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Quantitative meteor spectroscopy: Elemental abundances

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Abstract

Procedures are outlined to derive from a meteor spectrum the elemental abundances of its meteoroid, with particular application to observations obtained by an unintensified cooled-CCD slit-less spectrograph. Results are given for two Leonid meteors observed during the 2001 encounter of Earth with dust ejected by comet 55P/Tempel-Tuttle in 1767. The spectra contain air plasma lines of N and O, and meteoric metal atom lines of Fe, Mg, Na, Ca, Si, Mn, Al, and Cr. Excitation conditions are investigated from the relative line intensity of Fe and N^+ lines. The elemental abundances, normalized to solar system abundances, show a striking correlation with condensation temperature, defined as the temperature at which 50% of elements in a cooling gas mixture with chondritic abundance have condensed into a solid phase. Iron is depleted by a factor of 3, magnesium, calcium, and aluminum by a factor of 8. I conclude that rapid evaporation keeps the mineral surface temperature at ~1150 K. Much of the refractory elements in these fast 71.6 km/s Leonid meteoroids are deposited in the form of solid meteoric debris rich in Mg, Ca, and Al.

Keywords: Meteor; Meteoroids; Meteor spectroscopy; Elemental abundances; Interplanetary dust; Cosmic dust; Leonids; Comet 55P/Tempel-Tuttle

1. Introduction

Quantitative meteor spectroscopy is the only tool for deriving elemental compositions of mm–cm sized cometary dust grains short of sample return. Such large grains were not studied in past flyby missions of comets Halley and Wild 2. Meteorites are known to contain distinct morphological structures in this size regime, called chondrules and calcium–aluminum rich Inclusions (CAI). Comets may contain similar structural units (Campins and Swindle, 1998). Variations in elemental composition, mineralogy, or morphological structure at this size scale can arise from processes such as cometesimal collisions and radio nuclear heating in the solar nebula at the time of the origin of the solar system, and primordial comet crust processing by cosmic rays during residence in the Oort cloud. Short of sample retrieval, the remote sensing of meteors is the only way to study these larger grains.

The measurement of meteoroid elemental abundances from photographic meteor spectra has a long history, but quantitative results have been published only recently. Most of the early work has focussed on identifying the dominant emission lines in bright fireballs. This work is reviewed by Ceplecha (1968) and Millman (1980), and in the study of individual meteor spectra by Halliday (1961), Ceplecha (1971), and Borovicka (1994a).

For a long time, a quantitative interpretation of meteor spectra was hampered by insufficient knowledge about the physical conditions in the radiating plasma. In bright fireball spectra, according to Ceplecha (1973), all strong emission lines are self-absorbed (optically thick). The emitted photons are absorbed by other atoms in the plasma before escaping. The observed emissions originate from that surface of the emitting volume from where the photons can escape without secondary absorption. The effective volume and temperature of the emitting plasma, as well as residual Doppler speed and line profile, are a function of the absorption cross section and the abundance of the emitting atom or molecule. Excitation

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conditions can change at different depths in the plasma. If so, abundances cannot be derived from curve-of-growth analysis of emission lines from a given element relative to the curve-of-growth of iron (Ceplecha, 1964, 1973). Ceplecha showed that these problems were significant for meteors brighter than about magnitude −2 or −1, although meteors as faint as +5 magnitude were found to have certain emission lines that are not optically thin. Borovicka (1993) found a limit at +3 magnitude for the strong resonant 372-nm line of iron.

The alternative explanation for the observed line ratios was to assume that lines originating from a lower excited energy state originated from a larger region around the meteor, but this led to disagreement in the computed intensity of the iron emission and was deemed physically unrealistic by Brönshten (1983).

In recent years, Borovicka (1993, 1994b), Jenniskens et al. (2000b), and Trigo-Rodriguez et al. (2003) revisited the assumption of an optically thick plasma out of thermal equilibrium, arguing that most weaker lines are not self absorbed, following Harvey (1973) and Nagasawa (1978). Borovicka found reasonable metal atom abundances for one particular deeply penetrating and relatively large ~60 kg meteoroid EN151068 (−8.5 magnitude, entering Earth's atmosphere at an apparent speed of 19 km/s). Interestingly, the abundances along this fireball's path changed in a manner indicative of differential ablation. An electronic excitation temperature for iron of $T_e = 4390$ K was derived.

Because of their higher quantum efficiency, modern unintensified cooled CCD cameras typically observe meteors 5 magnitudes fainter than the bright fireballs studied by photography. This enables the study of the fainter lines that are not self-absorbed (Cook et al., 1971; Ceplecha, 1973). Moreover, fainter meteors have different flow conditions. They do not form shocks, but are in a rarefied or transitional flow regime when the meteoroids are smaller than the mean-free path at altitude. Cooled CCD-cameras were first used to study the excitation conditions in the air plasma. I found before, that the air plasma emissions are well characterized by optically thin emission from a local thermodynamic plasma in near chemical equilibrium, with an excitation temperature of $T_e = 4340 \pm 20$ K. This temperature does not greatly change with meteor mass or speed (Jenniskens et al., 2000b, 2004a). If indeed the atomic excitations are well characterized by one temperature, and the lines remain optically thin, then this implies that accurate metal atom abundances can be derived from line ratios in meteor spectra.

This paper investigates the excitation conditions of the emission lines in the spectra of two Leonids captured during the 2001 Leonid Multi-Aircraft Campaign mission. This is my first quantitative analysis of the metal atom emission lines from meteor spectra obtained by an unintensified cooled-CCD camera and for that purpose I outline the reduction procedures specific to this type of observation.

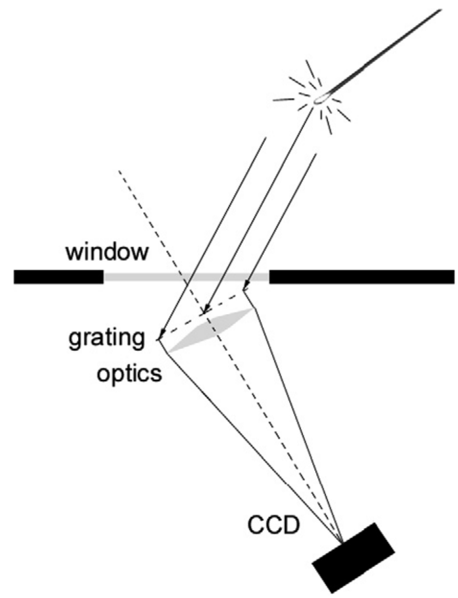

Fig. 1. Camera layout and observing geometry.

2. The instrument

The spectra were obtained with a Pixelvision scientific grade CCD camera with a two-stage thermoelectrically cooled 1024 × 1024 pixel back illuminated SI003AB CCD with 24 × 24 micron pixel size (24.5 × 24.5 mm image region). The CCD images are recorded in 16 bit counting units, called "ADU". The camera was equipped with an AF-S Nikkor f2.8/300D IF-ED 300-mm telephoto lens, providing a 4.7° field of view of the star background.

Directly in front of the camera was mounted an 11 × 11 cm plane transmission grating on 12 mm BK7 substrate (#35-54-20-660 by Richardson Grating Laboratory). The spectrum of a meteor can be observed when it occurs in a strip of sky 4.7° wide and up to 88.6° away from the zero-order viewing direction (Fig. 1). The grating dispersion is 600 l/mm and the blaze wavelength in 1st order is 540 nm (blaze angle 34°). This provides a full 2nd order spectrum out to ~925 nm, albeit with progressively lower response at higher wavelength due to the geometric dilution with increasing viewing angle away from the source (Fig. 1). The lens is transparent to light of wavelengths larger than about 360 nm. There is 3rd order line overlap in the 2nd order spectrum above 3/2 × 360 = 540 nm.

A 0.1 s exposure resulted in a limiting star magnitude of +10.6. Because of their higher angular velocity, the limiting magnitude for meteors was about +5.7, while spectra are recorded for meteors brighter than about +4 magnitude. Good signal-to-noise data are obtained for meteors with an apparent brightness better than −2 magnitude, or a factor of 100 less intense than traditional results from photographic techniques.