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ScienceDirect
Advances in Space Research 39 (2007) 513–516
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

The origin of the Ca(II) emission, in one of two plasma components, and the metallic abundances in a 2002 Leonid meteor spectrum

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Received 29 October 2004; received in revised form 27 July 2005; accepted 1 May 2006

Abstract

Fast-moving meteors such as Leonid meteors have two types of spectra. One is the main component composed of neutral atomic lines having low excitation temperature (~5000 K) and the other is the hot component composed of singly ionized lines such as Mg(II) and Ca(II) having high excitation temperature (~10,000 K). We observed the brightest fireball which appeared at, 03 h 47 m 54 s UT of November 19, 2002 in the 2002 Leonid aircraft campaign. The neutral atoms composing the main component such as Mg(I), Fe(I), Ca(I) and Na(I) were identified in the wavelength range of 300–650 nm. The singly ionized atomic emissions of Ca(II) and Mg(II) were also detected in this Leonid spectra during the temporal series of brightness of the fireball flight. So far, these emissions were considered to originate from the hot component. However, we found in several frames taken at the bright fireball during the period of the observation that the Ca(II) lines do not satisfy the hot-component condition even if the hot-component Mg(II) (448 nm) emission was observed. This indicates that the Ca(II) lines do not always satisfy the hot-component condition.

Keywords: Leonid meteor; Ionized calcium emission (Ca(II)); Main component; Hot component; Metallic abundance; Solar-system abundance

1. Introduction

Meteors are one of the representative phenomena of infalling meteoroids into the Earth from space. However, little is known about the physical conditions in ordinary meteors and the fate of ablated materials in the Earth's atmosphere. The latest activities of the Leonid meteor showers, associated with the passage of the parent comet 55P/Tempel-Tuttle, provided invaluable opportunities for ideal observational conditions of the meteors. Among the various world-wide campaigns coordinated, the Leonid Multi-Instrument Aircraft campaign (Leonid MAC) (Jenniskens, 2003; Jenniskens and Butow, 1999; Jenniskens et al., 2000), which had started in 1998, brought about one of the greatest advances in meteor astronomy. We participated in the Leonid MAC mission (Jenniskens, 2002) since 1998 and developed the High-Definition TV (HDTV) spectroscopic observational system focused on the near ultraviolet wavelength range where many lines of metallic atoms are present. The HDTV video spectroscopy enabled us not only to obtain higher temporal resolution for meteor spectra data (i.e., the time resolution of HDTV is 0.033 s), but also to study the detailed time variation of the metallic abundances, the excitation temperature and the blackbody temperature for each frame (Kasuga et al., 2005).

Borovička and Jenniskens (2000) assumed two types of the spectra observed in fast-moving meteoroids: one is called "a main component", which is composed of neutral atomic lines, and the other is called "the second component" or "a hot component" composed of Ca(II), Mg(II), Si(II), H(I), Fe(II) and Cr(II) lines. The excitation temperature of the main component is around 5000 K and that of the hot component is around 10,000 K. Borovička (1993) considers that the hot component is caused by a meteor

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0273-1177/$30 © 2007 Published by Elsevier Ltd on behalf of COSPAR.
doi:10.1016/j.asr.2006.05.006

shock wave. In very fast meteoroids, Mg(II) (448 nm) emissions are often observed. Indeed, the Leonid fireball exhibited Mg(II) (448 nm) emissions at 03 h 47 m 54 s UT in all frames (Kasuga et al., 2005). The presence of the Mg(II) (448 nm) line is called a hot-component condition (Borovička, 1993). The Ca(II) (393, 396 nm) lines are also often observed in the hot-component condition. However, this is not always the case; the Ca(II) (393, 396 nm) lines are sometimes not observed at an early stage of the ablation process (Kasuga et al., 2005). In this paper, we focus on the Ca(II) lines and discuss whether they are of the hot-component origin.

2. Analysis

We focus on the spectra obtained at 03 h 47 m 54 s UT November 19, which are one of the highest quality data in the first activity peak of the 2002 Leonids in the Leonid MAC 2002. The Mg(II) (448 nm) emissions were detected in all frames (Kasuga et al., 2005), indicating the presence of the hot component.

In order to obtain the elemental abundances, electron density is needed for considering the ionization of atoms. The methods of electron density estimates have two types; hot-component analysis and main-component analysis. In the hot-component analysis, Ca(II) is assumed in hot component and a value of the total metallic abundance, Ca/Mg of the main component, is equal to the ratio of that of the hot component and the pressure of the radiant gas of the main component, and hot components are balanced for the definition (Borovička, 1993). From this method, two types of electron densities were obtained as solutions, one with a positive value, the other negative. The proper electron density is finally selected as a positive value for the definition (Borovička, 1993).

However, in case of both derived values of electron density resulted in a negative, which is an unrealistic situation. This means Ca(II) may not be the hot-component (Kasuga et al., 2005). In that situation, Ca(II) was assumed under the main component condition instead of the hot one, and derive electron density. Metallic abundances are affected by electron density, which means Ca(II) origin.

Here, we estimate the electron density and the abundances of the metallic atoms taking into account of their ionization degree. The procedure of the line identification and the abundance of neutral metallic elements was described in Kasuga et al. (2005). The hot-component analysis (Kasuga et al., 2005) is applied to the Ca(II) emissions in the frames of 0.231–0.330 s at 03 h 47 m 54 s UT. The electron density, n_e, thus estimated is shown by the dotted line in Fig. 1. We applied the hot-component analysis to the Ca(II) lines at 0.066–0.198 s as well, but obtained negative n_e. This suggests that the Ca(II) lines observed at this early stage are not the hot components, in spite that the excitation temperature is as high as 10,000 K and the Mg(II) (448 nm) emission was observed at these times (Kasuga et al., 2005). The electron density at 0.066–0.198 s shown in Fig. 1 is that estimated by assuming that only the Mg(II) (448 nm) is the hot component. The thick lines show the electron density estimated by assuming that the Ca(II) (393, 396 nm) line are of the main-component origin in all frames, even if the Mg(II) (448 nm) emission appeared. In this case, the electron density is estimated from the ratio $(N_{Ca(II)}/N_{Ca(I)})_{sum}$ by using the fluxes of the Ca(II) (393, 396 nm) and Ca(I) (423 nm) lines.

2.1. Metallic abundance

Fig. 2 shows temporal variation of the abundances of the metallic elements Fe, Ca and Na, together with their

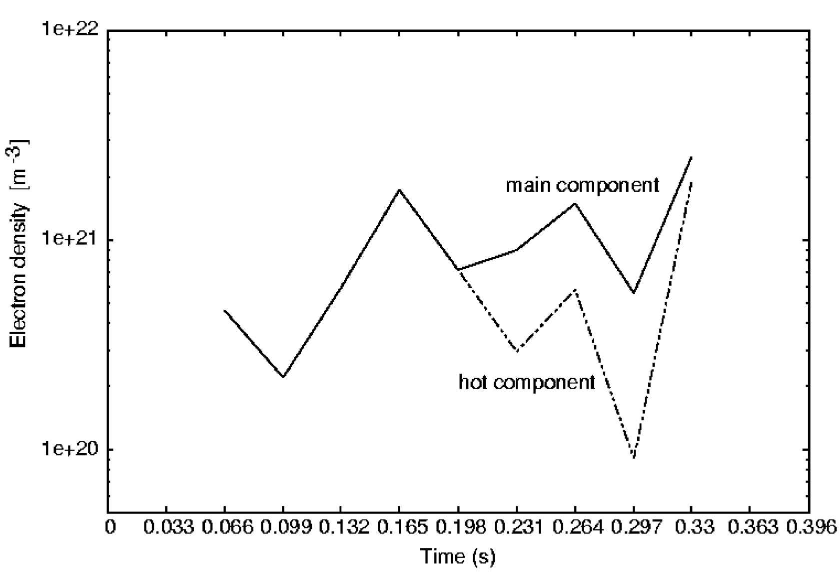

Fig. 1. Temporal variations of the electron densities n_e. The thick line shows n_e if the Ca(II) lines are of the main component, and the dotted line shows n_e if the Ca(II) lines are of the hot component.

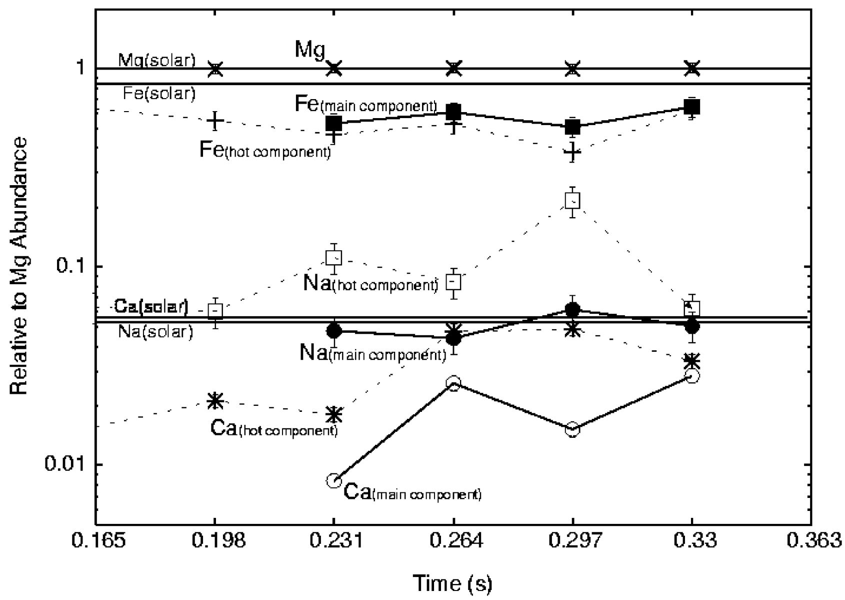

Fig. 2. Temporal variation of the abundances of Mg, Fe, Ca and Na relative to Mg at times from 0.198 to 0.330 s. The abundance values of 0.198 s frame and Fe (hot component), Ca (hot component) and Na (hot component) are taken from Kasuga et al. (2005). The lines labeled as Fe (main component), Ca (main component) and Na (main component) indicate the abundances of Fe, Ca and Mg if Ca(II) is the main component. The solar-system abundances Anders and Grevesse (1989) of Fe, Ca, Na and Mg are shown by the horizontal lines.

solar-system abundance shown by the horizontal lines (Anders and Grevesse, 1989). The errors of the abundances Fe/Mg, Ca/Mg and Na/Mg are estimated to be 12%, 8% and 17%, which are due to the errors of the system efficiency and the observed flux (Kasuga et al., 2005). The abundance values at 0.198 s frame and those of Fe (hot component), Ca (hot component) and Na (hot component) are given by Kasuga et al. (2005). The data for 0.363 s were omitted because the data did not include the 589 nm (Na(I)) line as the line was out of the FOV at that time.

In Fig. 2, we also give the abundances of Fe, Ca and Na at 0.231–0.330 s estimated by assuming the Ca(II) emission to be the main-component origin; those are denoted by Fe (main component), Ca (main component) and Na (main component), respectively. The abundance ratio of Ca(II)/Ca(I) in the ground state is given in Table 1, which is calculated from the ratio between observed fluxes of the Ca(II) (393, 396 nm) and Ca(I) (423 nm) lines.

3. Discussion

3.1. Metallic abundance

One of the remarkable features seen in Fig. 2 is that the abundance ratio of Fe/Mg is always lower than the solar-system abundance for both $(\mathrm{Fe/Mg})_{\mathrm{hot}}$ and $(\mathrm{Fe/Mg})_{\mathrm{main}}$, which are the abundance of Fe relative to Mg if Fe is the hot or main component, respectively. The average values except the saturated period at times 0.264 and 0.297 s are $(\mathrm{Fe/Mg})_{\mathrm{hot}}/(\mathrm{Fe/Mg})_{\mathrm{solar}}$ is 0.61 and $(\mathrm{Fe/Mg})_{\mathrm{main}}/(\mathrm{Fe/Mg})_{\mathrm{solar}}$ is 0.62 (See Table 2). Note that $(\mathrm{Fe/Mg})_{\mathrm{hot}}$ and $(\mathrm{Fe/Mg})_{\mathrm{main}}$ are almost of same value for each frame. This indicates that Fe/Mg is irrelevant whether Ca(II) is the hot or main component in this Leonid meteor.

The Ca/Mg ratio is also always lower than the solar-system abundance ratio. The average of $(\mathrm{Ca/Mg})_{\mathrm{hot}}/(\mathrm{Ca/Mg})_{\mathrm{solar}}$ is 0.28, whereas the average $(\mathrm{Ca/Mg})_{\mathrm{main}}/(\mathrm{Ca/}$

Table 1
The abundance ratios of Ca(II)/Ca(I)

t (s)	0.066	0.099	0.132	0.165	0.198	0.231	0.264	0.297	0.330
$(N_{\mathrm{Ca(II)}}/N_{\mathrm{Ca(I)}})_{\mathrm{sum}}$	3.6	5.0	6.6	6.3	8.5	**4.4**	**6.0**	**5.3**	**5.8**

The results of the present work are shown by the boldface. The values of those from 0.066 to 0.198 s are taken from Kasuga et al. (2005).

Table 2
Comparison of the abundances estimated by assuming the hot or main component and the first ionization potential for each element

	Fe/Mg	Ca/Mg	Na/Mg
Total (Ca(II); hot component (Kasuga et al., 2005))	0.51 ± 0.06	0.016 ± 0.001	0.059 ± 0.010
Total (Ca(II); main component (This work))	0.52 ± 0.06	0.014 ± 0.001	0.050 ± 0.010
Solar ratio (Anders and Grevesse (1989))	0.84	0.057	0.054
First ionization potential (eV)	$\chi_{\mathrm{Fe}} = 7.87$	$\chi_{\mathrm{Ca}} = 6.113$	$\chi_{\mathrm{Na}} = 5.139$

Mg)$_{solar}$ is 0.25 (see Table 2). The average Ca/Mg does not depend much on whether Ca(II) is the hot or main component for the 2002 Leonid meteor during this observation period. The Ca/Mg abundance ratio estimated by assuming that Ca is the hot component is always higher than that estimated by assuming that Ca is the main component.

The abundance ratio Na/Mg averaged over the time, except the saturated time at 0.264 and 0.297 s, is (Na/Mg)$_{hot}$/(Na/Mg)$_{solar}$ is 1.1 and (Na/Mg)$_{main}$/(Na/Mg)$_{solar}$ is 0.93 (Table 2). The abundance of Na is easily affected by the electron density because of its low ionization potential. Fig. 2 shows that, during the bright fireball emission seen in the 0.231–0.330 s frames, (1) (Na/Mg)$_{hot}$ are higher than the solar-system abundance and (2) the temporal variation of those abundances are remarkable. (Na/Mg)$_{main}$ remains almost equal to the solar-system abundance. The excitation temperatures varied substantially in each frame (Kasuga et al., 2005). According to Borovička et al. (2005), the Na abundances are rarely variable for very fast meteoroids like the Leonid meteors. The large temporal variation of the Na abundance in the present data suggests that Ca(II) should be regarded to be of the main-component origin rather than of the hot-component origin for the 2002 Leonid meteor during this observation period.

3.2. The origin of the CaII emissions?

Borovička (1994) and Jenniskens et al. (2002) consider that the hot component is produced by a shock wave associated with fast-moving meteors, although the detailed mechanism of the formation of meteor plasma will be very complicated. The spectra change with the distance from the meteoroid (Popova et al. (2000)). The lines with high excitation energies such as Mg(II) (~11 eV, 448 nm), Si(II) (~10 eV, 634, 637 nm), H (~12 eV, 656 nm), and O lines (~12 eV, 615 nm) originate mainly from the hot area of the wake and the meteor head. On the other hand, the lower excitation lines such as Mg(I) (~5.1 eV) and Na(I) (~2.1 eV) are emitted from a more extended area in the wake. The Ca(II) (~3.1 eV, 393, 396 nm) lines are not discussed by Popova et al. (2000). Because of its relatively low excitation energy, it is probable that the Ca(II) lines are emitted from the extended area.

Borovička (1994) considers that Ca(II) is classified into the hot component when Mg(II) appears in fast-moving meteoroids such as the Leonid meteor. Kasuga et al. (2005) showed that Ca(II) changed from main to hot during the temporal emission process in the Leonid fireball. The present work suggests that Ca(II) can be the main component, at least at the early stage of the ablation, even if the Mg(II) lines appeared at that stage.

4. Conclusions

Using the spectral data of the line emissions of the metallic atoms observed in the 2002 Leonid meteor at 03 h 47 m 54 s UT of November 19, 2002, we compared the temporal variations of the electron density and the abundances of metallic atoms for the two origins of the Ca(II) emissions. If we assume that the Ca(II) lines are the hot-component origin with the excitation temperature of 10,000 K, we obtain the negative electron density and the large temporal variation of the Na abundance. This suggests the possibility that Ca(II) emissions are of the main-component origin rather than of the hot-component origin, even if the Mg(II) lines are observed during the period.

Acknowledgements

The 2002 Leonid MAC mission was supported by grants from NASA's Planetary Astronomy and Astrobiology programs. The Leonid project in Japan was supported by the grants from the National Observatory of Japan (NAOJ) and the Japan Space Forum (JSF). T.K. thanks Dr. Y. Hirahara (Nagoya University) and JSPS Research Fellowships for young scientists. T.Y. acknowledges support by the grants-in-aid from the Japan Society for the Promotion of Science (JSPS).

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