A Study on Various Meteoroid Disintegration Mechanisms as Observed from the Resolute Bay Incoherent Scatter Radar (RISR)

A. Malhotra • J. D. Mathews

Abstract There has been much interest in the meteor physics community recently regarding the form that meteoroid mass flux arrives in the upper atmosphere. Of particular interest are the relative roles of simple ablation, differential ablation, and fragmentation in the meteoroid mass flux observed by the Incoherent Scatter Radars (ISR). We present here the first-ever statistical study showing the relative contribution of the above-mentioned three mechanisms. These are also one of the first meteor results from the newly-operational Resolute Bay ISR. These initial results emphasize that meteoroid disintegration into the upper atmosphere is a complex process in which all the three above-mentioned mechanisms play an important role though fragmentation seems to be the dominant mechanism. These results prove vital in studying how meteoroid mass is deposited in the upper atmosphere which has important implications to the aeronomy of the region and will also contribute in improving current meteoroid disintegration/ablation models.

Keywords meteor radar · meteoroid disintegration · meteoroid fragmentation · ablation

1 Introduction

Meteoroids are responsible for thousands of kilograms of mass flux into the earth's upper atmosphere annually (Mathews et al. 2001).These meteoroids are not only the only source of metallic ions in the upper atmosphere (Kelley 1989) but also, as a result of this very high mass flux, pose a threat to our space infrastructure (Caswell and McBride 1995) and are responsible for a variety of ionospheric phenomenon such as the Sporadic-E (Malhotra et al. 2008) and Polar Mesospheric Summer Echoes (Bellan 2008). This makes it imperative that we know and understand the form in which meteoroids disintegrate into the upper atmosphere in order to understand the aeronomy of the region.

As the meteoroid enters the earth's atmosphere, it collides with the air molecules and heats up. When the temperature reaches around 2000K – usually between 80-120km – surface particles start evaporating from the body. These particles quickly ionize, also ionizing the air molecules around them, forming a ball of plasma around the meteoroid. Radar scattering from this ball of plasma surrounding the meteoroid is called the head echo. Although meteor head echoes were first observed in the 1940s (Hey et al. 1947), their study gained momentum only in the 1990s when they were observed using the High Power Large Aperture [HPLA] radars (Mathews et al. 1997). Since then, these head echo observations have proved invaluable in determining meteoroid velocities (Janches et al. 2000), mass flux (Mathews et al. 2001) and radiants (Chau and Woodman 2004). More recently, these head echo observations are being studied to determine the form that meteoroid mass flux takes when it enters into

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the earth's upper atmosphere. As outlined below, these initial studies on meteoroid disintegration using various HPLA radars have produced contrasting results, generating much interest and even controversy in the meteor community.

Kero et al. (2008), using the EISCAT 930 MHz UHF radar, provide "the first strong observational evidence of a submillimeter-sized meteoroid breaking apart into two distinct fragments" i.e. fragmentation. Fragmentation can take place either due to thermally induced stresses (Jones and Kaiser 1966) or due to the separation of a molten metal droplet from the lower density chondritic compounds of a heated meteoroid (Genge 2008). Kero et al. (2008) provide an example of a "beat pattern" light curve event [the light curve is defined as the pulse-integrated Signal-to-Noise Ratio (SNR)], their Figure 2, and interpret it as being due to interference from two distinct scattering centers. They show that the result is consistent with interference from two fragments of unequal cross-sectional area over mass ratio, separating from each other due to different deceleration along the trajectory of the parent meteoroid. They also provide examples of a "smooth" light curve where the measured SNR follows the antenna beam pattern (their Figure 1) i.e. simple ablation and a quasi-continuous disintegration event (their Figure 3).

Mathews at al. (2008), carrying out a similar analysis for the meteor echoes observed by the Sondrestorm Radar Facility (SRF) 1290 MHz radar, conclude that almost all the meteors observed by the SRF radar are fragmenting large meteoroids that are observed only in the terminal phase of their encounter with the upper atmosphere.

Roy et al. (2009) use a genetic-algorithm based search and fitting procedure to solve for the number of scatterers and their differential speeds in estimating the properties of complex light curves observed by the Poker Flat ISR radar. Based on the above-mentioned analysis, they conclude that fragmentation is the cause of complex light curves.

Dyrud and Janches (2008) determine meteoroid properties by comparing expected results from a theory based ablation model of the meteor head echo and observed meteor properties using the Arecibo 430 MHz UHF radar. They do not include the effects of fragmentation in their model as they "find no evidence that meteoroid fragmentation plays a role in the vast majority of head-echo observations at Arecibo". However, they also conclude that a simple ablation model cannot account for the non-smooth light curves observed by the radar.

Janches et al. (2009), using the Arecibo 430 MHz UHF radar, provide the first observations of differential observations in micrometeoroids. In the differential ablation process, the particle's more volatile components (Na and K) are released first when the temperature is still relatively low followed by the evaporation of less volatile components (Si, Fe and Mg) as the particle descends through the atmosphere, increasing its temperature. Events undergoing differential ablation are characterized by a sudden decrease or increase in the light curve. Though they observed features of the differential ablation process only in small percentage of the detected events, they still conclude that differential ablation is the main mechanism by which micron-sized particles deposit their mass in the upper atmosphere.

Mathews et al. (2010), using data collected from simultaneous observations using the same Arecibo 430 MHz UHF radar and the Arecibo 46.8 MHz common-volume VHF radar, present many unreported features in the radar meteor return that are consistent with meteoroid fragmentation. Based on modeling studies and statistical analysis, they conclude that fragmentation is the dominant process by which micrometeoroids deposit their mass in the upper atmosphere — a conclusion at direct odds with the one reached by Janches et al. (2009), though both the studies use the same radar.

It is clear from the above introduction that the process by which micrometeoroids deposit their mass in the upper atmosphere remains is a topic of much interest in the community and the relative roles of fragmentation, differential ablation and simple ablation is a subject of much debate and speculation.

However, to-date there has been no statistical study studying the relative contribution of the three mechanisms. In this paper, we present the results from first-ever such study. In Section 2, we present details of the observational set-up and radar parameters. The results are presented in Section 3, followed by the discussion in Section 4. We end with the conclusions of our study and the scope for future work in Section 5.

2 Observational Set Up

The results presented herein happen to be one of the first published results from the newly-operational 442.9 MHz Resolute Bay Incoherent Scatter Radar (RISR) located in Resolute Bay, Nunavut, Canada (74.72950° N, 94.90539° W). For these observations carried out on 24-25 and 26 August 2009 from 2140 to 0040 hours (UT) and 1120 to 1455 hours (UT) respectively (totally ~ 6.3 hours of data), the radar beam was pointed in a direction parallel to the Earth's rotation axis and the maximum power transmitted was ~ 1.7 MW. Transmission and reception was done using all the 128 panels of the radar. A pulse width of 90 μs with an IPP (Inter Pulse Period) of 2 ms was used for transmission.

3 Observational Results

We observe meteor signatures of all three micrometeoroid disintegration mechanisms, i.e. fragmentation, differential ablation and simple ablation using the Resolute Bay Incoherent Scatter Radar (RISR), enabling us to conduct a statistical analysis of the relative role of these mechanisms. We begin by presenting representative examples of all the three mechanisms as observed by RISR. These events will also serve to facilitate future similar studies using RISR and the other HPLA radars.

Figure 1a is a RTI (Range-Time-Intensity) plot of a typical fragmenting meteor event. Note the structure present in the meteor return. The beat pattern can be noticed even without the aid of the light curve. Figure 1b shows the light curve (pulse integrated SNR for each IPP) for the event shown in Figure 1a. As expected from the RTI plot, the beat pattern associated with fragmentation is observed. An explanation on the cause of this observed beat pattern is given in a companion paper by Mathews and Malhotra in this issue.

Figure 2a is a RTI plot of a typical meteor event undergoing differential ablation and the corresponding light curve is shown in Figure 2b. Notice the abrupt decrease in SNR received at ~ 32 ms; a possible signature of differential ablation [Figure 2 of Janches et al. (2009)]. Janches et al. (2009) attribute this sudden decrease in received power to the complete ablation of the main meteoroid constituents (Si, Fe and Mg). The reduced power received after the sudden decrease is due to the plasma created in ablation of the refractory metals (Ca, Al and Ti).

Figure 3a is a RTI plot of a typical meteor event undergoing simple ablation and Figure 3b is the corresponding light curve for this event. Notice the relatively smooth pattern (compare to the cases presented in Figure 1b and 2b) obtained for this event in Figure 3b. We assume simple ablation occurs due to the homogeneous composition of the meteoroids.

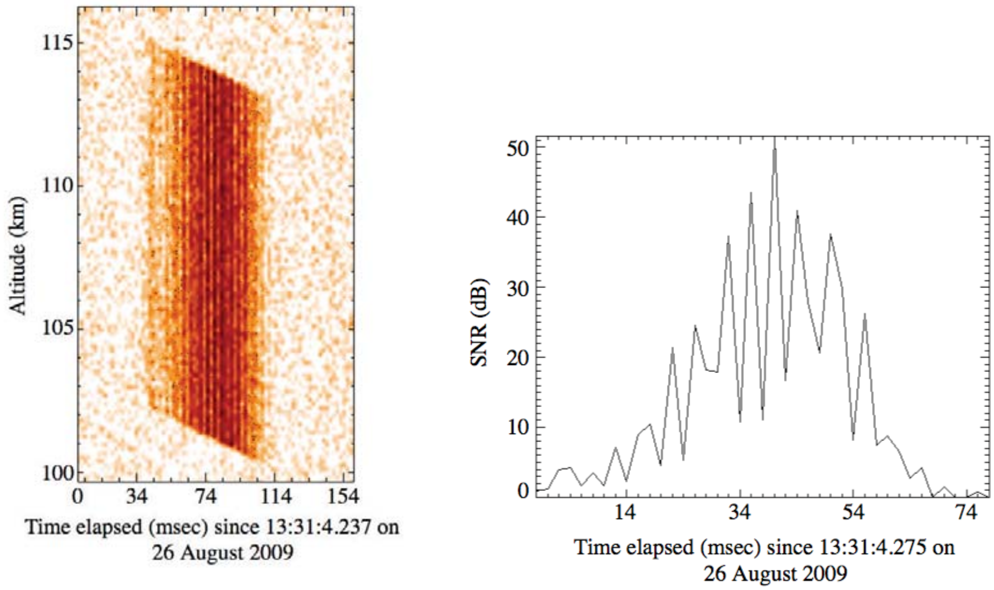

Figure 1. (a) Range Time Intensity (RTI) plot of a fragmenting meteor event. Notice the structure within the meteor return. (b) The light curve for this event. The "beat pattern" observed is obtained due to alternate in-phase and out-of-phase scattering due to change in separation between multiple particles.

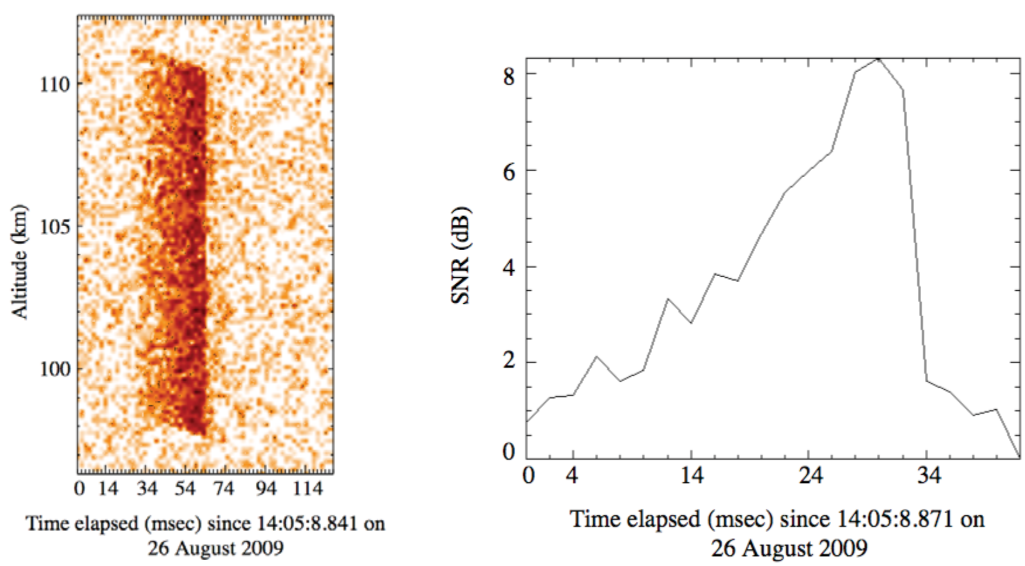

Figure 2. (a) RTI plot of a meteor event undergoing differential ablation. (b) The light curve for this event. The sudden drop in SNR is attributed to the complete ablation of the more volatile meteoroid constituents.

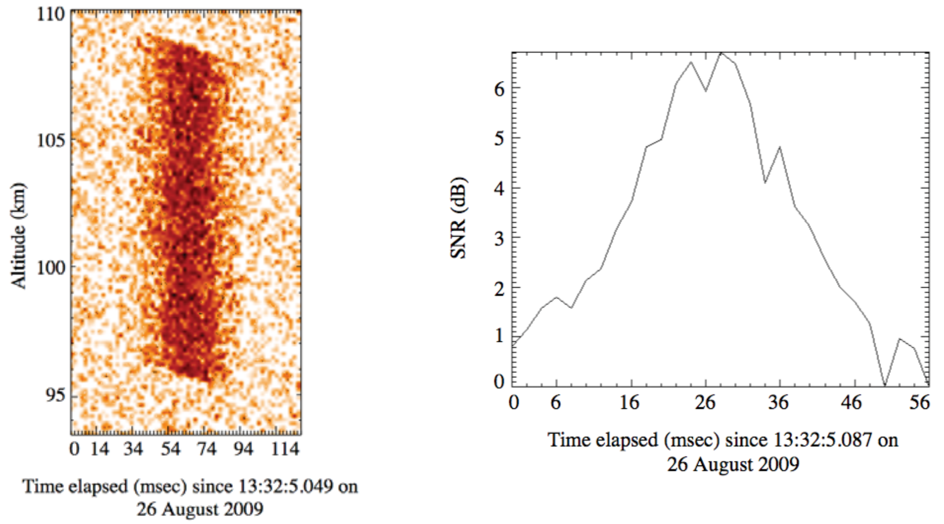

Figure 3. (a) RTI plot of a meteor event undergoing simple ablation. (b) The light curve for this event. Notice the relatively smooth profile compared to the events shown in Figure 1 and 2.

4 Discussion

Figures 1-3 show typical meteor events observed by RISR exhibiting fragmentation, differential ablation and simple ablation respectively. Note that we use Figures 1-3 to define what we interpret as these processes. We present the results from the statistical analysis determining the relative contributions of the three meteoroid disintegrating mechanisms. For the purpose of this analysis, we ignored low SNR events (SNR less than 2dB) as in these cases, even small changes in received power might result in giving an impression of a beat pattern, which might be wrongly interpreted as fragmentation. The events that exhibited two or more of the mechanisms were classified in all the relevant categories.

Following the above-mentioned criteria, we were able to classify 318 events in our data sets. 153 or ~48% of these events exhibited signatures of fragmentation, 62 or ~20% of the events exhibited signatures associated with differential ablation while 103 or ~32% of the events showed signatures of simple ablation. Fourteen events showed signatures of both fragmentation and differential ablation. Though we also observe events exhibiting both simple ablation and fragmentation, they are all low SNR cases and thus not included in the final count for the reasons mentioned above.

From these results, it is obvious that meteoroid disintegration in the upper atmosphere is a complex process in which all the three disintegration mechanisms play an important role, though from these results it seems that fragmentation is the dominant disintegration mechanism. This result has important implications on the aeronomy of the MLT (Mesosphere-Lower Thermosphere) region as it implies that majority of the mass flux from the micrometeoroids is deposited in form of dust rather than atomic metal form obtained due to ablation. The abundance of this meteoroic dust could also provide valuable insights into the formation of PMSEs. The fact that all the three mechanisms play a vital role in meteoroid disintegration is an equally important conclusion as it differs from the conclusions arrived at by Janches et al. (2009) and Mathews et al. (2010), which lay emphasis on differential ablation and fragmentation only, respectively. This result stresses the need for all the three disintegration mechanisms to be taken into account while coming up with any model for meteoroid ablation. The models currently in use to estimate radar meteor head echo properties consider only simple ablation and the above analysis shows that there clearly is a lot of scope for improvement in these models.

5 Conclusions

We have presented results from the first-ever study determining the relative importance of the three meteoroid disintegration mechanisms, namely fragmentation, differential ablation and simple ablation – a topic of much discussion and debate presently in the meteor community. We present "type specimen" meteor events that serve to define the presence of the three disintegration processes. Additionally, these results also constitute the one of the first reported observations from the newly-operational Resolute Bay Incoherent Scatter Radar. Our results suggest that meteoroid arrival and disintegration in the upper atmosphere observed by the UHF is a complex process in which all the three mechanisms play an important role though it seems that fragmentation is the dominant mechanism – an important result as it implies that majority of meteoroid mass flux is deposited in the upper atmosphere in dust rather than atomic form. The meteoroid disintegration process is further complicated by presence of events exhibiting signatures of more than one disintegration mechanism. Our results strongly suggest that any theoretical model explaining meteoroid disintegration should consider all the three disintegration mechanisms. Finally, we recommend that a similar classification study should be conducted not only at RISR with a larger data set but also at other radars such as the Arecibo, PFISR, SRF, ALTAIR and Jicamarca radars. Such a study would help in understanding the difference in the type of meteoroid flux observed by these radars at different locations operating at different frequencies and also lend further insights into the aeronomy of their respective MLT regions.

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