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A 2004 Geminid meteor spectrum in the visible–ultraviolet region

Extreme Na depletion?

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Abstract. This paper shows the first result of a Geminid meteor spectrum in the visible–ultraviolet region. Wavelengths between 300–600 nm were observed on the meteor which appeared at $17^{\rm h}41^{\rm m}24^{\rm s}$ UT on 2004 December 14, and strong emissions of neutral atoms such as mainly MgI, FeI, CaI and NaI were identified. The abundances of metallic atoms and their excitation temperature were obtained on the assumption that a Boltzmann distribution for the population of each energy level.

The results suggest the possibility that the abundances of Geminid meteors are slightly different from solar abundances. Na/Mg = 0.0036 ± 0.0005, which is much lower than other meteor showers. On the other hand, the Ni/Mg ratio is 0.078 ± 0.012, which is larger than solar abundance, and that of meteors of other showers. Extreme Na depletion, and moreover, excess Ni are derived for a Geminid meteor. The excitation temperature value, 4640.6 ± 1.5 K is consistent with their moderate velocity.

Key words. ultraviolet wavelength region – Geminid meteor spectrum – solar abundance – 3200 Phaethon

1. Introduction

The Geminid meteor shower, whose parent is thought to be 3200 Phaethon (e.g. Williams & Wu 1993), is one of the strongest showers every year.

Spectroscopy has been carried out since the 1950s (e.g. Russell et al. 1956; Millman 1955, 1973, 1975), and Harvey (1973) reported on the 1969 data of spectrum from around 340 to 680 nm. Borovička (2001) and Trigo-Rodrìguez et al. (2003) reported on the spectra of the Geminid meteors deduced from above the 360 nm wavelength range. Borovička (2001) described Na abundance of Geminid meteors as being poor without including Ni. Trigo-Rodrìguez et al. (2003, 2004) shows the Na abundances of Geminid are slightly richer than solar abundance without considering Fe. The physical structure and chemical composition of parent objects, 3200 Phaethon debris in the form of meteoroids will provide important clues concerning both the origin and the evolution of the parent body.

Parents of meteor showers are generally expected to be comets rather than asteroids (Williams et al. 1985). However, 3200 Phaethon seemed to be a rocky-asteroid rather than having a cometary appearance (Green et al. 1985; Birkett et al. 1987). The easily volatile species signature in comets, for example the CN band emission feature was not detected within 3-sigma for 3200 Phaethon (Chamberlin et al. 1996). Studies of the relationship between 3200 Phaethon and Geminid may clarify any connection that may exist between comets and some asteroids in comparison with other meteors, whose parents are comets.

We first succeeded in obtaining the Geminid spectroscopic data from the 300 to 600 nm wavelength range, where the bands of CHON related molecules such as OH and CN are expected. Furthermore, we first applied the 3367 atomic catalog lines in this wavelength range for analysis, not focusing only on multiplets as seen in previous meteor research, and derived metallic abundances. The multiplets analysis method is very risky in terms of accuracy of result, and particularly in terms of inaccuracy for new identification of unknown emission lines due to the very limited catalog lines. Our method will be able to reduce these uncertainties to the utmost. Then, Letter to the Editor

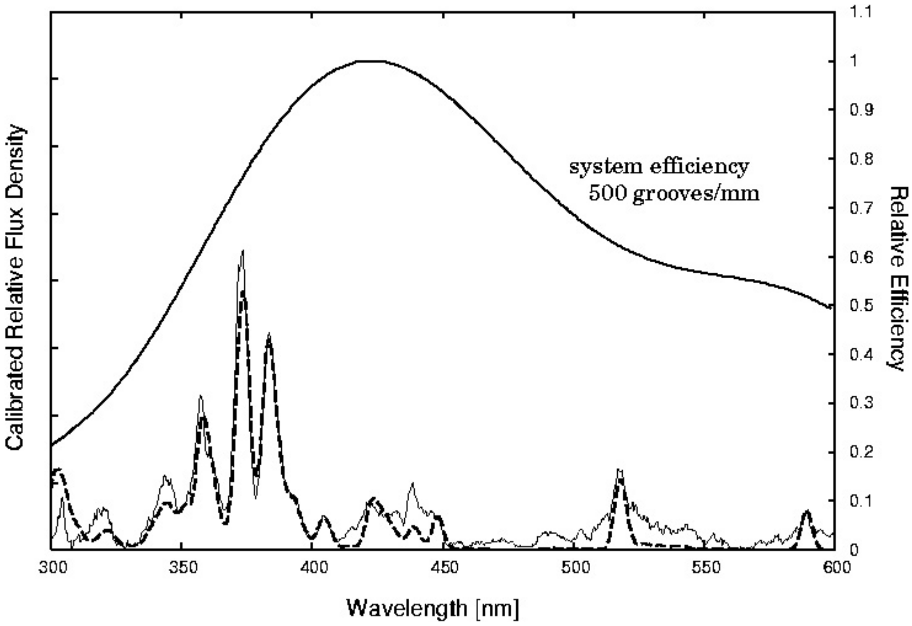

Fig. 1. The normalized system efficiencies (NSEs) with the reflective grating of 500 grooves/mm (blaze 330 nm) was calibrated by Sirius and includes the air extinction. The thin line is a calibrated Geminid meteor spectrum obtained at $17^h41^m24.264^s$ on December 14 UT and dotted lines are the best fit models of MgI, FeI, CaI, NiI, NaI, MnI, CrI, MgII, FeII and CaII derived from the least square value.

derived metallic abundances, especially Na/Mg and Ni/Mg in Geminid meteor shows different features from other meteors whose parents are comets. In this paper, we focus on the metallic abundances of Geminid meteors and their relation with the parent 3200 Phaethon.

2. Observation

The HDTV spectroscopic observation was performed at the Nobeyama Radio Observatory of Japan, Nagano Prefecture in Japan from $11^h00^m00^s$ UT on December 13 to $18^h30^m00^s$ UT on 15 December in 2004. The observation site was located at a latitude of +35.94° N, a longitude of 138.48° E and an altitude of 1350 m as measured by the GPS system.

The HDTV spectroscopic observational system, with sensitivity to UV–visible (in 250–700 nm), consists of a reflective grating (500 grooves/mm, blaze 330 nm), a UV lens (f = 30 mm, F1.4), an Image Intensifier (I.I.) with sensitivity to UV–visible, and HDTV camera. It should be noted the F-number of the UV lens changes with the applied wavelength up to F1.2. An HDTV camera has been used as a meteor imager since 1998 (Watanabe et al. 1999). The 1-inch 2M pixel FIT CCD of the HDTV has resolution as high as 1150 TV lines, and the meteors were recorded as 8-bit images. The diagonal coverage of the field of view (FOV) was 30°, and the observable bands were in the 300–600 nm range, where the region shorter than 310 nm is not reliable due to lower atmospheric transmission. The maximum spectral resolution of ~3.0 nm ($\lambda/\Delta\lambda \sim 100$) was achieved for the reflective grating mentioned above. Then, we obtained one spectrum at $17^h41^m24^s$ UT on December 14. That meteor was observed from $17^h41^m24.165^s$ UT to 17^h41m24.495^s UT.

Figure 1 shows the system efficiency of the observation using the 500 grooves/mm grating, calibrated observed spectrum together with the reproduced model spectrum of the Geminid meteor. Observed and model spectra are described later.

The calibration star was Sirius (α CMa). Here, the system efficiency $f(\lambda)$ is defined as

$$f(\lambda) = \frac{\text{OSS [count value]}}{\text{CSS [erg s}^{-1}\text{ cm}^{-2}\text{ nm}^{-1}]}, \quad (1)$$

where OSS [count value] is observed data of Sirius, and CSS [erg s^{-1} cm^{-2} nm^{-1}] is Sirius data from the Pulkovo spectrophotometric catalog (Alekseeva et al. 1997).

The efficiency of the HDTV spectroscopic observation system is affected by both the air extinction and the instrumental efficiency. The system efficiency shown in Fig. 1 are normalized to be unity at their maxima.

The flux density F of the meteor spectra was derived using the efficiency curve $f(\lambda)$ by the

$$\frac{F(\lambda)}{\text{erg s}^{-1}\text{ cm}^{-2}\text{ nm}^{-1}} = \frac{\text{OMS [count value]}}{f(\lambda)}. \quad (2)$$

where, OMS [count value] is the observed meteor spectrum data.

3. Analysis and discussion

Figure 1 shows the observed spectrum of the Geminid meteor. The data shown in this figure is the highest quality taken at $17^h41^m24^s$ UT December 14. The meteor's brightest magnitude was about 0th mag. The observed meteor spectrum, which is calibrated by Sirius, is shown in the thin line in Fig. 1.

3.1. Abundances of metallic elements

In this study, we assume a Boltzmann distribution for the population of each energy level. The least square method to obtain

Table 1. Metallic abundances of the Geminid meteor, solar abundances and other Geminid meteor research.

	Geminid (this study)	Solar abundance (Anders & Grevesse 1989)	Geminid (other research) (Trigo-Rodrìguez et al. 2003)
Fe/Mg	0.43 ± 0.07	0.84	–
Ca/Mg	0.0031 ± 0.0005	0.057	0.017 ± 0.009
Ni/Mg	0.078 ± 0.012	0.046	–
Na/Mg	0.0036 ± 0.0005	0.054	0.10 ± 0.03
Mn/Mg	0.0072 ± 0.0011	0.0090	0.0054 ± 0.0020
Cr/Mg	0.0082 ± 0.0012	0.013	0.0078 ± 0.0035

the metallic abundances is described in Kasuga et al. (2004, 2005). To begin with, the total neutral metallic abundance ratio $z_{\rm X\,I} = N_{\rm X\,I}/N_{\rm MgI}$ for six neutral atoms (FeI/MgI, CaI/MgI, NiI/MgI, NaI/MgI, MnI/MgI and CrI/MgI), the excitation temperature $T_{\rm e}$ and the width of the Gaussian instrumental profile σ are determined by the method. In the next step, we have to consider the degree of ionization of atoms in order to obtain the elemental abundances.

Firstly, we applied ionized emissions (MgII, FeII and CaII) for hot component theory to obtain FeII/MgII and CaII/MgII using fluxes and least square method (Borovička 1993). However, the application of this analysis process failed. Nevertheless the temperature of the hot component could be fitted in 10 000 K as described in Kasuga et al. (2005). According to this theory, two types of electron densities are obtained as solutions. However, both the values of the electron density derived using CaII/MgII resulted in negative values, which is unrealistic. On the other hand, both values of electron densities derived using FeII/MgII, resulted in positive values. However, their positive values of electron densities are not consistent with those of CaII/MgII. This is unrealistic for a hot component condition. We conclude that this is not a hot component condition. Here, we assume that the CaII was under the main component condition (the lower excitation temperature region of meteor plasma) instead of the hot component condition, in order to derive the electron density. The electron density is obtained as 4.2×10^{20} m^{-3}. We derived the total metallic abundances using this electron density, the same as in Kasuga et al. (2005).

The results of abundances and those of errors estimated by S/N are shown in Table 1. The fitting errors of abundance derived from the least square calculation are negligible because they are extremely small (Borovička 1993; Kasuga et al. 2004, 2005). The excitation temperature $T_{\rm e} = 4640.6 \pm 1.5$ K, and the spectral profile $\sigma = 2.12 \pm 0.0060$.

In Fig. 1, the dotted line was obtained by applying the atomic catalog lines; MgI, FeI, CaI, NiI, NaI, MnI, CrI, MgII, FeII and CaII. These elemental line positions in the observed wavelength region, together with the Einstein A coefficient, energy levels $E_{\rm l}$ and $E_{\rm u}$ of the lower and upper levels, configurations, and the statistical weights $g_{\rm l}$ and $g_{\rm u}$ of the lower and upper levels were obtained by the Physical Reference Data of National Institute of Standard and Technology (NIST). We included 3367 lines from the 300 to 600 nm wavelength range for this study.

It is revealed that the metallic abundances of the Geminid meteor are slightly different from solar abundances (Anders & Grevesse 1989, see in Table 1).

Fe/Mg is about 51% of that of solar abundances. This might indicate the presence of the Mg-rich silicate meteoroid as observed in Leonid meteor showers (e.g. Kasuga et al. 2005; Borovička 1993).

Ca/Mg is lower than the solar abundance ratio. It is likely that Ca could not evaporate completely during the meteor ablation as described in previous research (e.g. Kasuga et al. 2005; Trigo-Rodrìguez et al. 2003; Borovička et al. 1999). There is a possibility that most of the Ca in the Geminid meteor is not evaporated completely under the $T_{\rm e} = 4640.6 \pm 1.5$ K conditions because Ca may survive even during high-speed Leonid ablation process under the $T_{\rm e} \sim 5500$ K conditions (Kasuga et al. 2005).

Na/Mg is 7% of that of solar abundances. Borovička (2001) also reported the Geminids are generally poor in Na. We confirmed the previous result on the Na depletion on Geminid meteoroids by Borovička (2001). Na is a volatile element among these seven elements, and NaI (589 nm) is always clearly observed in other meteor showers, such as the Leonids (e.g. Kasuga et al. 2005). However, the line is faint in the Geminid meteor as shown in Fig. 1. We have to obtain Na abundance very carefully from two serious points of view. One is that of electron density, and the other is that of intrinsic abundance of Na in Geminid meteor. Na abundance is seriously affected by the applied electron density, because the ionization energy has a low value (5.139 eV). Both our result and Borovička (2001)'s results indicate that Na abundance is poor, nevertheless the electron density was derived by a method different from this study's (Borovička et al. 1993). However, this study and Borovička (2001) show a different result from that obtained by Trigo-Rodrìguez et al. (2003, 2004). Nevertheless Borovička (2001) and Trigo-Rodrìguez et al. (2003, 2004) derived the electron density by the same method, which may have resulted in larger abundance. Another possibility is that Na abundance may largely fluctuate within the Geminid meteoroids, depending on mass and size. Borovička et al. (2005) suggested that the Na content is correlated with the time the meteoroid is orbiting the Sun as a separate body. In any case, no suggestion is conclusive at the present time. We need more samples of Geminid meteor.

Ni/Mg was first obtained for the Geminid meteor in this study by evaluating the wavelength region shorter than 320 nm, and the value is larger than solar abundances. Ni in other meteors such as the Leonids and Perseids is lower than the solar abundances as described in Borovička (1993) and Trigo-Rodrìguez et al. (2003). Ni-rich abundance in Geminid meteor leads to the feature of parent body, 3200 Phaethon, which is classed as a B-type asteroid in Bus's taxonomy (Bus & Binzel 2002). The first spectroscopy in the ultraviolet region of the Geminid derived an Ni/Mg criterion, because most strong Ni emission lines exist around the 340–350 nm and under 320 nm wavelength range. Ni is a very important element if we discuss metallic abundances using the ultraviolet wavelength region, although the atmospheric transmission will affect it.

Mn/Mg and Cr/Mg are lower than their solar abundance. Although Ni, Mn and Cr are not clearly observed as lines, we assumed that they exist in Geminid meteoroids (e.g. Russell et al. 1956; Harvey 1973). In order to obtain more precise abundances of minor elements such as these, high resolved spectrum data are needed.

The excitation temperature, $T_{\mathrm{e}} = 4640.6 \pm 1.5$ K is related to the medium velocity of the Geminid meteor (36 km s^{-1}). The Leonids show the highest excitation temperature, ~5500 K, because of the highest kinetic energy caused by the retrograde trajectory (72 km s^{-1}). The excitation temperature value of the June Boötid meteor is low, ~3900 K, and that is in agreement with their slow moving velocity (18 km s^{-1}) described in Kasuga et al. (2004). It is possible that Geminid meteor is not evaporated enough because of their medium velocity.

In the near ultraviolet region around 300–400 nm, the bands of CHON related molecules such as OH and CN are expected as well as many metallic atom lines. The lines near 309 nm, bands of interesting molecules such as OH $A^2\Sigma^+ - X^2\Pi$ (0–0) were observed in another Leonid meteor in a different year (Jenniskens et al. 2002c). However, we could not detect any emissions related to the OH and CN.

4. Conclusion

We carried out an HDTV spectroscopic observation of the 2004 Geminid meteor shower on December 14 UT, 2004, and we obtained one spectrum of the Geminid meteor. We show the first result of ultraviolet observation of the Geminid meteor spectrum in the 300–600 nm wavelength range, and derived metallic abundances. From these results, we achieved the following conclusion on this one meteoroid:

1. Metallic abundances to Mg are slightly different from their solar abundance.
2. Mg-rich abundance to Fe is similar to abundances detected in other meteor showers such as the Leonids.
3. Ni abundance is larger than the solar abundance and that of other meteors.
4. Na abundance is sharply lower than solar abundance and abundances detected in previous research on other meteor showers.
5. Bands of interesting molecules such as OH and CN are not detected in this study.

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References

Alekseeva, G. A., Arkharov, A. A., Galkin, V. D., et al. 1997, Baltic Astron., 6, 481

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197

Birkett, C. M., Green, S. F., Zarnecki, J. C., et al. 1987, MNRAS, 225, 285

Borovička, J. 1993, A&A, 279, 627

Borovička, J., Stork, R., Bocek, J., et al. 1999, Meteoritics & Planetary Science, 34, 987

Borovička, J. 2001, Proc. Meteoroids 2001 Conf., ESA SP-495, 203

Borovička, J., Koten, P., Spurnỳ, P., et al. 2005, Icarus, 174, 15

Bus, S. J., & Binzel, R. P. 2002, Icarus, 158, 146

Chamberlin, A. B., McFadden, L.-A., Schulz, R., et al. 1996, Icarus, 119, 173

Green, S. F., Meadows, A. J., & Davis, J. K. 1985, MNRAS, 214, 29

Harvey, G. A. 1973, NASA SP, 319, 103

Jenniskens, P., Tedesco, E., Murthy, J., et al. 2002, Meteoritics & Planetary Science, 37, 1071

Kasuga, T., Watanabe, J., Ebizuka, N., et al. 2004, A&A, 424, L35

Kasuga, T., Yamamoto, T., Watanabe, J., et al. 2005, A&A, 435, 341

Millman, P. M. 1955, J. R. Astron. Soc. Can., 49, 169

Millman, P. M., Cook, A. F., & Hemenway, C. L. 1973, NASA SP, 319, 147

Millman, P. M., & Clifton, K. S. 1975, Can. J. Phys., 53, 1939

Russell, J. A., Sadoski, M. J., Jr., & Sadoski, D. C. 1956, PASP, 68, 64

Trigo-Rodrìguez, J. M., Llorca, J., Borovicka, J., et al. 2003, Meteoritics & Planetary Science, 38, 1283

Trigo-Rodrìguez, J. M., Llorca, J., & Fabregat, J. 2004, MNRAS, 348, 802

Watanabe, J., Abe, S., Takahashi, M., et al. 1999, J. Geophys. Res., 26, 1117

Williams, I. P. A., Carusi, G. B., & Valsecchi (ed.) 1985, Dynamics of Comets: Their Origin and Evolution, 115

Williams, I. P., & Wu, Z. 1993, MNRAS, 262, 231