Meteoritics & Planetary Science 35, 647–649 (2000)
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Fire in the sky: The 1999 Leonid multi-instrument aircraft campaign (MAC)

On 1999 November 17, the skies over the Middle East gave a spectacular display of meteors with a rate of ~70 per minute during the peak of the Leonid storm that returns every 33 years. The Tel Aviv home base for this campaign became the logical site for the Leonid MAC-99 workshop held from 2000 April 16–19. For the second time (Jenniskens and Butow, 1999), a wide range of observers onboard two aircraft and on the ground gathered to study last year's Leonid storm. The time of the peak activity in the storm was predicted with an error of only five minutes, which means that looking for meteors has moved from guesswork to science. This predictive power is important to be able to protect our satellites in Earth orbit from damage by these fast-moving (72 km/s) meteoroids. This time the participants of the 1998 Leonid MAC campaign came with experience and expectations, which has paid off handsomely particularly in the area of astrobiology. The latest radar observations show that ablation of Leonid meteors begins at ~200 km altitude where there is almost no air and well above the 130–100 km altitudes of the visible meteors. One possible interpretation is ablation of volatile hydrocarbon materials at these very high altitudes. This may offer a clue why particles consisting of carbon, hydrogen, oxygen, and nitrogen (Halley's CHON particles) have yet to be collected among the chondritic interplanetary dust particles in the lower stratosphere. This second Leonid MAC campaign also observed "diffuse meteors" (*i.e.*, almost comet-like objects with "jets" above ~150 km). They evolved into the familiar "sharp" fireballs at altitudes below ~130 km. The most recent mid-infrared spectroscopy observations hint at CO_2, H_2O, and "organic material" or CH_4 in Leonid meteors and their persistent trains. The source of Na in Leonid meteors is not yet fully settled, and atmospheric chemistry may be involved to create the seemingly high-Na contents. Yet, careful monitoring of Na during ablation showed that Na in these meteors is locked up in two different reservoirs, *viz.* volatile organic materials and "refractory" silicates. Materials from a wide range of solar system objects reach the Earth's atmosphere where they enter a black box out from which a fraction reaches environments wherein we can collect the surviving debris. Two Leonid MAC campaigns are slowly opening this black box and provide new and exciting information of the atmospheric interactions between extraterrestrial materials decelerating in the Earth's atmosphere.

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The significance of lunar glasses

In the January 1970 issue of *Science*, the first reports were published on the direct investigation of lunar samples. Among the more fascinating results were the measured high concentrations of TiO_2 and the anhydrous nature of the material returned compared to terrestrial magmas. On the other side, glasses are abundant in mature lunar soils. Pristine lunar glasses are also formed by several processes, such as volcanism (lava fountaining) or impacts. The continued bombardment with high energetic particles leads to the formation of glassy patches, the size of which is a function of the dimensions and energy of the impacting particles. The melting glass may glue together soil components forming "agglutinates." The nine lunar missions (six Apollo and three Luna) brought back material for direct investigation in our laboratories. In addition, in the last decades lunar meteorites have been collected and recognised to have originated from the Moon, enlarging the suite of lithologies accessible for detailed examination. Some extraordinary samples were found to be of special interest to the scientific community, especially glasses. Among them were the green glass of Apollo 15 and the orange glass of Apollo 17.

In the last 30 years, enormous efforts have been put into the investigation of the composition of the different samples, and the analysis of the distribution of ages to unravel the history of lunar material for the understanding, for example, the formation of the magmas leading to the sampled basalts. Authors have searched for answers to questions like: When did the early differentiation take place? When did the lunar oceans and their cumulates form? When did the magmatism leading to the formation of highland material occur? When did the primary anorthositic crust form? And what was the history of all the collected glasses? Many models have been presented in the past explaining the results obtained by the quantity of perfomed investigations. The best model must fulfill all the restrictions regarding time sequence, density, viscosity (magma oceans forming cumulates followed by later sinking), energy considerations (time of melting, remelting, or partial melting), or whether volcanism formed all the varieties of samples collected from the lunar surface. Some authors have pointed out that pristine glasses are better candidates to define the composition of primary magmas than well-crystallised specimens.

For the characterisation of lunar samples, their concentrations of TiO_2 are important. Mare basalts, the dominant rock type of the nine lunar missions, show a bimodal distribution of this element. The high-Ti samples can not be the result of direct crystallisation from a primary magma.

When we want to understand the formation of the lunar crust, we need also to comprehend the origin and importance of the different types of glass.

The origin of ultramafic glasses is not easily explained. Several hypotheses have been brought forward for the origin of high-Ti ultramafic glasses. Among them are cumulate remelting, overturning of stratigraphic layers, assimilation of ilmenite and high-Ca pyroxene in the proper ratio into low-Ti ultramafic primary magma, or a combination of several parts of the mentioned models. So, the final answer is still open to debate, and it is important to continue the research dealing with problems of formation of the different lithologies with the goal of modelling the composition of all the returned lunar materials at hand.

In this sense, the contribution of van Orman and Grove in this volume gives an additional insight into the complex fractionation processes needed to explain and model all the minerals and glasses of the samples in our collections that have originated from our closest neighbour in the solar system.

In contrast to other authors, they claim that the composition of the high-Ti glasses must be the result of the source region, a hybrid source containing orthopyroxene and olivine as well as clinopyroxene and ilmenite. Their conclusion is also based on melting experiments under high pressure in which Longhi (1996) produced liquids containing up to 21% of TiO$_2$.

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Primitive R3 material

A major problem in studying chondritic meteorites is distinguishing primary nebular features from features caused by parent-body modification. Fortunately, we have the type-3 chondrites, rocks that have experienced minimal amounts of thermal metamorphism, aqueous alteration, and, in most cases, shock metamorphism. These rocks offer us a chance to learn about nebular processes and deduce the nature of asteroidal alteration.

About 2% of ordinary chondrites are petrologic type ≤3.5 and can be considered reasonably pristine. All of the CO and CV chondrites are type 3; the reduced CV chondrites (notably, Vigarano) and three CO3 chondrites (Yamato (Y)-81020, Allan Hills (ALH) A77307, and Colony) represent the most pristine materials among carbonaceous chondrites. (Although some nebular effects can be inferred from CI, CM, and CR chondrites, severe aqueous alteration has altered their matrices and modified or destroyed their chondrules. Among CK chondrites, all the rocks are type 4–6.) Among enstatite chondrites, many relatively pristine EH3 (*e.g.*, Qingzhen, Y-6901) and EL3 (*e.g.*, Elephant Moraine 90299, Queen Alexandra Range 93551) samples have been recently identified.

Our chances of inferring nebular processes for the R-chondrite formation location have been hampered by the paucity of pristine R3 material. Most R chondrites are type 3.8–4; some breccias contain large R5 and R6 clasts. Although one R chondrite, ALH 85151, is type 3.6, the sample is small (13.9 g) and significantly shocked. However, there is some primitive type-3 material in R-chondrite breccias as noted by previous investigators. Bischoff (2000) has studied two new R chondrites (Dar al Gani 013 and Hughes 030) and reported the characteristics of seven R3 clasts. His paper serves as the best available description of R3 materials while we wait for the fall of a large R3.0 chondrite in Ed Scott's backyard.

Primitive R3 material is characterized by 400 μm size chondrules of all textural types exhibiting a flat olivine compositional distribution ranging from Fa$_{<1-45}$. The chondrules are surrounded by matrix material containing very ferroan olivine (generally Fa$_{>50}$) and small grains of sulfide, Ti-bearing Cr-rich spinel, plagioclase (An$_{\sim 6-16}$), and Ca-pyroxene. Little metallic Fe,Ni is present.

The R-chondrite chondrule–matrix modal abundance ratio is close to unity, similar to those of CO (~1.1) and CV (~0.9) chondrites and appreciably lower than that in ordinary chondrites (approximately 5–6). But the similarity to carbonaceous chondrites is mainly confined to this ratio; the abundance of refractory inclusions is intermediate between carbonaceous and ordinary chondrites (Russell, 1998), and most other R-chondrite properties suggest a closer connection to ordinary chondrites. These include similar refractory lithophile abundances, similar chondrule sizes and textures, and similar chondrule O-isotopic compositions. Greenwood *et al.* (2000) recently found similarities in the O-isotopic compositions of R- and LL-chondrite magnetite grains and suggested that both groups may have contained asteroidal water with the same Δ^{17}O.

The characterization of primitive materials provides vital information about conditions at different nebular locations. The more groups that are represented by type-3 material, the deeper our appreciation of the diversity of nebular processes. Bischoff's current study is a step in this direction.

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No meteorite is an island

> *No man is an island, entire of itself,*
> *Every man is a piece of the continent, a part of the main.*
> John Donne (1572–1631)

There are chondrites and there are chondrites. The carbonaceous chondrites, which so clearly preserve many early solar system signatures, are many cosmochemists' favourite meteorites. Ordinary chondrites, the most abundant meteorites to fall to Earth, are similarly well-studied. But enstatite chondrites, making up a mere ~1% of the chondrite population, tend to get overlooked. Two papers in this issue help to set the balance right.

Tim Fagan and his colleagues at the University of Hawai'i have studied calcium-aluminium-rich inclusions (CAIs) from unequilibrated enstatite chondrites. Calcium-aluminium-rich inclusions are a rarity in these Al-poor meteorites. Indeed, because CAIs are composed mainly of oxidised minerals and the majority of enstatite chondrite material is reduced, it is a puzzle that CAIs exist in this meteorite class at all. Fagan *et al.* (2000) point out that there is more than one explanation for their presence. Conditions in the enstatite chondrite forming region may have changed over time, perhaps because of fluctuations in the abundance of water, or alternatively the CAIs originated somewhere else and were then sprinkled into the enstatite-forming region before final accretion. (We could even speculate that CAIs in all meteorite classes have an exotic source, but only in the reduced enstatites do they stick out so clearly as being mineralogically distinct.)

Over on the other side of the world, a group from the Open University in the U.K. have also been beavering away on enstatite chondrites. Jason Newton (now at University of Tokyo) and colleagues have reanalysed the O-isotopic composition of several enstatite chondrites using a precise IR-laser fluorination technique. They found that, as expected, the O-isotopic composition of most of the chondrites fall on a trend that can be explained simply by mass fractionation from a single initial composition. However, four of