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A spectral analysis of ablating meteors

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ABSTRACT

Meteor ablation features in the spectral lines occurring at 394, 436, 520, and 589 nm were observed using a four-camera spectral system between September and December 2015. In conjunction with this multi-camera system the Canadian Automated Meteor Observatory was used to observe the orbital parameters and fragmentation of these meteors. In total, 95 light curves with complete data in the 520 and 589 nm filters were analyzed; some also had partial or complete data in the 394 nm filter, but no usable data was collected with the 436 nm filter. Of the 95 events, 70 exhibited some degree of differential ablation, and in all except 3 of these 70 events the 589 nm filter started or ended sooner compared with the 520 nm filter, indicating early ablation at the 589 nm wavelength. In the majority of cases the meteor showed evidence of fragmentation regardless of the type of ablation (differential or uniform). A surprising result was the lack of correlation found concerning the K_B parameter, linked to meteoroid strength, and differential ablation. In addition, 22 shower-associated meteors were observed; Geminids showed mainly slight differential ablation, while Taurids were more likely to ablate uniformly.

1. Introduction

When meteoroids collide with the atmosphere they produce light mainly by excitation of atoms, with much of the light coming from specific metal lines. The brightest lines in the spectra of faint meteors tend to be sodium (Na I ~ 589 nm), magnesium (Mg I ~ 520 nm), iron (Fe I ~ 436 nm) and calcium (Ca II ~ 394 nm) (Borovička et al., 2005; Vojáček et al., 2015); these elements are not normally the main constituents of the meteoroid, but they are important tracers for the minerals which are present. Borovička (2007) has used the ratio of brightness between the iron, magnesium, and sodium lines to categorise meteors of different origin. This analysis is complicated by the need to model the line emission to determine the relative quantities of each element.

In addition to bulk composition, the spectrum of a meteor as a function of time can be used to look for differential ablation and fractionation of meteoroid minerals when the meteor is melting and vaporizing, as predicted by models (McNeil et al., 1998). Sodium is often seen to ablate earlier than magnesium and iron (Borovička, 2006), an example of differential ablation whereby the constituents of the meteor ablate in stages instead of all at once. Studies of Leonid meteors (Borovička et al., 1999; Murray and Beech, 1998) show mainly early ablation of sodium compared to magnesium, though some show uniform ablation, where the meteor ablates its material non-discriminately (uniformly) instead of in stages; Taurids, on the other hand, have been found to have Na curves which closely follow the Mg curve (Borovička, 2001). It is because of the ablation properties of sodium and magnesium that throughout this study a comparison is often performed between the 520 and 589 nm light curves to highlight the differences in ablation, assuming these curves embody the characteristics of neutral magnesium at 520 nm (Mg I) and neutral sodium at 589 nm (Na I) respectively.

The ablation of meteors is strongly influenced by the way in which they fragment during their descent, and may have a significant effect on differential ablation, since exposure to heating of the whole meteoroid may allow for the more volatile constituents to completely fractionate and evaporate early. Subasinghe et al. (2016) found, using the high-resolution tracking system on the Canadian Automated Meteor Observatory, that approximately 90% of meteors display some degree of fragmentation.

The relative volatility or strength of a meteoroid can also be measured with the K_B parameter (Ceplecha, 1967, 1988), which takes into account the begin height corrected for the meteor speed and entry angle. Furthermore Ceplecha (1967) defined the K_B parameter in such a way that it depends on two factors: the ratio of the temperature needed for intensive ablation and the heat transfer coefficient (objects with more intensive ablation at lower temperatures have lower values of K_B), and a density/specific heat term (this increases the K_B parameter for

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denser objects which need more energy to ablate). While the volatility is not directly included in these calculations, if the object fragments however, the heat transfer coefficient will effectively increase because of the increase in surface area, causing the meteor to appear more volatile. For this reason we considered meteors that began at larger heights and had low K_B parameters, compared to other meteors at the same speed, as being more volatile in nature.

In this paper, we investigate the properties of ablating meteors by observing the filtered wavelength range of meteors at 394, 436, 520, and 589 nm, for meteors observed with the CAMO tracking system. In particular, we look for relationships between differential ablation and fragmentation behaviour, and differential ablation and corrected begin height. It should be mentioned that since this study did not involve the use of a camera with grating there was no way to validate the chemical species detected by the filtered cameras. Future studies will be sure to include the use of a grating system to confirm the observations. This study does however provide a new method for observing meteor spectra.

2. Observations

A four-camera spectral system was constructed to observe ablation features in the spectral lines at 394, 436, 520, and 589 nm. The system was co-located with the Canadian Automated Meteor Observatory (CAMO), at the Elginfield, Ontario, Canada site. Three of the four cameras (at 436, 520, and 589 nm) used COHU - 4910 Series monochrome CCD cameras (30 interlaced frames per second, standard NTSC video), lens coupled to Gen III ITT NiteCam image intensifiers, and the 394 nm camera used an Intensified Retiga Fast 1394 Digital CCD camera (10 progressively scanned frames per second, 1392×1040 pixel image size). The Retiga camera has an integrated Gen III ITT image intensifier with extended blue photosensitivity, since the sensitivity of the standard Gen III intensifiers falls off sharply shorter than 500 nm, and an initial test of the system in 2014 demonstrated that no data could be collected at the shortest wavelengths. Each COHU camera used a 25 mm Fujinon f/0.85 objective lens,for a field of view of $22 \times 16.5^{\circ}$, and the Retiga had a 50 mm Navitar f/0.95, and a field of view of $14 \times 11^{\circ}$ field of view. Each camera was equipped with a custom notch filter with center wavelength corresponding to the spectral line of interest. Each notch has with a full width-half maximum (FWHM) of 10 nm, FWHM tolerance of $\pm$ 2.0 nm, and a minimum transmission $\geq 85\%$. A WAT 902H2 Ultimate Watec CCD camera, equipped with a 50 mm Navitar f/0.95 lens (fov $14 \times 11^{\circ}$) was co-located with the spectral cameras as part of a separate experiment.

All four spectral cameras were pointed co-axially at the center of the field of view of the wide field of the CAMO tracking system, which was used for a white-light reference for the meteors observed by the spectral system. The CAMO system (described in detail in Weryk et al. (2013)) also provided the velocity, heights and orbit of meteors which were observed at both stations. Meteors which were well tracked in the CAMO system also had narrow field data, which give a resolution of a few meters per pixel and allow the fragmentation behaviour of the meteors to be quantified. When meteors were automatically detected with the CAMO tracking system, video from the spectral systems was cut out and saved, so that the data collection was fully automated.

Video from all of the systems were automatically time stamped with GPS time, but the Retiga camera suffered a slight time delay compared to the other systems because of the time required to ingest the video. The times were calibrated using the position each meteor against the background stars: since the cameras were located within tens of centimeters from one another, this was effective.

Data were collected with the spectral system from September to December 2015. The collected meteors were manually reviewed to determine which cameras had detected each event, and recorded events were reduced using the METAL (METeor AnaLysis) (Weryk and Brown, 2012) software package to produce light curves. Priority was given to events captured by more cameras and those with two-station CAMO data.

In order to do absolute photometry on the filtered cameras, custom star catalogs were made for each notch filter. The original star catalog used, Sky Catalog 2000, was situated in the R-band whose spectral range was insufficient to analyze the wavelengths of interest for this study. In the development of the custom star catalog it was assumed that each star had a blackbody spectrum (M stars were excluded, since their spectra are dominated by molecular absorbtion lines) at the characteristic temperature for its spectral type. The difference in magnitude between the Johnson-Cousins R band (or V band, in the case of the 394 nm band) and the notch filter band was calculated from the blackbody spectrum, and these differences were used with a catalog of known stellar magnitudes to generate catalogs for each of the metal lines. These catalogs were then used to obtain line intensities, so that the fraction of the total light intensity present in each filter could be calculated. For some of the brighter events, saturation was a problem on the 8-bit Cohu cameras and these events were not included in this analysis.

Throughout the campaign 2726 meteor events were observed in the CAMO tracking wide field system. Unfortunately, no usable data were collected with the 436 nm filtered camera due to the low sensitivity of the intensifier at that wavelength. Because of the different fields of view and sensitivities, most of these events were not present on all cameras. In total, 95 events captured from beginning to end on both CAMO stations and by the 520 and 589 nm systems were reduced for this study. The 394 nm system had a smaller field of view, so only 50 of these events were reduced, and most of those had incomplete light curves. Of the 95 meteors reduced, 93 had valid orbits and 89 were also tracked by the narrow field CAMO tracking system. It is not surprising that such a high fraction of these events were tracked, since the requirement that events be observed in the notch filters selected bright meteors, which are most likely to be well tracked.

3. Classification

A three-tier classification scheme was developed based on the author's inspection of the events to categorize the ablation features of the 95 reduced meteors. Unfortunately an objective numerical measure for classifying these events has not yet been established and as such this classification was subjective to the opinion of the authors. Events were classified as having "uniform" ablation if the filtered light curves had the same general shape, similar peak magnitudes, and the same beginning and end times (Fig. 1). Meteors with "slightly differential" ablation (Fig. 2) had light curves which displayed significantly earlier or later begin or end times, or a slight shift in the time of peak magnitude, compared to other lines. Meteors with light curve shapes

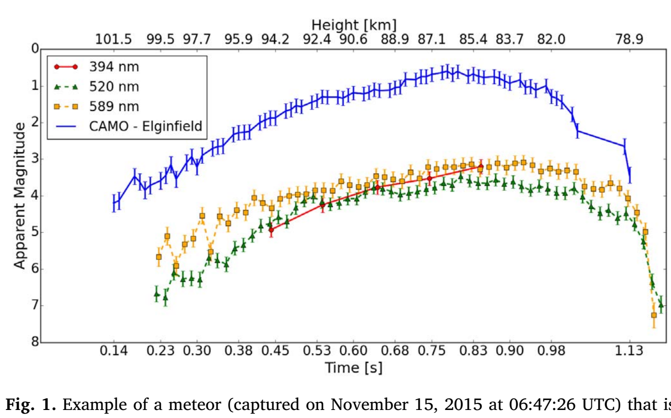

Fig. 1. Example of a meteor (captured on November 15, 2015 at 06:47:26 UTC) that is ablating uniformly. Note the overlap of the three light curves. The curves all peak around the same time and the start and end times of the 589 and 520 nm curves are very close. Note that the 394 nm light curve is incomplete because of the small field of view of that camera.