Ongoing meteor work

Morphology of persistent trains is due to fragmentation

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Persistent trains often show two parallel bands of light, a morphology that until now has been interpreted as due to a tubular structure and a phenomenon called 'limb brightening'. A problem with this interpretation is that the brightness between the two bands is less than expected. A recent study of meteoroid breakup now shows that fragmentation often leads to the survival of two relatively large fragments. Here, we show that this can explain the dominant morphological features of persistent trains.

1 Introduction

Persistent trains can be defined as all those luminous glows of meteors that linger due to chemiluminescence. They tend to last longer than several tens of seconds, because the time scale of the chemistry is limited by diffusion processes. Persistent trains were described as early as 1856 (Hind, 1866; Mann, 1856; Newton, 1869a; Newton, 1869b) and have since puzzled all those who witnessed or studied them. Spectacular trains were observed during the 1998 Leonids (Figure 1).

Proof that chemiluminescence was the luminous mechanism came only during the 1999 Leonid storm, when it was shown that most of the visible light is emission from the FeO (iron oxide) molecule and from sodium atoms (Jenniskens et al., 2000a). The light is produced as a result of chemical reactions that recombine the oxygen atoms in the train with ambient ozone molecules to form oxygen molecules, a process catalyzed by (amongst others) meteoric iron and sodium atoms ($O_3 + Fe \rightarrow FeO^* + O_2$; $FeO + O \rightarrow Fe + O_2$). Chapmann (1955) first proposed the mechanism. Other airglow-type mechanisms may be at work, especially in the near-IR, see Kruschwitz et al. (2001).

2 Train morphology

Drummond and co-workers (Drummond et al., 2001a, 2001b) have proposed a classification of persistent trains in two types: those that have two parallel bands of luminosity (Type II) and those that show abundant billowing structure (Type I). However, on closer inspection it is clear that even the trains with strong billowing (Figure 1) sometimes show two parallel bands.

That morphology of persistent trains has always been a puzzle. The simplest explanation is that the glow comes from the edge of a cylinder, where ambient ozone molecules gradually diffuse into the oxygen atom rich meteor path (Trowbridge, 1911; Hawkins, 1957). At the edge of the cylinder, the line of sight is parallel to that zone, causing limb brightening, while at the center it cuts perpendicularly through that zone, causing a factor of two lower brightness (Jenniskens et al., 2000b; Kruschwitz et al., 2001). On closer inspection, one finds that the void between the two bands is too dark, a point illustrated nicely by the ROTSE meteor in Figure 1, which shows a high contrast.

Alternative explanations include wing-tip vortices, such as those observed in the wake of an aircraft (Gerz and Holzapfel, 1999). Wingtip vortices are created be-

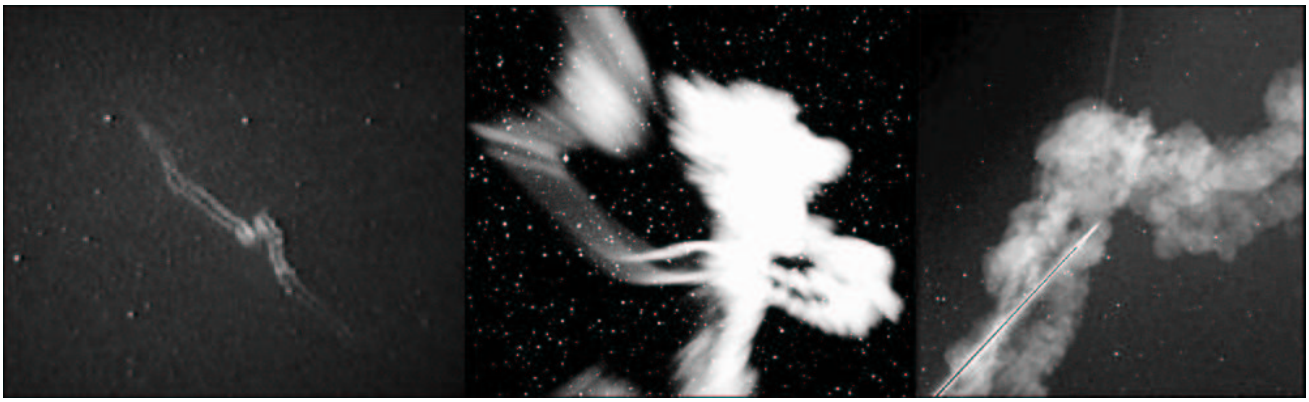

Figure 1 – Three well-studied Leonid persistent trains from 1998 Nov 17, all showing parallel bands with various levels of turbulent billowing. **Left:** A magnitude −10 Leonid at 01^h31^m UT left the 'Chippenham' train with two parallel bands along its entire path (Jenniskens et al., 2000b); **Middle:** a magnitude −11 Leonid left the 'ROTSE' train close to the radiant at 08^h32^m UT, which shows an abrupt change from little to much turbulence along its path (Zinn et al., 1999); **Right:** the product of a magnitude −14 Leonid at 10^h05^m UT studied by lidar (the diagonal streaks) with much billowing along its entire length (Chu et al., 2000). See also the discussion in (Kelley et al., 2000).

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cause air is pushed down by the wings and rolls upward at its wing tips, thus creating a corkscrew shaped flow of air made visible on occasion by moisture in the air. If meteoroids flatten out to structures larger than the mean-free path in air, they could cause similar vortices. However, this explanation runs into problems because the bands have a large separation at the onset. In the case of the Chippenham meteor, we found an initial separation of 136 m at 86 km (Jenniskens et al., 2000b). The meteoroids responsible for bright Leonid meteors are thought to be much smaller, of order 5–20 cm.

3 Fragmentation as the cause for persistent train morphology

The observations point to both bands being independent trails caused by individual fragments (Kruschwitz et al., 2001), but how can there typically be only two fragments? In a recent study of video records of the Morávka fireball (Borovička et al., 2002), Jiri Borovička and colleagues made an important observation that, I believe, has relevance for cometary meteoroids and persistent trains. They found that many structurally strong meteoroid fragments during the breakup were lost abruptly at different altitudes. They concluded that during these breakups much of the mass is lost in the form of dust. If something survived big enough to cause a meteor, it was frequently two large fragments, with masses of 10%–30% of the initial mass. Only very rarely are there three fragments remaining. In particular, the measured frequency of one, two, three and four fragments was 8, 6, 1, and 0, respectively (Borovička et al., 2002). In my opinion, this could be a feature of catastrophic fragmentation in a collision with the air at the point of breakup pressure, where pieces on the back of the rock are typically spared. In collision experiments, a rock hitting a solid surface at high enough speed for a catastrophic fragmentation tends to break into smaller pieces at the front and spares larger fragments at the back (Fujiwara et al., 1989). This could also be the case for a rock hitting the air layer where the pressure exceeds the breakup pressure.

If comet dust too breaks apart early in flight and one or two dominant fragments remain, then the origin of the two bands in many persistent trains is explained. Because, just as in the luminous light during the descent, the fainter fragments will contribute little to the persistent train emission.

Fragmentation may increase the visibility of the train by increasing the volume of air involved in the chemistry. During the 2001 Leonid Multi-Instrument Aircraft Campaign, a slow (23 km/s), grazing, 12-second long, magnitude ~ -11 Taurid fireball was recorded on November 18 at $12^h52^m48^s$ UT by intensified video cameras (Figure 2). This fireball showed an unmistakable persistent train at a position early in the trajectory, when the fireball was only about magnitude -2. To our knowledge, this is the first time that a persistent train was reported for such a slow meteor. The train was visible for more than 14 minutes, until the plane turned away. It showed all the typical features, such as an initial increase in brightness (Jenniskens et al., 2000b), a long duration, and changes in shape due to the strong upper atmosphere winds. Hence, persistent trains are not unique to very fast and very bright fireballs! We can only understand why this particular slow meteor had a persistent train, when it was not so bright, by assuming that it was the fragile nature of cometary dust that helped create a number of fragments and make it bright. Taurids derive from comet Encke. I have found that Perseid fireballs, too, show persistent trains when viewed by a small telescope, although they tend not to be visible by the naked eye.

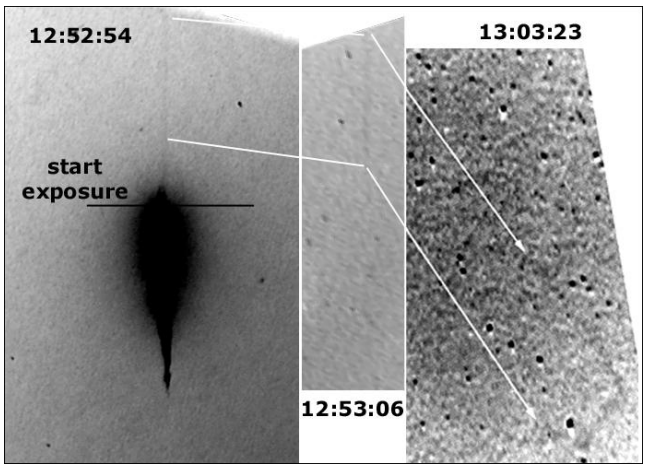

Figure 2 – The November 18, $12^h52^m48^s$ UT Taurid fireball, in a 10^s exposure by Dean W. Armstrong from Las Vegas, Nevada. The exposure was started while the meteor was in flight, moving top to bottom. The pictures to the right show the persistent train as seen from the FISTA aircraft at $+38^s$ and $+7^m$.

Further support for this hypothesis comes from a unique photograph that was obtained by Robert Haas of the Dutch Meteor Society during the Sino-Dutch Leonid campaign in China, which provided support to the 2001 Leonid MAC (Haas, 2001). Following a magnitude -6 earth-grazer at 2001 November 19, $16^h03^m58^s$ UT, he obtained a guided exposure of a persistent train that appears to consist of three parallel bands of light (Figure 3). Each band develops billows at a different rate, just as expected if three fragments survived the early breakup and were of different sizes.

4 Discussion

The breakup of the original Leonid meteoroid must have occurred above the $\sim$ 90–75 km altitude range where persistent trains are observed. The separation of the fragments is driven by the breakup and pressure generated in the process. As the fragments fall, they should continue to separate. I have re-examined the Chippenham data to see if the initial band separation increases with decreasing altitude as would be expected. Indeed, there is such an increase, which points to an initial separation of the fragments at an altitude of 130–160 km, with a horizontal velocity component of ± 100 m/s (Figure 4). The bands drift apart at a rate of 10.5 m/s, possibly due to pressure generated by the expanding heated air columns.

The breakup occurred just at the time of, or just

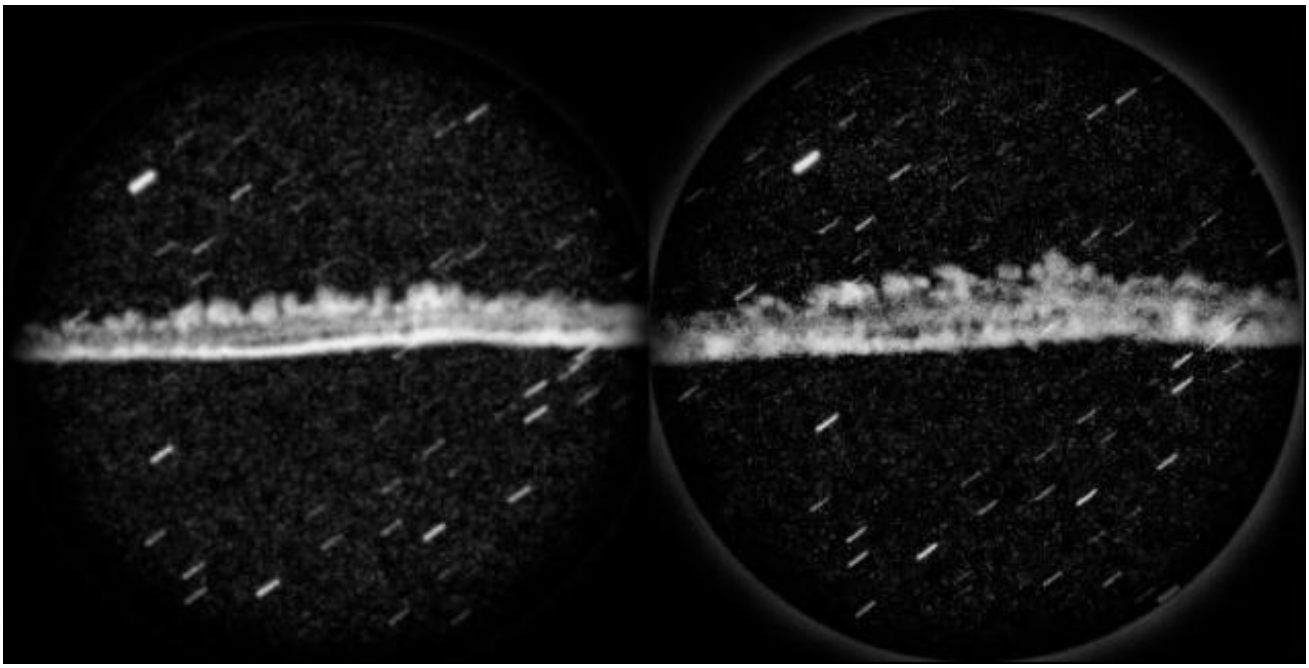

Figure 3 – Composite of two photographs of the magnitude −6 Leonid persistent train on 2001 November 19, $16^h03^m58^s$, showing three bands. Photograph by Robert Haas, Dutch Meteor Society (Haas, 2001).

before, the onset of the massive evaporation of silicates at ∼ 135 km altitude (Spurný et al., 2000; Popova et al., 2000). The mechanism of the fragmentation can not be the same as that for structurally strong meteoroids, because the pressure is still very low at 135 km. Rather, it is believed that the heating of the meteoroid by air collisions leads to the evaporation of a volatile 'glue' at an altitude higher than 120 km (Hawkes and Jones, 1975). Cometary meteoroids include many organic volatiles with boiling points of 400–600 K. These will presumably boil before minerals do. This evaporation process can be rather violent and the breakup could also be catastrophic in nature, with one or two large fragments remaining if the heating occurs preferentially at the front. Alternatively, stresses caused by heating could lead to a catastrophic breakup in these rather fragile meteoroids. It is not clear if the sudden increase in the total surface area would already be noticed if the breakup occurs before the main minerals start to evaporate. The catastrophic nature of the breakup is key to understanding why there are typically only (one or) two large fragments.

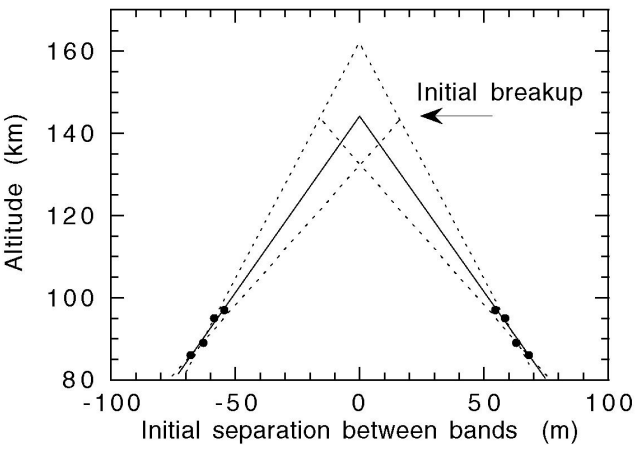

Figure 4 – Separation of the Chippenham bands just after deposition. Each set of dots represents the separation of the bands extrapolated back in time the drift of the persistent train to the time of formation. I measured this initial separation at four altitudes. The solid lines are the best fit, the dotted lines are the most extreme cases that will fit in 1-σ accuracy of all points of each quartet.

It is often observed that the two bands have different brightnesses. The intensity of each band depends on the rate of mixing between oxygen atoms created in the meteor's path and ambient ozone molecules, and mixing is enhanced by turbulence.

The source of turbulence could be the flow around the body, or the instability of the column of heated air in its path. The flow around the body has too low a Reynolds number (Re ∼ 800) and too high a Knudsen number (Kn ∼ 1) to generate turbulence, but roughness, heat, and ablation vapor can disrupt the flow. The most likely explanation for the observed billowing, however, is that the heated air column behind each fragment becomes unstable. The size of the column behind each fragment is about 10 mean-free paths wide, which amounts to a few meters at 95 km, and various fluid dynamical processes can occur. Shortly after the collisions heat the air in the meteor's path, the plasma will tend to expand to pressure equilibrium with its surroundings. When the hot gas in the meteor's path accelerates against the colder heavy ambient environment there will be Rayleigh-Taylor (R-T) instabilities. Small irregularities in the interface quickly grow to larger structures, when the hot gas penetrates the denser and colder ambient air. Indeed, the images by Haas (Figure 3) appear to show a preferred expansion of the air in upward direction, as expected for R-T instabilities in an environment with gravity.

A characteristic of R-T instabilities is that, after

an initial exponential growth, at larger amplitudes the hot gas penetrates linearly with time into the ambient medium in the form of fingers or bubbles (Taylor, 1950). Those fingers then merge into larger structures before dissipating when the pressure difference that drives the instability is gone. The observed width of the Chippenham bands does seem to increase linearly in time at 3 m/s before slowing down, although a (square root with time) diffusion-like expansion cannot be excluded (Jenniskens et al., 2000b).

The amount of vorticity created during the initial exponential growth (which determines the appearance of the pattern shortly after) is a function of the pressure and density of the heated gas. Larger fragments should create more heated air plasma, producing billowing trains. Indeed, very bright (magnitude −12 to −14) Leonids tend to show larger billows (Figure 1). Turbulence should be more prominent during peak brightness when ablation rates are high deeper in the atmosphere. Abrupt changes in the brightness of the meteor can explain the sudden increase in billowing observed in the ROTSE meteor (Zinn et al., 1999). In other cases, the trains can remain relatively free from turbulence (such as the Chippenham train) if much of the light results from the ablation of dust in the flow and the persistent trains are caused by relatively small fragments.

Kelvin-Helmholtz instability can perhaps play a role as well in creating initial irregularities. K-H instabilities are caused by velocity shears between the heated plasma and the ambient atmosphere. In bright fireballs, it has been shown that such velocity shears do exist immediately after the passage of the meteor, as a result of kinetic energy of the meteor being imparted on the meteor plasma (Borovička and Jenniskens, 2000).

5 Conclusion

In conclusion, the multi-band morphology of persistent trains is not due to limb brightening of a tubular train, but a result of fragmentation of meteoroids at high altitudes, after which each fragment creates its own turbulent wake.

The implication is that persistent trains may be used to study the stresses that cometary matter can be subjected to before breaking, which is important information for future comet landing missions. The surface of comets is thought to consist of fallen back meteoroids. Studies of the onset of meteors too may teach us when and how cometary meteoroids first fall apart.

Acknowledgments

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