '05 data. This probably results from the different pointing direction of the array.

5. Discussion and Conclusions

[17] During the day there are far fewer trails and those that appear last a far shorter time. The strongest bias in the '05 data results from heads and trails running into previous extended trails, preventing us from counting them. From this we conclude that the difference in day/night trail formation probably exceeds the factor of 6–7 we found. The '07 data had the added complexity that the night-time data had sustained electrojet interference, making us only able to measure stronger heads and trails. Nevertheless, when we normalize for the number of heads measured we get a day/night difference similar to that found in '05.

[18] *Dimant and Oppenheim* [2006a, 2006b] argued that earlier models which neglected the influence of currents in the background plasma were neglecting essential physics. This physics changes from night to day as the ionization level rises by two orders of magnitude. The day/night variation in the rates of non-specular trail echoes described in this paper provide strong evidence that this difference impacts meteor trail evolution. Alternative hypotheses such as differences in numbers of meteors, neutral temperature or density, winds, or electrojet currents are unlikely to provide such a consistent and large change.

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