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DETECTION OF VOLATILES IN COMETARY METEOROIDS USING IR METEOR SPECTROSCOPY

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ABSTRACT

There is a need to develop an IR spectrograph for SOFIA's Upper Deck in order to study the interaction of meteoroids with the upper atmosphere and related phenomena. No infrared spectra of meteors have yet been obtained despite their intrinsic scientific interest. SOFIA offers a unique capability for such observations over a long enough period of time to sample sufficient meteors. If successfully applied, the technique of IR meteor spectroscopy can provide valuable information on the volatile content of meteoroids and also on the processes related to the fate of organics during the ablation of meteoroids in the Earth’s atmosphere.

INTRODUCTION

Comets are composed of ices, dust and organic material (see e.g. Jessberger et al., 1988; Greenberg & Li, 1999; Greenberg, 2000). The role of comets in bringing a major fraction of the volatiles to the forming Earth has often been proposed but has been difficult to establish with certainty (Oró, 1961; Delsemme 2000). Previous studies gave detailed consideration only to the delivery of organic matter through direct impacts with large comets or asteroids, but we can expect that dense cometary streams also played an important role in the delivery of volatiles to the Earth (Jenniskens et al., 2000, Trigo-Rodríguez et al., 2004a). In a similar way, because cometary nuclei are formed by a diversity of materials including organics and ices, the fragments released from these nuclei should be also rich in these compounds. Our knowledge of the presence of organics and volatiles in cometary meteoroids is meager. Giotto spacecraft analyses of the dust of comet 1P/Halley revealed a large abundance of organic particles, called CHON, an acronym of the four dominant chemical elements that are forming them (Kissel et al., 1986; Jessberger et al., 1988a,b). Future missions to obtain in-situ samples of cometary matter are planned but beyond the economic cost, they can only provide information of a particular object, even when we know the huge variability in the properties from comet to comet (Delsemme, 2000). The advances obtained in the last decade in meteor spectroscopy enable this technique to serve as a complement to expensive missions allowing the study of the spectra and orbits of cometary meteoroids reaching the Earth from different sources. Moreover, by using meteor spectroscopy we are able to understand better some of the mechanisms that regulate the entry of cometary matter to the Earth and the survival of volatile compounds of astrobiological significance (Jenniskens, 2004a,b,c).

UNVEILING THE CHEMISTRY OF METEOR COLUMNS.

The study of ablation columns of meteoroids using photographic and video spectroscopy in the visible has provided important information about the temperature and composition of the mineral phases forming meteoroids (Borovicka, 1993, 1994; Borovicka et al., 1999; Trigo-Rodríguez et al., 2003, 2004b). Unfortunately, these techniques are not able to provide us detailed information about the chemical evolution of the organics that are presumably present in these meteoroids. In fact, meteoroids should be rich in organics. Levasseur-Regourd et al. (2000) demonstrated that organic carbon is able to survive exposure to the vacuum of space during relatively long time scales at the typical temperatures existing at 1 A.U. Despite this, the detection of organic matter in meteors continues to be elusive although the application of high-resolution CCD spectroscopy of air plasma emissions and a better theoretical knowledge of the associated chemistry in these high temperature rarefied flow conditions have offered the first clues (Jenniskens et al., 2004a). All seems to point towards organic matter surviving in the form of large molecules.

Application of IR techniques to study the generic organic mid-IR vibration bands can be a new step to obtain direct information on the survival of volatiles and organic matter in meteoric columns. The ideal wavelength range covered by this instrument would be in the range of 1 to 20 μm with a resolution between 0.1 to 0.01 μm in order to register the emission and absorption bands of the principal expected volatiles. A spectrograph sensitive to these wavelengths could be located in the Upper Deck of the airplane (Jenniskens et al., 2004d). The instrument has to have a wide field and sufficient temporal resolution to make possible the study of the temperature evolution of the meteor columns.

SOFIA’s high cruising altitude provides excellent conditions for spectroscopy in the near- and mid-IR, particularly with low absorption in the water vapor bands that can be useful in studying the presence of water and other volatiles in cometary meteoroids. The large number of flight hours would increase our chances of capturing a bright enough meteor, and could in principle permit the study of many different meteor showers.

The possibility to develop a spectrograph with these characteristics is exciting because no direct IR spectra of meteors have yet been obtained despite consistent efforts during the Leonid MAC missions. This is an important reason to propose a project with these objectives to be placed on board SOFIA. Rossano et al. (2000) and Peterson et al. (2003) did detect meteors in mid-IR cameras, but so far no bright enough meteor passed the field of view of the spectrographs. The main problem is the difficulty of capturing signals through IR sensors with small field of view that have sufficient resolution and sensitivity. Moreover, a spectrograph distributes the available light over a wide range of wavelengths so that only a small fraction of the available light totally falls within one spectral line. Consequently to obtain a particular signal to noise ratio in faint lines we need very sensitive spectrographs or high beam filling factor (large telescopes) to avoid constraining our study to very bright and consequently infrequent meteors. We will discuss both possibilities separately.

The unpredictability, velocity and short duration of meteors so far allowed observations and spectra to be made only of bright persistent trains to which an instrument could be pointed (Russell et al., 2000). Indeed, the SOFIA telescope could be used in this manner to study bright fireball trains. Any specific project to study fireball trains during some expected meteor activity outburst would be of great interest.

In contrast, the small field of view makes it very unlikely to register a meteor directly. In fact, only a few optical meteor spectra have been obtained until now through large optical telescopes and practically all of them by chance. The most valuable have been the high-resolution spectra. One example being the possible first detection in this manner of lithium in the spectrum of a fireball registered over Spain on 1988 December 18/19 (Borovicka & Zamorano, 1995). Another example is the recent near-IR spectrum captured by the ESO/VLT telescope, which extended the range of known meteor spectra to 1050 nm (Jenniskens et al., 2004e).

POTENTIAL RESEARCH LINES IN IR METEOR SPECTROSCOPY.

In this section I present some examples of the different research fields involved in the use of IR techniques. Pioneer work in the detection of meteors in mid-IR is relatively recent and was made during the 1998 Leonid Multi-instrument Aircraft Campaign (Leonid MAC) (Rossano et al., 2000). One year later, the first mid-IR spectra of persistent trains with probable identification of CH_4, CO, CO_2 and H_2O species were obtained from the 1999 Leonid MAC (Russell et al., 2000). Although these authors proposed the condensation of such volatiles after the pass of the meteor when the temperature in the gaseous column was about 300K, recent observations (Jenniskens et al., 2004a) propose that some of these molecules or even more complex organic compounds would survive to the ablation phase. High-resolution IR spectroscopy of meteor columns using SOFIA could confirm if molecules contained in the meteoroids are able to survive or if they are broken into more simple molecules. Additional simultaneous observations in the range of 780-840 nm can provide information on the presence of the OH Meinel Band that has been recently proposed as linked to the presence of water in meteoroids (Jenniskens et al., 2004c). The understanding of the mechanisms that participate in the production of these radicals could provide new ideas of the role of meteors in the enrichment of organics of the early Earth (Jenniskens et al., 2004b).

The particular chemistry of meteor columns is still partially unknown, especially the presence of volatiles that produce particular emissions or absorptions of part of the outgoing infrared radiation. We can identify from an accurate spectrum the energy levels of molecular vibrations and rotations of these volatiles. Incorporating the study of temporal evolution of the train after the pass of the meteor head is particularly relevant for studying the possible formation of molecules at particular temperatures. In this sense, the probable detection of methane in fireball trains is an exciting result (Russell et al., 2000). Is it preserved from the meteoroid or formed under a particular catalytic process? To answer this question we need to know more details on the physical properties associated with the possible production of methane in the meteor column. If the methane was formed in the meteoric column, this would corroborate the formation of this compound and other hydrocarbons through Fischer-Tropsch reactions catalyzed on the surface of small metal Fe-Ni grains (Kress & McKay, 2003). This process has been proposed for fireball plumes but it could also be working in small meteoric columns. In fact, there is evidence that Fe-rich meteoric dust survive the ablation being produced in the meteoric column (Rietmeijer, 2001). In any case it is important to remark that the time available for reactions in the column of hot gas is very short and that the temperature interval where this kind of catalysis is produced also is very restricted (Kress & McKay, 2003). In fact, Borovicka & Jenniskens (2000) resolved temporally for the first time the evolution in the temperature of a Leonid fireball; they showed that the temperature in the meteoric column decreases quickly, going below 1000 K in a few seconds. This is an important reason to believe that cometary organics would be able to survive this process especially in a short period of diffusion of the meteoric vapors in the rarefied environment. This topic is of sufficient interest to be studied in more detail because methane and other hydrocarbons could be produced in this way. In fact, this study could have direct implications in the production of greenhouse gases in the earliest stages of the atmosphere of the Earth, when meteor phenomenon was more frequent and the atmospheric composition was probably more favorable for organic catalysis.

The ablation of a meteoroid produces a characteristic rarefied flow in the upper atmosphere where the physical conditions are too complicated to simulate in the laboratory. The high-velocity flow with probable heterogeneous temperature and rapid fragmentation of cometary particles can provide pathways to the survival of organic compounds. Meteoric vapors leaving the meteoroid during ablation are usually at temperatures in the range of 4000-4500 K (Trigo-Rodriguez et al., 2003; Jenniskens et al., 2004b) that are reached by air plasma just behind the meteoroid (Boyd, 2000). Borovicka (1993; 1994) demonstrated that these vapors are in local thermodynamic equilibrium and that the majority of the spectral lines can be modeled using a simple model of chemical equilibrium. Using these ideas as a basis, Trigo-Rodriguez et al. (2003) obtained the relative chemical abundances in meteor columns for a wide sample of meteoroids, obtaining results consistent with the hierarchical accretion model of dust formation proposed by Rietmeijer (2002). From spectroscopy in the visible we know that spectral lines associated with the wake are probably out of equilibrium (Borovicka, 1993; Trigo-Rodriguez et al., 2003). The study of the temporal evolution in the atmosphere of these wakes and also of long-endurance meteor trains using an IR-spectrograph would aid in understand the nature of the relevant chemical non-equilibrium processes.

All of these research lines are relevant and are of direct astrobiological significance in helping understand the origin of prebiotic molecules. I conclude that SOFIA's Upper Deck offers a unique capability to pursue the promising field of mid-IR meteor spectroscopy, with the promise to bring answers to the important question about how organic matter and other volatiles from minor bodies were delivered to the early Earth surface. Meteor spectroscopy in the IR can explore the role of these processes in the origin of life on Earth.

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