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Micrometeorites and the Origin of Life: A Broad Program to Study their Survival and Modification by Passage through the Earth's Atmosphere

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Abstract. We describe a novel method to study the physics of the interaction of micrometeorites (MMs) with the atmosphere and MMs as vehicles of organic molecules from space. We have begun a broad study of the relationship of MMS with comets and asteroids, the mechanisms of their interaction with the atmosphere, and their chemical and organic contents before, during, and after entering the atmosphere as part of a broad project related to the origin of life. Although space-based observations are required to achieve definitive results in this field, several gradual steps must be taken during a long-term program. These include balloon-borne experiments in conjunction with laboratory calibrations (to determine discriminating spectro-photometric signals), ground-based radar observations, and background measurements. In particular, we link this study to the EUSO telescope (on board the International Space Station) but is very general in approach. This project will be described addressing objectives, experimental approaches, and the scheduled activity.

Key words. Meteorites: track analysis – Meteorites: organic contents – Meteorites: radiating processes – Meteorites: observations – Astrobiology: prebiotic molecules

1. Introduction

How life emerged on the primitive Earth, and what might be possible in other close or remote planetary systems, remains one of the fundamental open problems of modern science. The picture has been developed along two divergent lines.

The first, beginning with A. Oparin and J.B.S. Haldane, proposes an endogenous origin. In this scenario, solar radiation in par-

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ticular UV radiation and electrical charges in the primordial atmosphere provided the energy source necessary for driving chemical synthesis of complex organic molecules (amino acids, bases, sugars, etc.). Once they had precipitated into the primordial hydrosphere, these complex molecules further evolved, eventually up to cells and simple micro-organisms. This scenario postulates a highly reducing atmosphere as the inital state for the Earth's atmosphere. Although the Miller and Urey experiment showed that, under the action of electrical charges, amino acids can effectively form in an atmosphere containing H_2O, CH_4, NH_3 and CO_2 (along with other organic compounds, such as HCN, H_2CO, and urea), current models describing the primordial atmosphere do not support this scenario. Instead, these models indicate that the primordial atmosphere was a weakly reducing mixture of N_2, CO_2 and H_2O plus lesser quantities of H_2, CO, SO_2 and H_2S. The models lack CH_4 and NH_3 and, with this composition, the atmospheric composition does not promote the formation of the complex organic molecules in particular HCN necessary for the emergence of life.

The alternate scenario posits exogenous origins, assuming that complex organic molecules capable of triggering pre-biotic synthesis of biochemical compounds may have been deposited on Earth by comets, meteorites, and/or interplanetary dust particles within about 800 Myr after the planet formed, most probably between the end of the heavy moons cometary bombardment and the appearance of the more ancient known microfossils. The efficiency of the delivery is a critical feature of the scenario, and its principal uncertainty, and this is what we propose to address.

Significant evidence exists for an extraterrestrial – possibly interstellar – origin for the organic material found on the early Earth. Observations show that comets are largely composed of interstellar matter that has not been modified by solar heating; indeed, up to 25% of the cometary mass is organic. Both water and HCN essential ingredients in pre-biotic "cuisine" are present and 3% of the organic carbon in meteorites is in the form of amino acids. In particular, amino acids extracted from the Murchinson meteorite show a very high D/H ratio compared to their terrestrial counterparts, suggesting an interstellar origin (the deuterium overabundance is a fingerprint of interstellar gas phase ion-molecular chemical reactions). Nucleobases and sugar-like molecules are also present in meteorites. Finally, nine of the known interstellar molecules are among the pre-biotic precursors of all the biochemical compounds present in living organisms.

In the *early exogenous* scenario, comets delivered organics to early Earth. However, delicate complex organics required for the origin of life cannot survive impact, so interplanetary dust particles, micrometeorites (MMs), and meteors, all of which at least partially survive atmospheric entry, should be considered (Maurette 1998). In particular, the "giant MMs with sizes ranging from 50 to 500 μm are thought to be the dominant source of extraterrestrial material currently accreted by Earth, around 5×10^4 times more than the amount delivered by meteorites. Giant MMs recovered from Antarctic ices have clearly survived their high velocity impact with the atmosphere, a conclusion supported by the detection of indigenous PAH in 200 MMs (Clemett et al. 1998). Matrajt et al. (2003) report that the distribution of carbon and nitrogen contained in Antarctic MMs are correlated and may come from organic material. Mineralogical analyses, chemical and isotopic analysis of the giant MMs indicate that these bodies represent a new population of solar system objects (Maurette et al. 2000). Thus, MMs may have been the dominant source of organic carbon that, on the primitive Earth, contributed to the origin of life. Here we describe a new comprehensive collaborative effort to study the physics and material science aspects of this problem and an extended plan for in-situ atmospheric (balloon) and satellite missions based on the laboratory studies.

2. The experimental stairway

2.1. Step 1. Simulation and modeling

The physics of the interaction of MMs with the atmosphere is far from clear. Thermal heating, ablation, shock waves, and fluorescence are possible sources of emission when MMs pass through the atmosphere. The parameters related to all of these processes have been estimated using laboratory simulations but the conditions for these experiments and their assumptions must be carefully checked since many of them are very uncertain. Calibration, background contribution, emission fluxes and ratios at different wavelengths are not known, as well as their actual fluxes and spatial distribution. An accurate study of these aspects is necessary for any experimental investigations and it will be carried out to identify the specific targets of the next steps, i.e., lab- and space-experiments.

2.2. Step 2. Lab experiments

The experimental investigation of MMs properties while passing through the atmosphere has been started with the construction of a simulator in our labs at the XUVLab - Dept. of Astronomy and Space Science in Florence and at Alta (formerly Centrospazio) in Pisa. In Florence, the simulator will consist of an experimental chamber that can be evacuated down to 10^{-11} mbar (the best would be 10^{-12} mbar but this is technically difficult and at the limit of vacuum technology) a very low-pressure (10^{-6} – 10^{-11} mbar) gas jet, an UV-VIS spectrometer and two imaging cameras: an IR camera and an UV-optical camera. A MM can be placed in the center of the vacuum chamber and the gas flow simulates its transit through the atmosphere at different pressures, that is different altitudes. The cameras and the spectrometer will record all the image and spectral features, thus providing information on the emitting mechanisms and the main signatures of elements included in the MMs. Meteorite samples from Antarctica could be used or those embedded in the components retrieved from space telescopes or experiments. In the Ata plasma wind tunnel, originally designed for ion engine design and testing and satellite re-entry simulations – we will be simulating the initial stages of meteor entry into the exosphere at approximately the same environmental thermodynamic and dynamical conditions. Instead of using thermal and/or laser flashing, this heating by ion interactions will more closely approach the processes acting during the early stages of MMs entry.

2.3. Step 3. Balloon-borne experiments

Balloon-borne experiments represent a preliminary in-situ measurement of both UV-IR-MW backgrounds and MM tracks. However, it is necessary first to have a clear idea of backgrounds and sources of confusion before attempting any MM measurement. Such measurements serve other purposes as well, for instance related to studies of atmospheric fluorescence induced by ultrahigh energy cosmic ray passage through the atmosphere. The backgrounds are diffuse atmospheric emission, light pollution from human activities, lightning, etc. These can be measured in the UV, IR and microwave bands using an experimental setup consisting of three downward-looking and three upward-looking cameras to discriminate between and find correlations among different emission sources. A separate experimental arrangement with improved sensitivity, fast tracking and imaging capabilities can be operated using a balloon. We have begun feasibility studies of a tri-band measurement system (similar to the background measurement) against single-band measurement. The latter means a series of flights measuring MM tracks: the disadvantage is non-contemporaneous measurements but the advantage is increased event statistics, if we assume that each MM emits always in the three wavelength bands.

2.4. Step 4. Micro-satellites

Micro-satellites (MS) offer a very good opportunity to search for MM tracks. The instrument payload can be an improved version of the balloon model. Tri-band, imaging and spectroscopic measurements can be performed using the Airwatch/EUSO approach, i.e., very wide FOV and photon counting regime to measure very low fluxes, triggering of tracks disregarding background photons, must be used. Constraints are mass, below 100 kg, power and cost: the failure rate is around 50%. MS can be launched using Russian rockets, even if also Japan and China are starting launch programs for Agency or private MS. The advantage of MS is to measure MM tracks from top of the atmosphere looking downward. This requires measured values of backgrounds, so balloon-borne must anticipate space experiments. Another advantage is low typical costs and the possibility to launch a MS every year. Finally, MM track observations from orbiting MS is done on several orbits around the Earth, increasing observation time and providing measurements at different latitudes. We are currently studying several options in the near term (5-6 years). It could be possible to have the first MS flight before 5-6 years and the flight duration can be as long as needed, depending on the selected orbit and the observation time to achieve the required statistics. Other options are passive (observational studies) from sounding rockets or the International Space Station (ISS) and to orbital satellite or ISS instruments to capture MMs before they enter the atmosphere to study presence, abundance and features of organic molecules. We are studying possible MSs based on using an aerogel block to trap impinging MMs with subsequent in situ mass spectrometer analysis, imaging cameras, and spectrometers in our principal 3 wavelength bands. With recoverables, the samples could be subsequently delivered to ground-based labs for further analyses.

2.5. Step 5. EUSO-like telescope

EUSO is a telescope to detect ultra-high energy cosmic rays that should be launched after 2011. This serendipitously presents an opportunity to carry out improved imaging measurement of MM tracks. EUSO is a large aperture (2 m) and very wide FOV telescope (60 degree) with good angular resolution (6 arcmin) and photon counting capabilities to detect signals above 5 photons in a 2 msec unit gate time. This telescope will be placed on the ISS, looking downward from 400 km, for 3 years (with a possible extension to 5 years). A thorough analysis must be done to understand if MM observation from EUSO is feasible because the trigger system is optimized for ultra-fast events like cosmic rays: these emits UV fluorescence light during a 100-200 msec time lapse, which is very short compared to the MM emission. Our laboratory simulations will be used to determine the UV component of the MM emission during their transit in the atmosphere.

3. Conclusions

We have begun many of the proposed steps in this long-term, wide-ranging program but many parts remain to be properly scoped. With this first public presentation, we strongly recommend that international working groups (within ESA and other agencies) deal with this challenging and exciting long-term program with proper human and financial resources. National research institutions in Italy – INAF, INFN, and Universities – are linking their efforts and we propose to collaborate with ESA to make all of the described steps and other ideas possible.

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