Ready for the Storm

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Astronomers are gearing up for a possible spectacular Leonid meteor storm on November 18, which could tell scientists how the stuff of life was brought to Earth.

On most nights, meteors are so rare that, as folklore has it, a single sighting can make your wishes come true. But every now and then, a meteor shower will dazzle the eye with thousands of blazing trails across the sky in just a few hours. Astronomers call these spectacular displays “meteor storms.” Of all the meteor showers that occur each year, the Leonids of mid-November are the only one known to produce a storm in our lifetime. Professional and amateur astronomers alike are gearing up for this year’s Leonid shower, because experts predict that it could produce two of the best meteor storms in recent memory.

The most spectacular meteor storm on record was probably the Leonid display of November 12-13, 1833, when witnesses in North America reported that “never did rain fall much thicker, than the meteors fell towards the Earth.” The spectacle was so powerful that people assumed the world was coming to an end. This storm led to the systematic observing of meteor showers and the realization that meteors originate from outside the atmosphere.

The Leonids put on impressive storms again in 1866 and 1867. These displays led to the recognition that the storms were somehow linked to the return of the parent comet 55P/Tempel-Tuttle every 33.25 years. Unfortunately, the returns of 1899 and 1932 were disappointing, and many astronomers gave up on ever seeing anything like the 1833 storm again. Indeed, the spectacular November 1966 storm went mostly unnoticed by the scientific community and came as a real surprise to viewers in North America.

The comet returned to perihelion in 1998, leading to spectacular showers in 1998 and 1999. This time, the scientific community was ready. The recent storms have inspired a new group of scientists that can pry surprising information from the elusive flashes of light. We want to learn more about meteors to prevent damage to satellites. We still need to learn a great deal about how comet dust causes meteor storms. We also want to learn more about the comet and comet dust itself and how meteors may have brought critical organic material to Earth, perhaps leading to the origin and prevalence of life on our planet.

Scientists have recently mounted airborne campaigns to be at the right place at the right time under perfect weather conditions. The Leonid Multi-Instrument Aircraft Campaign (MAC) consisted of two research aircraft that flew 120 kilometers apart for stereoscopic viewing. Missions to Japan in 1998 and to Europe in 1999 collected a bounty of information, leading to a new understanding of meteoroid streams, meteors, and their persistent trains. We discovered that the view at 10 kilometers altitude is spectacular, especially near the horizon, where meteor rates peaked four to five times higher than reported from the ground. And we discovered that meteors provide a surprisingly soft landing for complex organic molecules.

This is an ongoing effort. We anticipate impressive storms in November 2001 and 2002, with potentially intense displays over North America. But professional and amateur astronomers need to prepare themselves for these storms, because we may not see another one until 2099.

Predicting Meteor Storms

Meteor showers occur when Earth plows through debris left behind by comets. As these wandering balls of ice and rock wind around the Sun, they are buffeted by solar radiation, which warms the ice and knocks off grains of dust in a gale of water vapor. Much of that activity occurs in geyser-like fountains of gas and dust. The solar wind and radiation pressure blow the smallest dust particles into a familiar comet dust *tail*. But the larger dust grains are not affected and remain as a gradually expanding cloud of dust around the comet nucleus. By the next return of the comet, that debris spreads along the comet’s orbit in a thin dust *trail*. That spreading is simply due to some particles making a wider orbit and returning later. Meteor storms occur when Earth encounters one of these dust trails.

Only recently, astronomers recognized the full implication of the fact that each 33.25-year return of Tempel-Tuttle creates a new dust trail. The dust trails are often separated from one another, because the comet’s orbit differs slightly each return. An observer on Earth with super eyes would see a series of parallel and collimated streams of dust particles going in the same direction as the comet’s orbit, like the rivers in a delta. Because of the ever-changing pull of the planets, those rivers of dust follow a different path each year, and only when one of the narrow trails happens to lie in Earth's path do we get to see a meteor storm.

Forecasting meteor showers used to be about as accurate as weather predictions in the era before satellites and computers. But in recent years, as our understanding of comet dust trails has grown more sophisticated, meteor forecasting has passed from the realm of speculation to science. Leading up to the 1999 storm, astronomers realized that they could calculate the position of one of Tempel-Tuttle's dust trails by tracking the various gravitational influences on a single test particle. The line along which that test particle passes Earth's orbit is the center of the dust trail. This method provides the time of the storm, and by comparing the activity of past Leonid storms, astronomers can determine how wide the dust trail is and predict shower rates in future trail encounters.

In November 1999, David Asher from Armagh Observatory in Northern Ireland and Esko Lyytinen, an amateur astronomer in Finland, calculated that the 1899 dust trail would lie in Earth's orbit where our planet would hit it at 2:08 Universal Time (UT), November 18. The storm materialized on schedule and peaked at 2:00 UT with a zenithal hourly rate (ZHR) of 4,600 per hour, meaning an experienced observer under a very dark sky would see 4,600 meteors per hour (about 77 per minute!) if the radiant was situated directly overhead. In most other years, the peak ZHR of a Leonid shower is only 13. Onboard Leonid MAC, we studied the storm just west of Greece, while flying from Israel to the Azores. The view from the aircraft was truly amazing. We occasionally saw six or seven meteors falling at the same time.

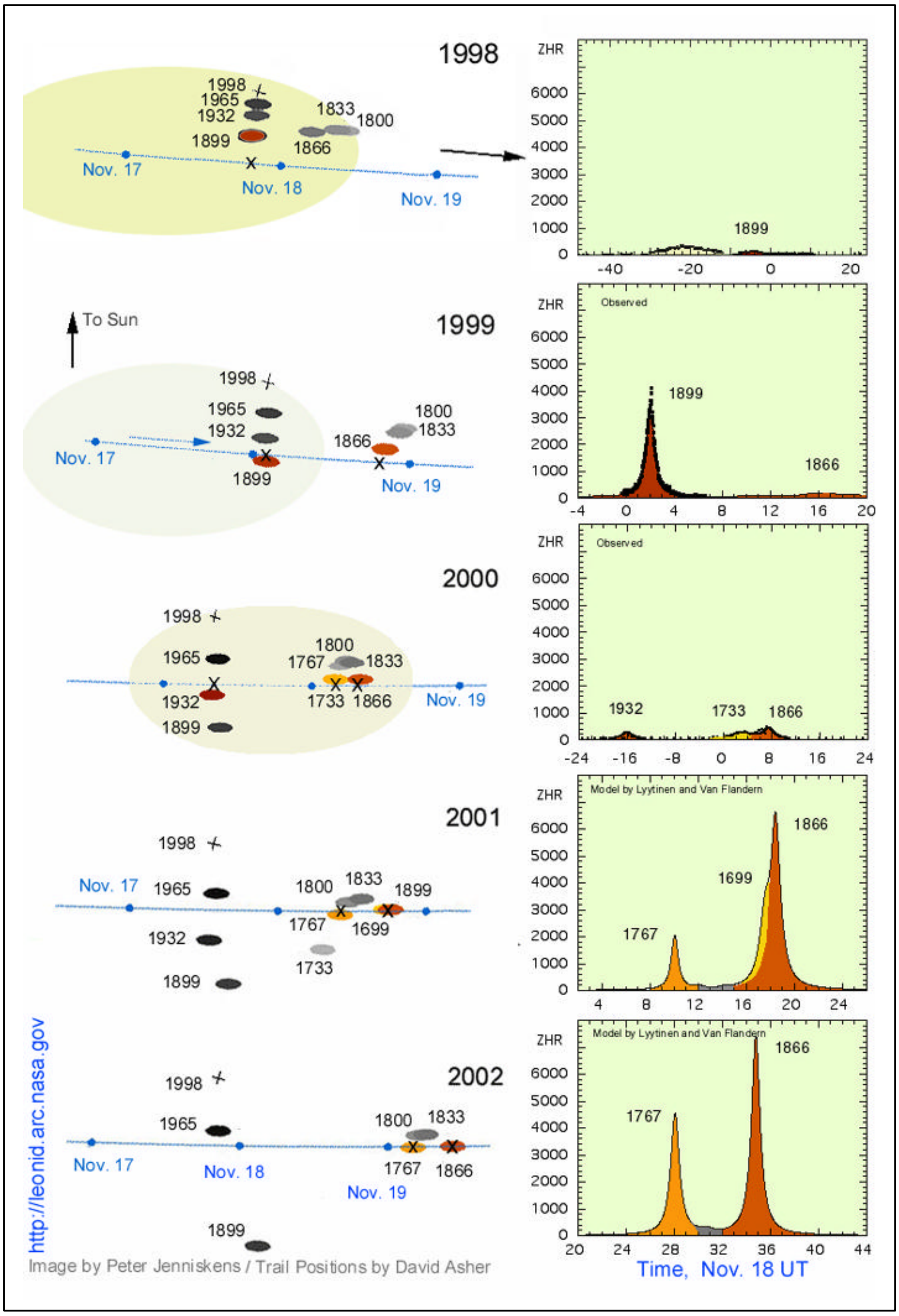


Figure 1 : *Earth's path through 55P/Tempel-Tuttle dust trails and observed (1998-2000) and predicted (2001-2002) Leonid shower activity. The Leonid Filament is schematically shown as a yellow shaded region.*

If you missed this 1999 storm, there is good news. According to the latest models, the best storms are yet to come. Earth crosses as many as *three* dust trails this November. Earth will cross the 1767 dust trail on the outside, and 8 hours later, it will cross the 1699 and 1866 dust trails on the inside (close enough for the shower profiles to merge into one storm). The storm from the 1699 and 1866 trails should be visible over the western Pacific, Japan, Australia, and parts of China in the predawn hours of Monday, November 19. The 1767 trail, on the other hand, can be seen over nearly all of the continental United States on a Sunday morning and under moonless conditions at around 5:00 a.m. EST (2:00 a.m. PST) on November 18. Only clouds and city lights can spoil the view. We expect a repeat show next year, but under a full Moon. After that, it's all history. Earth will not go through any dust trails for the next century. Only our grandchildren may

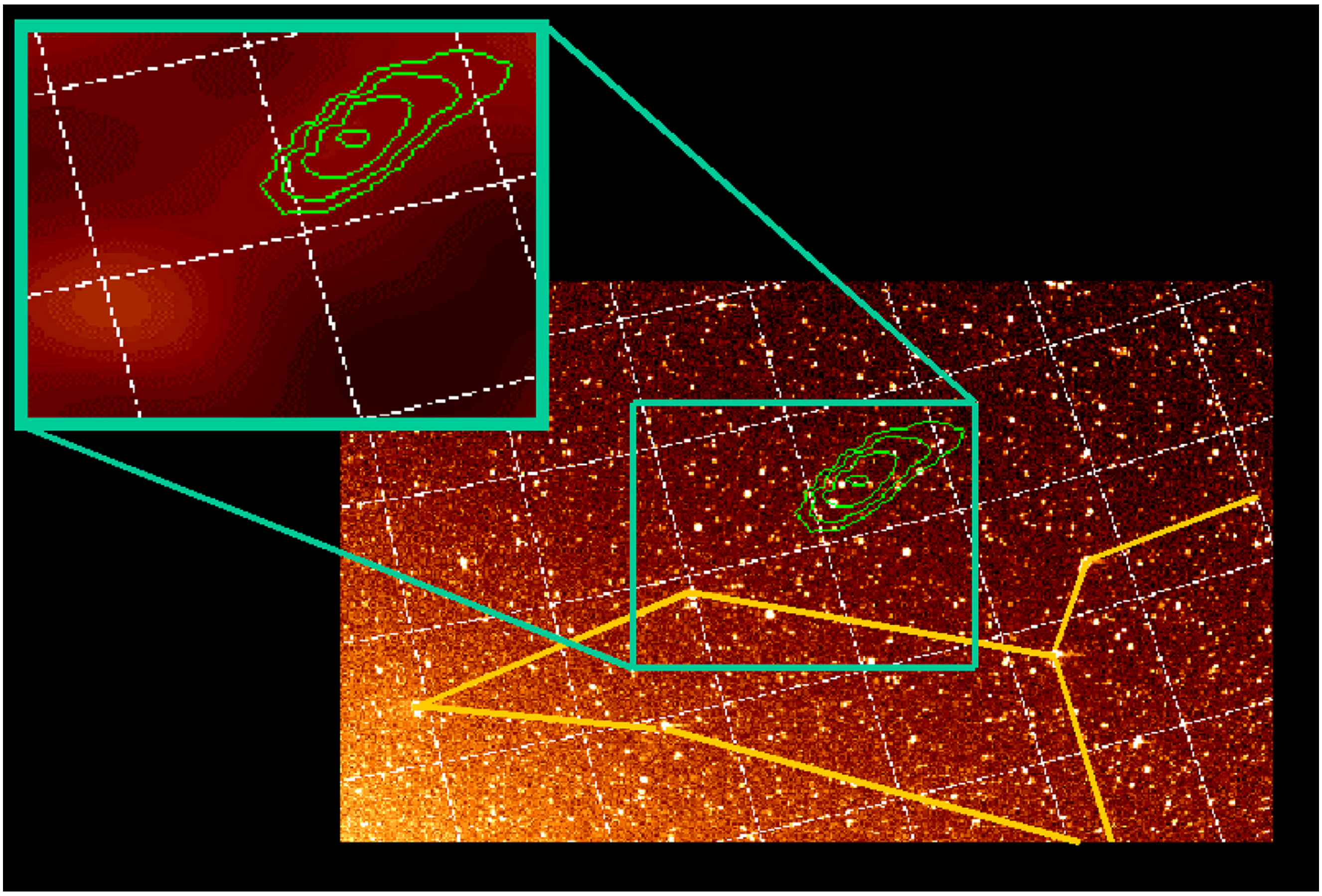


Figure 2 : *Faint cloud of scattered sunlight from Leonid meteoroids in space was seen just above the body of the constellation of Leo by Leonid MAC participant Ryosuke Nakamura and colleagues on the ground in Hawaii.*

see anything like it again when the comet returns in 2099.

Where To Go?

Professional and amateur astronomers are struggling to decide where to go for the best viewing this year. The peaks will occur 8 hours apart, so one has to decide between one or the other. Asher calculated a rate for the Pacific peak up to 10 times higher than the North America peak, while Lyytinen predicts a Pacific peak rate four times higher. But these calculations assume that there are no mistakes in the estimated position of the trail centers.

The calculations, however, are based on very simplified assumptions about dust ejection. Asher assumed that his model dust grain is ejected forward in the direction of the comet motion at perihelion, while Lyytinen assumed no ejection velocity at all. He thinks that radiation pressure alone will make the particle's orbit wider than the comet's. Both assumptions lead to almost the same orbit for the test dust particle and thus much the same positions for the dust trails. But are they correct?

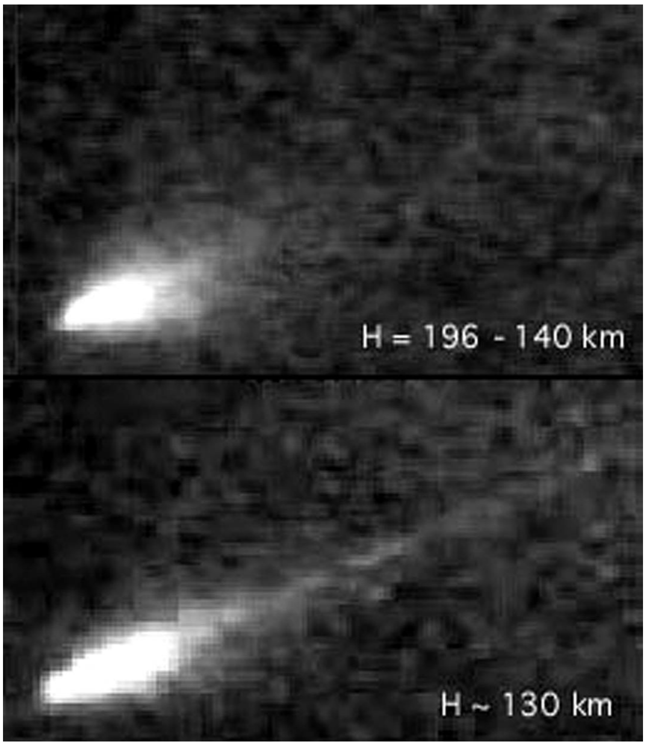
Analysis of 1999 and 2000 airborne meteor counts show that the pattern of trails may be shifted slightly inward relative to the calculated positions. The reason for these small displacements could be the presence of a "geyser" of gas and dust, called a jet, that astronomers saw during the comet's 1998 return. Jets tend to shoot the dust particles in a specific direction rather than spread them around equally.

The narrowest and most intense storms occur when the trail position is calculated to be just outside Earth's orbit, like the 1767 trail. If we abandon the idea that the dust distribution has to be centered on the calculated position, and accept the notion of trail shifts, then the 1767 dust trail will be closer to Earth's orbit and the North America peak becomes the more intense one at a ZHR of about 4,200 per hour. However, the Pacific peak at a ZHR of about 3,700 consists of two slightly displaced and somewhat broader trails, so it still has a 60% higher total influx for Earth-based observers. These calculations suggest that observers in both North America and the western Pacific will enjoy an outstanding storm of similar intensity as the 1999 storm

Check out the activity of the shower from your own location at: http://leonid.arc.nasa.gov/estimator.html).

The Fragile Leonids

Meteor science involves more than just predicting storms. We also want to learn about the meteoroids themselves, which in turn tell us a great deal about the parent comet. For example, by tying all recent stream encounters together to build a picture of how comets lose dust, I calculated that Tempel-Tuttle loses about 2.4 times as much



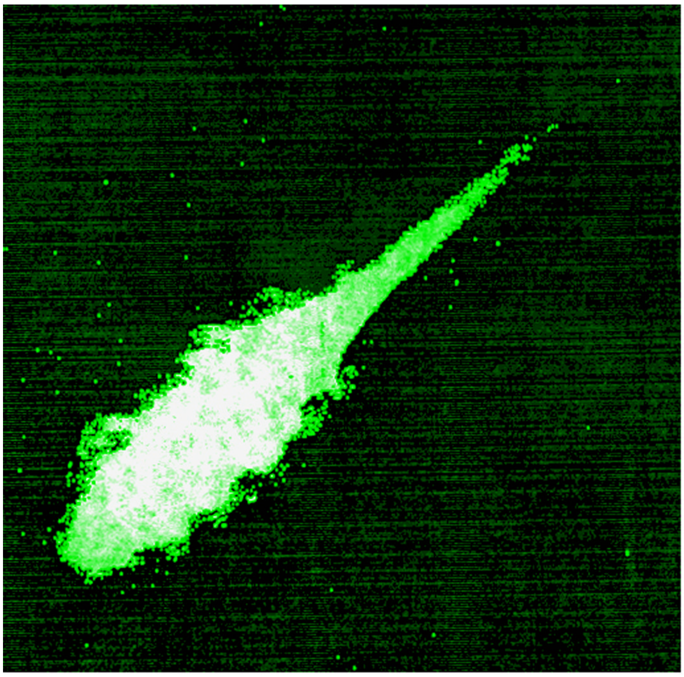


Figure 3 (left) : *Fan-shaped glow above 135 km in the video image of a bright Leonid.*
Figure 4 (right) : *Meteor image (1/30th second exposure) through MgI (518 nm) filter.*

mass in the form of dust than in the form of water vapor.

The best showers occur in the year following the comet's return. Because the pressure of sunlight effectively lowers the Sun's gravitational pull on cometary dust particles, the particles tend to make a wider orbit than the comet. As a result, the dust density in the comet's orbit is higher behind the comet than in front. How much the dust particles tend to lag the comet depends on how much sunlight a particle of given mass captures. From that, I calculated that the density of a typical Leonid meteoroid is about 0.97 gram per cubic centimeter, almost the same density as water ice.

But there is no water ice in Leonid meteoroids. All the original water ice from the comet vaporizes in the vacuum of space before the meteoroids — which are typically the sizes of pebbles — enter Earth's atmosphere. Rather, the low density results from the fact that the meteoroids are loose assemblies of tiny rocky grains that are partially held together by a sticky glue of complex organic matter. Freshly ejected Leonid meteoroids, those that have been free in space for only 100 years or less, are more fragile than the meteoroids of older showers such as the Perseids and Taurids, which are thousands of years old. If Leonid meteoroids become more compact in space as time passes, astronomers might be able to measure this effect by comparing older dust trails, such as the upcoming 1767 and 1699 dust trails.

The Violent Breakup of Meteoroids

Meteors emit light because the dust particles are traveling so fast through the atmosphere (71 kilometers per *second* for the Leonids) that violent collisions with air molecules evaporate material from the meteoroid, a process called ablation. Until recently, astronomers often assumed that meteoroids melted throughout as they got bombarded by air molecules, and that volatile minerals evaporated first. That picture changed dramatically in 1998 when Leonid MAC aircraft observer Ian Murray of Regina University in Canada and his ground-based colleague Alan Le Blanc of Mount Allison University in Canada, observing from Mongolia, discovered that some Leonids exhibit jet-like features. The jets formed almost instantaneously and extended up to two kilometers from the pebble-sized meteoroids.

Some scientists thought that lightning might be responsible for the jets. But Mike Taylor of Utah State University followed up in the 1999 Leonid MAC mission, and discovered that rapidly-spinning meteoroids eject small bits of meteoric matter at high speed during their descent. Taylor tuned his camera to the light of one specific atom: magnesium. This atom evaporates from the meteoroid's core olivine and pyroxene minerals and produces a bright green emission line at 517 nanometers. Images at this wavelength clearly show the jets, which have a turbulent and repetitive pattern left and right of the meteor trails. The ejected bits of matter greatly increase the volume of air that can be chemically altered, leading to the jets.

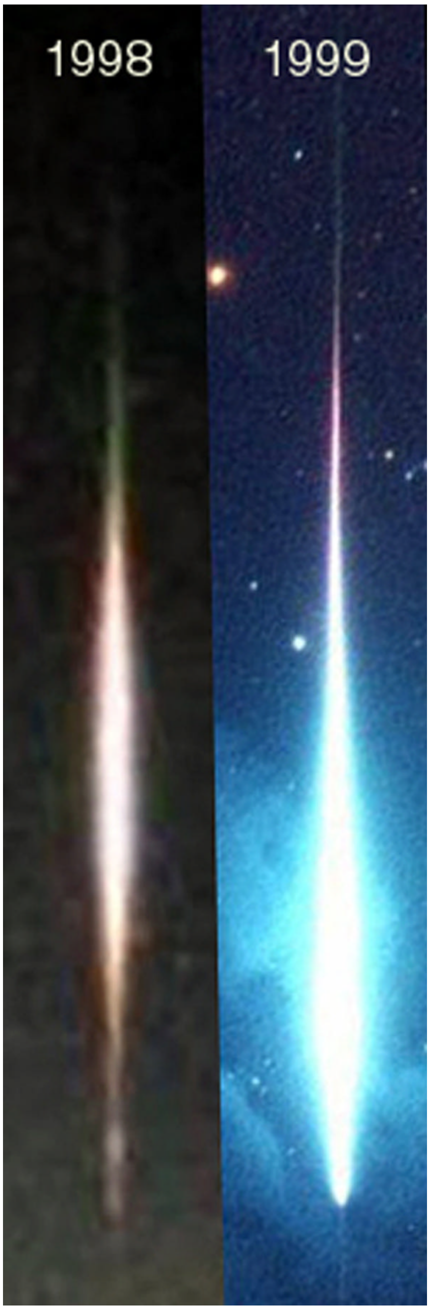


Figure 5 : *Leonids photographed in 1998 (R. Haas, Netherlands) and 1999 (Arne Danielsen, Norway) show the typical light curve profiles encountered in the work by Murray.*

Images with a narrow 5° to 20° field of view are most likely to reveal the jets. High frame-rate video imaging could provide further insight into dust spinning rates and dust fragmentation. Amateur observers can try to image this phenomenon by using intensified video cameras with a small field of view, and a lot of good luck!

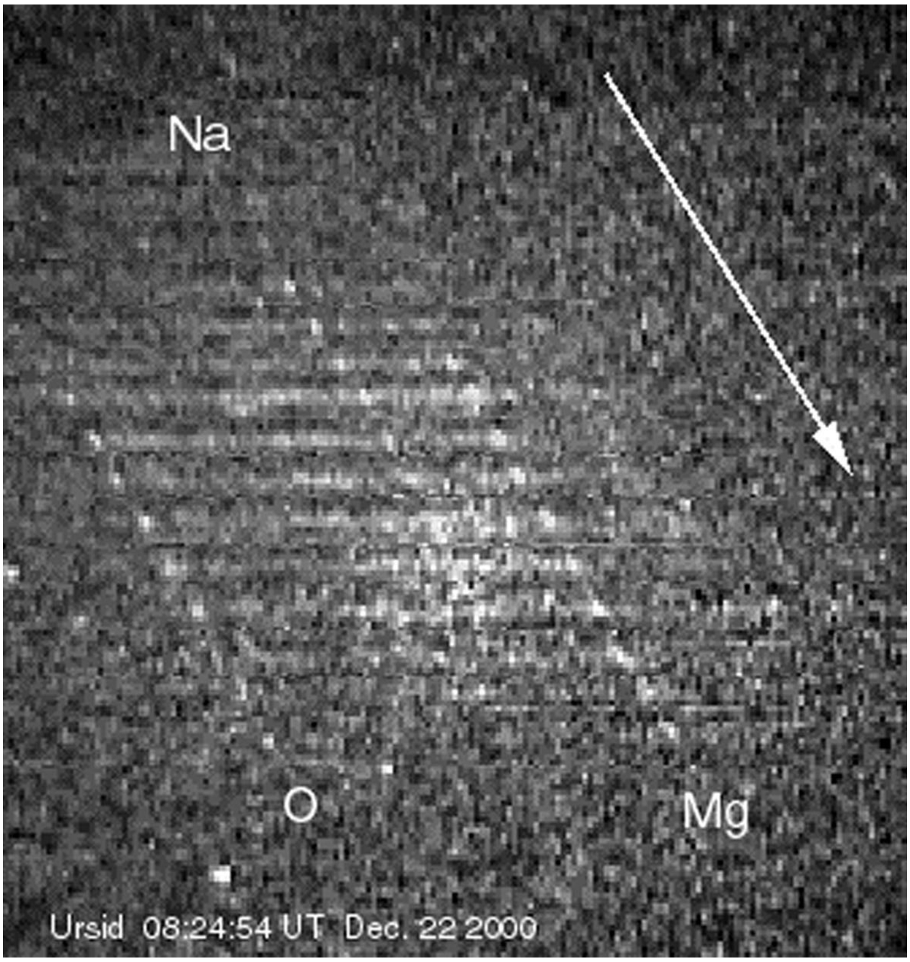


Figure 6 : *Meteor spectrum of an Ursid (08:24:54 UT on Dec 22, 2000), showing the same early release of sodium. Direction of motion is indicated. Spectrum runs from blue (right) to deep red (left). Courtesy the author.*

The Loss of Organics

Some of a meteoroid's minerals can survive in solid form deep into Earth's atmosphere. But at what altitude do the meteoroids lose their organic glue? The organic matter is expected to evaporate at half the temperature of the minerals, so it should come off higher in the atmosphere, peaking at around 117 kilometers in the case of the Leonids. The most volatile organic components could disappear even higher.

At a record breaking 196 km altitude, meteor astronomers Pavel Spurny of Ondrejov Observatory in the Czech Republic and Hans Betlem of the Dutch Meteor Society discovered a peculiar V-shaped glow on video images of bright Leonid fireballs during ground-based observations in support of Leonid MAC in China. That is twice the altitude at which meteors typically burn up. The air density at 196 kilometers is a hundred times less that at 100 kilometers, so low that it is on the verge of outer space. It is possible that very volatile organic compounds in the meteoroid are responsible for this luminosity. However, very few collisions with air molecules must be capable of generating a lot of light, so we're not sure what's happening. The fan shape suggests a rapid spreading of charged particles into the ambient ionized air with speeds up to 40 kilometers per second.

The diffuse V-shaped glow quickly transforms to the usual droplet shape when these meteoroids reach 135 to 130 kilometers, where the minerals start to evaporate, and a meteor wake of metal atom emissions and the green-

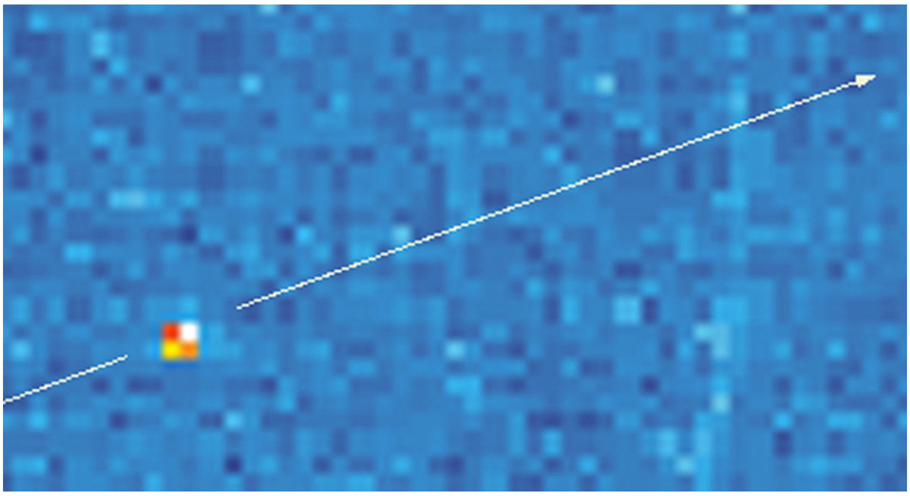


Figure 7 : *A dot of infrared light detected from a meteor track (arrow).*

ish oxygen OI emission start to develop. The latter can persist for several seconds.

Something volatile does appear to quickly leave the meteoroids at about 117 km. During the 1998 Leonid MAC mission, George Rossano and coworkers at the Aerospace Corporation in Los Angeles detected two bright dots in infrared light that matched the video record of two bright meteors. In both cases, the dots represent a specific point just before the peak brightness at visible wavelengths. The dots represent short exposures of brief flares of infrared emission whose luminosity was 25 times that of visible light. Observers on both MAC aircraft saw the meteors in visible light, so triangulation made it possible to calculate the height of the phenomenon. Rossano's team found that the two infrared dots were located at 117 and 113 kilometers altitude, respectively, just before the peak optical brightness.

These infrared dots possibly represent the ablation of organic matter. If true, this result is important because meteors represent the bulk of infalling extraterrestrial matter, with the possible exception of very large but very rare asteroid and comet impacts. If a significant fraction of meteoritic organic matter survives in some form suitable for initiating interesting organic chemistry on Earth's surface, then meteors might represent the dominant pathway for transforming organic matter in comets and asteroids to early life on our planet.

Unusual Conditions in the Meteor

In order to understand what happens to organic molecules once they evaporate, we must understand the physical conditions in the meteor itself. After the 1998 Leonid MAC mission, we discovered that the light that we see does not come from the actual evaporation, but from a warm wake just behind the meteoroid. During that mission, Mike Wilson of NASA's Ames Research Center and the author used a cooled unintensified CCD camera with an objective grating to measure the meteor's visible light intensity. The spectra we obtained are so detailed that the measurement can be compared directly with models of air plasmas. Christophe Laux and Denis Packan of Stanford University calculated that a temperature of about 4000° C matches the data best. This is a surprisingly low temperature, given that Leonid meteoroids are faster than meteoroids of any other shower, so the collisions with air molecules are extremely violent.

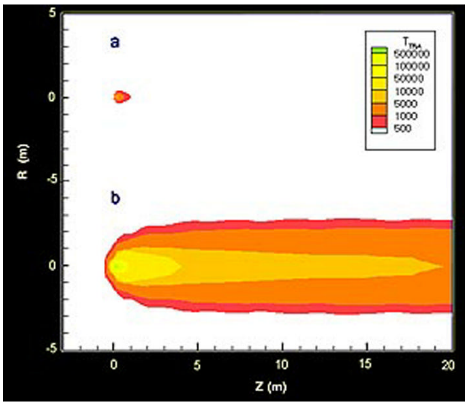


Figure 8 : *A Monte-Carlo model of air flow in a meteoroid. The different colors show different temperatures. Case (a) includes no ablation, case (b) includes ablation.*

To understand this relatively cool temperature, Iain Boyd of the University of Michigan created a meteor model using statistical calculations to follow the trajectory of individual air molecules and ablated material from the meteoroid. At the same time, Olga Popova of Moscow's Institute for Dynamics of Geospheres RAS calculated what physical conditions may exist near the meteor's head, where air molecules sputter off meteoric material.

Our results paint a fascinating picture of a meteor. Each impacting air molecule knocks off up to 40 molecules and atoms from the meteoroid. This interaction creates a small spherical cloud of dust and gas following the meteoroid on its downward path. The cloud is much bigger than the meteoroid in volume, so more air molecules interact with this "vapor cloud" than with the meteoroid itself. Most collisions occur on the outer edges of the cloud, away from the line of motion, because that is where the surface area is biggest. Secondary collisions inside the vapor cloud then gently knock out the colder vapor near the surface of the meteoroid. This slowed down meteoric vapor then mixes with the heated air but keeps its cool by expanding ten times in size into a warm 4000° C plasma right behind the particle. The light we see from a meteor originates in this wake. The wake itself cools off quickly, so the organic molecules will endure only a limited number of violent collisions. This process opens new pathways for organic molecules to survive the plunge through the atmosphere. We may owe our very existence to the details of this interaction.

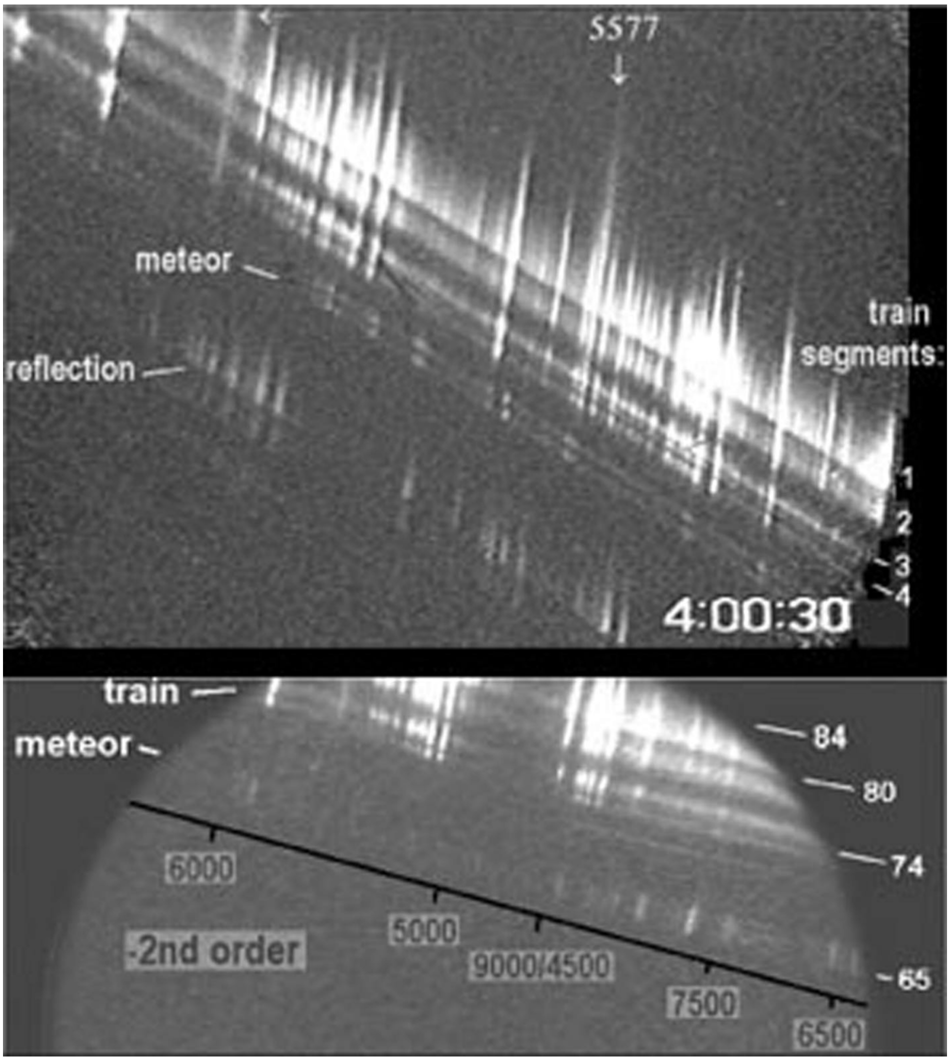


Figure 9 : *Two video frames from the 04:00:29 UT "Y2K" fireball. A grating in front of the camera creates a spectrum of the meteor and of its afterglow. Notice the different spectral lines in meteor and afterglow.*

The Organic Fingerprint

There are other ways organic matter can survive the violent passage through Earth’s atmosphere. As the Leonid MAC aircraft flew over the island of Corsica at 04:00:29 UT, November 18, 1999, a fireball as bright as the full Moon lit up the sky. The 1-kilogram meteoroid responsible for this fireball carried enough kinetic energy so that every single molecular bond could be broken a thousand times.

Meteor spectroscopist Jiri Borovicka of Ondřejov Observatory and I obtained spectra of this afterglow that show a series of parallel images of the meteor. Each image represents the afterglow as seen in a specific color of light emitted by a single atomic species. The emissions are interrupted at least four times with a sharp edge, possibly because the 12-centimeter-diameter meteoroid was spinning and thus broke up unevenly. The meteor emissions lack some of the usual atmospheric emission lines and only come from meteoric metal atoms. This data is consistent with the process of secondary ablation, where atoms evaporate from small debris fragments that are left in the wake of a fireball.

Borovicka also discovered a red glow spreading over many wavelengths — the signature of solid matter. The character of that emission implies a temperature of 1100° C, which would be the first measurement of the melting temperature of cometary matter. It is in fact close to the melting temperature of primitive asteroidal material. To our knowledge, this is the first time anyone has established the formation of meteoric debris as high as 84 kilometers, as determined from the stereoscopic view of both aircraft. Further observations of the afterglow could shed light on how much debris can survive this process in even larger cometary fragments.

Once the afterglow had faded, a persistent emission remained that was visible for at least 11 minutes. Upper atmosphere winds carved the train into the shape of the numeral “2” and immediately it was called the Y2K train. The aircraft operators quickly changed course and put the train in view of the researchers. Ray Russell and George Rossano of Aerospace Corporation pointed their mid-infrared spectrograph at the train to study how the collisions with air molecules may have changed the air composition. They discovered an emission feature at 3.4 microns that has much the same shape as the fingerprint of organic matter found in comet dust.

This finding suggests that organic matter survived more or less intact in the solid debris. Indeed, organic matter in comet dust is intimately mixed with mineral grains. This mechanism offers yet another pathway for organic matter in meteoroids to survive the meteor phase.

A Glowing Effect

Any story on the Leonid storms would not be complete without mentioning some tantalizing atmospheric phenomena observed during the 1999 storm, which had a positively glowing effect on Earth’s atmosphere. At the peak of the storm, Mike Taylor and Japanese scientists Hajime Yano and Shinsuke Abe onboard Leonid MAC started recording an unusually large number of elves and sprites, which are lightning-induced flashes of light in the upper atmosphere, just below the meteor layer. At the same time, physicist Joe

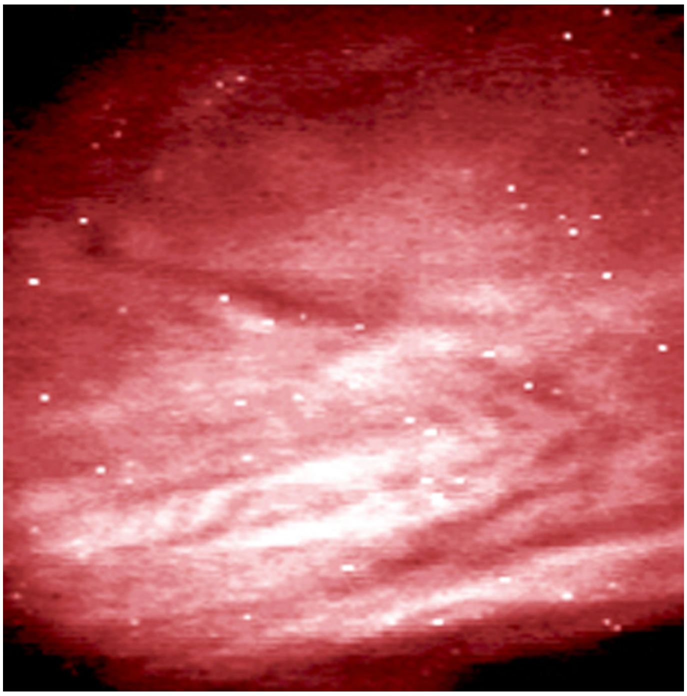


Figure 10 (left) : *Persistent train of the 19h13m53s UT fireball of November 17, 1998. By Kazumi Terakubo (FAS). Exposure of 15 sec. From Narusawa village (Yamanashi pref. Japan) on Fuji Super G Ace800 (ISO 800).*

Figure 11 (right) : *OH airglow at near-infrared wavelengths measured by Joe Kristl and Mike Taylor from FISTA.*

Kristl and colleagues of Stewart Radiance Laboratory near Boston measured that the nighttime hydroxyl airglow became 30% brighter during the storm. With only one case study in hand, we cannot be certain that the meteor storm was responsible for the observed increase in OH, or had anything to do with the observed elves and sprites. These are just a few reasons why we need to continue these studies and validate results from our one prior Leonid storm encounter. With the 2001 and 2002 Leonid storms ahead of us, we have an opportunity to further develop the models of comet dust trails, meteor ablation, persistent trains, and the influence of meteoric matter and meteors on Earth's atmosphere. Further Leonid MAC missions are being organized, with flights to Guam in 2001 and over the continental United States in 2002. Other astronomers will join the effort from observatories and other sites on the ground. My hope is to understand someday the complex chemistry of organic matter in meteors that may have set the stage for the chemistry that led to the first living organism on Earth.

Persistent trains

Leonids are famous for producing persistent trains, a luminescent glow in the path of an unusually bright meteor that persists for a few tens of seconds to several minutes. NASA Ames Astrobiology Academy student Matt Lacey and the author discovered during the 1999 Leonid MAC mission that most of the eerie yellow-orange glow of persistent trains is caused by a broad emission across many wavelengths, which was identified as the emission of iron oxide by John Plane and colleagues of the University of East Anglia in England.

Lacey used a small telescope coupled to a spectrograph via an optical fiber, developed at Ames, and was wearing a video headset display to help point the instrument. The luminescent glow is caused by the same type of chemistry that is responsible for the natural airglow emission of sodium, except that now the iron atoms in the meteor train catalyze the reaction of ambient ozone molecules and oxygen atoms in the train. This makes persistent trains an ideal laboratory to study such chemical reactions.

Scientists have developed the first models of persistent trains, but much remains unknown about Leonid trains: How are they caused? What accounts for their dark centers, their rate of expansion, their turbulent structure? Future work will benefit from good imaging with short (less than 10 second) exposures, best with intensified video cameras zoomed in to a 2° to 5° field of view. This too is a project that is within reach of amateur astronomers.