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DETECTION OF THE N_2^+ FIRST NEGATIVE SYSTEM IN A BRIGHT LEONID FIREBALL

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ABSTRACT

An ultraviolet-visible spectrum between 300 and 450 nm of a cometary meteoroid that originated from 55P/Tempel-Tuttle was investigated, and its new molecules, induced by atmospheric interaction, were discovered. The spectroscopy was carried out using an intensified high-definition TV camera with a slitless reflection grating during the 2001 Leonid meteor shower over Japan. A best-fit calculation mixed with atoms and molecules confirmed the first discovery of N_2^+ $B\,^2\Sigma_u^+ \rightarrow X\,^2\Sigma_g^+$ bands in the UV meteor spectrum. The N_2^+ temperature was estimated to be 10,000 K with a low number density of 1.55×10^5 cm^{-3}. Such unexpectedly strong ultraviolet emission, in particular for N_2^+ (1, 0) at 353.4 nm, is supposed to be formed through the wide dimensions of high-temperature regions caused by a large meteoroid. Spectroscopic observations of reentry capsules will provide us with good opportunities for confirming the discovered N_2^+.

Subject headings: astrobiology — comets: individual (55P/Tempel-Tuttle) — interplanetary medium — meteors, meteoroids — molecular processes

1. INTRODUCTION

Spectroscopic observations of meteors reveal not only the chemical composition of the cometary meteoroids but also the emission processes of hypervelocity impacts in the atmosphere; these processes are difficult to reproduce in laboratory experiments at present. Leonid meteoroids that correspond to cometary grains from the comet 55P/Tempel-Tuttle have produced the best meteor shower because of its high incident velocity at ~72 km s^{-1} among known annual meteor showers and because of the bright flux of its meteors at ~10,000 hr^{-1}.

Of particular interest is the question as to whether or not meteoroids could have delivered organics and water to the early Earth (Jenniskens et al. 2000). Rietmeijer (2002) suggests that Leonid meteors are large aggregates that might include precursors to the interplanetary dust particles (IDPs) and that the survival of meteoritic compounds through the atmospheric entry is feasible even if its at high-velocity ablation. To determine whether large cometary grains contain mineral water or trapped water in any forms, it is necessary to confirm the presence of OH $A\,^2\Sigma^+ \rightarrow X\,^2\Pi$ emission around a wavelength of 310 nm. Harvey (1977), Abe et al. (2002, 2003), and Jenniskens et al. (2002) reported an excess of emission at 310 nm.

Here we report the discovery of N_2^+ $B\,^2\Sigma_u^+ \rightarrow X\,^2\Sigma_g^+$ [$N_2^+(1-)$] in the wavelength range of 320–450 nm meteor emission from a Leonid meteoroid through the investigation of the OH A–X (0, 0) band. The $N_2^+(1-)$ plasma emission in meteors has been argued by Millman et al. (1971) and Mukhamednazarov & Smirnov (1977). Meanwhile, Jenniskens & Laux (2004) found a N_2^+ $A\,^2\Pi_u \rightarrow X\,^2\Sigma_g^+$ Meinel band in the range of 780–840 nm. Thus, our discovery is important for identifying unknown meteor emissions in the ultraviolet region, in particular, for understanding the variety of emission phases in meteors and the delivery mechanisms of organic matter, content minerals, and water.

2. OBSERVATIONS AND DATA REDUCTION

During the 2001 Leonid maximum, spectroscopic observations were carried out using Image-Intensified High-Definition TV (II-HDTV) cameras in the ultraviolet (UV), visible (VIS), and near-infrared (near-IR) wavelength regions (250–700 nm). The II-HDTV system consisted of a UV image intensifier (ϕ 18 mm photocathode: S20), two relay lenses ($f = 50$ mm, f/1.4), and an HDTV camera with a 2 megapixels CCD. In order to focus precise optical concentration on the wavelength range of 250–1000 nm, we developed UV lenses of $f = 30$ mm, f/1.2 with a field of view of 23° × 13°. The HDTV digital imagery has 1920 (horizontal) × 1035 (vertical) pixels that result in 6 times higher resolution than the NTSC/PAL standard video conversion system. The recording rate was 30 frames (60 fields) per second. Spectroscopic observations were performed by the II-HDTV system equipped with a reflection grating, which is 500 grooves mm^{-1}, blazed at 330 nm, manufactured by the Richardson Grating Laboratory.

Background stars were removed by subtracting a median frame shortly before the appearance of the meteor. After flatfielding and averaging the meteor spectrum, the wavelength was determined carefully by means of numerous well-known atomic lines in the meteor emission. The effective spectral sensitivity of the instrument, including atmospheric extinction during the observations, was constructed by measuring spectra of bright stars in the observing field. Its sensitivity covered the wavelength at 300–700 nm, with the maximum at ~430 nm.

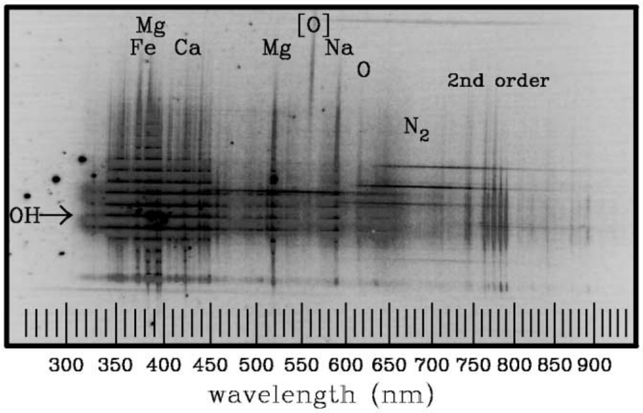

FIG. 1.—Raw data of first- and second-order spectrum of 2001 Leonid fireball at 18:58:20 UT on 2001 November 18. This image (with a field of view of 23° × 13°) is composed of 15 consecutive frames during a total duration of 0.5 s. The meteor moved from top to bottom in this image. The dispersion direction is from left to right, and parts of the second- and third-order spectra are on the right.

The resulting dispersion of the spectrum is 0.37 nm pixel^{-1}, and FWHM = 2.5 nm in the first order. Since no order-sorting filter was used, it turns out that the first-order spectrum was mixed with the second-order spectrum in the wavelength longer than 600 nm. Details of the instrument and the first results of the II-HDTV spectrum of 1999 Leonids were described in Abe et al. (2000).

Ozone in the stratosphere strongly absorbs below 290 nm, preventing the UV light from reaching the Earth's surface. In order to prevent air extinction owing to mainly aerosol scattering in the UV wavelength below 380 nm, the spectroscopic observation was performed at a high-altitude site in the Nobeyama Radio Observatory of the National Astronomical Observatory of Japan (N35°.93, E138°.48, altitude = 1340 m). Thanks to excellent observing conditions, clear weather, and strong meteor storm activity during the Leonid maximum, its peak activity was well observed around 18:16 UT on 2001 November 18 with the zenithal hourly rate of 3730, based on reports of the Nippon Meteor Society and the International Meteor Organization (Arlt et al. 2001).

3. RESULTS

In Figure 1, we show a clear spectrum of a Leonid meteor fireball, which was obtained at 18:58:20 UT on 2001 November 18, within a dust trail ejected by comet 55P/Tempel-Tuttle in 1866 (McNaught & Asher 1999). Assuming the Leonid radiant ($\alpha = +153°$, $\delta = +22°$) and velocity (72 km s^{-1}), the meteor distance R and its altitude H at each frame were inferable. The altitudes for the fireball entering our field of view and for it disappearing were $H = 108.1$ km ($R = 136.8$ km) and $H = 80.1$ km ($R = 124.6$ km), respectively.

From a comparison between meteor emission lines and the field-star spectrum, a maximum brightness of −4 visual magnitude at the standard range of 100 km was derived, which corresponded to a photometric meteoroid mass of ~1.8 g and a diameter of ~15 mm by assuming a density of 1.0 g cm^{-3} for the Leonid meteoroids. All spectral luminosities were normalized at 100 km altitude above the observer. In the next section, we shall focus on the best spectrum at $t = 0.434$ s and $H = 84.1$ km among these sequences.

First, in order to consider atomic lines only, we focus on emission lines in the UV-VIS region below 450 nm, where the measurement of the sensitivity calibration is expected to be the brightest. Assuming the local thermal equilibrium (LTE), the atomic synthetic spectrum was computed by adjusting five parameters: temperature T and the column densities of four atoms (Fe, Mg, Ca, and Na). We made sure that all other possible atoms, such as H, N, O, Al, Si, Ti, Cr, Mn, Co, or Ni, could be negligible in this wavelength region because these minor emissions blended into strong emission lines owing to low-resolution spectroscopy and because no significant contribution was identified. This analytical method was described in Borovička (1993). In general, meteor spectra consist of two components at different temperatures (Borovička 1994). A typical temperature of the "main (warm) component," which contains most of the above spectral lines, is $T \sim 4500$ K. The "second (hot) component" is excited at $T \sim 10{,}000$ K and consists of a few ionized elements such as Ca II and Mg II.

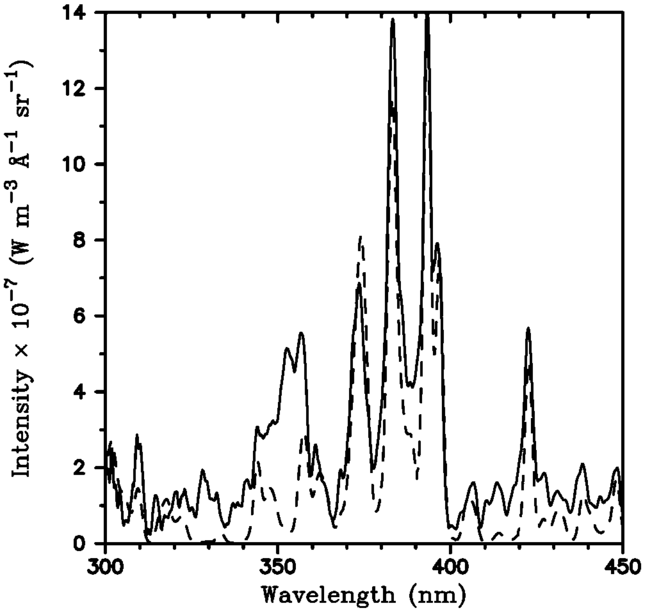

FIG. 2.—Observed spectrum (*solid line*) compared with synthetic spectrum considering only atoms (*dashed line*). The synthetic spectrum consists of Mg I at 383.8 nm and Ca II at 393.4 and 396.8 nm, Ca I at 422.7 nm, and Mg II at 448.1 nm with numerous iron lines. There are unexplained emissions at ~350, ~330, and ~310 nm.

Although overlaps of numerous iron lines prevented us from determining the precise temperature owing to rather low-resolution spectroscopy, LTE temperatures of 4100–4700 K for the main spectrum of this Leonid meteor have resulted in all spectrum frames, except saturated frames. Thus, we applied typical temperatures of 4500 and 10,000 K for its warm and hot component spectra, respectively. Figure 2 shows the comparison between observed and synthetic atomic spectra. The resulting column density of Fe I atoms was 2×10^{15} cm^{-2}, and we derived the following atomic ratios in the radiation gas: Mg I/Fe I = 11, Ca I/Fe I = 0.1, and Na I/Fe I = 0.03. A higher than chondritic Mg/Fe ratio was also detected in a 2001 Leonid fireball (J. Borovička 2004).

After the comparison between observed and synthetic spectra in Figure 2, we found that these atomic lines could not help us identify some unknown bands around 350 and 330 nm. These unknown bands clearly appeared from $t = 0.167$ s ($H = 100.1$ km) and suddenly disappeared after $t = 0.467$ s ($H = 82.1$ km). The 350 nm excess was particularly strong. In order to explain these enhancements in accuracy, the SPRADIAN nu-

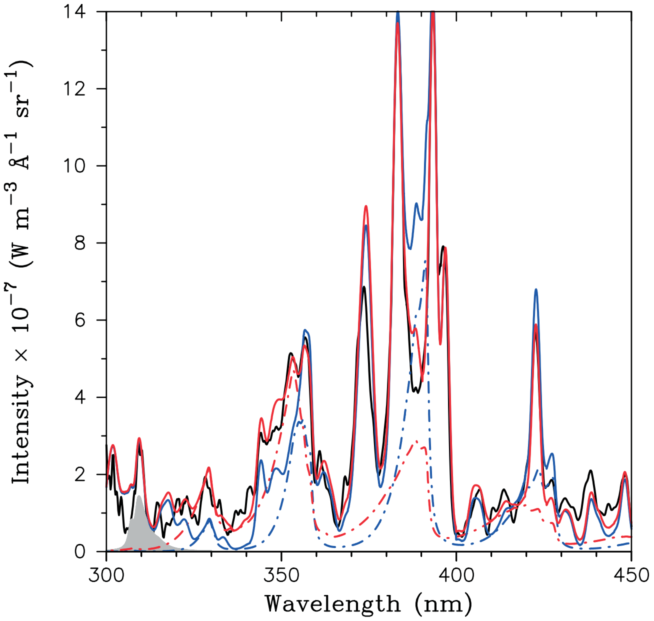

FIG. 3.—Observed spectrum (*black line*) compared with synthetic spectrum considering atoms and molecules of $N_2^+(1-)$ with a temperature of 10,000 K (*red line*) and 4400 K (*blue line*). The dash-dotted lines indicate $N_2^+(1-)$ at the appropriate temperature. The gray area near 310 nm shows OH *A*–*X* bands.

merical code considering with Franck-Condon factors, which can produce a molecular spectrum at the appropriate temperature and density, was used (Fujita & Abe 1997). As a result, the best account for two excess bands at 330 and 350 nm was found to be the "first negative *B*–*X*" band of the molecular nitrogen ion $N_2^+(1-)$. Figure 3 shows the model spectrum of $N_2^+(1-)$ with four bands heads (329.3, 353.4, 391.4, and 427.8 nm) caused by different vibrational states of $(v', v'') = (2, 0), (1, 0), (0, 0)$, and $(0, 1)$, respectively. The model spectrum is wonderfully in complete agreement with the observational spectrum in the UV range from 320 to 360 nm. This finding is the first detection of the N_2^+ *B*–*X* molecule in the UV meteor spectrum. The final values of number densities and chemical abundances for this meteor spectrum are summarized in Tables 1 and 2.

4. DISCUSSION

The presence of the molecular nitrogen ion $N_2^+(1-)$ in meteor spectra was first suspected by Millman et al. (1971). Mukhamednazarov & Smirnov (1977) reported the detection of the (0, 1) and the (0, 0) bands in the spectra of faint 3–5 mag meteors with the aid of intensified TV cameras. However, since the resolution was low (∼5 nm), the presence of these bands could not be separated from the strong emissions of Ca I at 422.7 and Ca II at 393.4 nm. Also, the (0, 0) band was almost at the edge of the their instrumental sensitivity. Figure 2 shows a clear contribution of Ca I at 422.7 nm and many iron lines that overlap with the (0, 1) band. In addition to that, these (0, 0) and (0, 1) bands of $N_2^+(1-)$ were never found in fireballs. That is, previous reports could not identify the $N_2^+(1-)$ because it was difficult to detect these bands clearly in the VIS region because of the overlaps with strong Ca and Fe emissions.

On the other hand, Jenniskens & Laux (2004) found excessive emissions between 770 and 840 nm with the maximums centered at ∼789 and ∼815 nm, which could be caused by the "first negative *A*–*X*" band of the molecular nitrogen ion N_2^+ Meinel bands. The evidence of a N_2^+ Meinel system was identified in two fireballs (with magnitudes of −1 and −7) obtained during the Leonid meteor shower in the 2001 and 2002 Leonid Multi-Instrument Aircraft Campaign (MAC; Jenniskens 2002). Because their unintensified slitless CCD spectrograph could provide a high spectral resolution with the precise determination of wavelength in the near-IR region, these must be reliable findings. In their research, the LTE abundances ($T = 4400$ K) of $[N_2^+]/[N_2]$ for the −1 and −7 mag fireballs were estimated at 5×10^{-7} and 2×10^{-9}, respectively. In addition to this, a tentative identification of the first negative N_2^+ *B*–*X* (0, 0) band in the VIS region was proposed (Jenniskens & Laux 2004; Jenniskens et al. 2004).

TABLE 1

CHEMICAL COMPOSITION OF THE LEONID METEOR SPECTRUM ($t = 0.434$ s, $H = 84.1$ km) AT 18:58:20 UT ON 2001 NOVEMBER 18

Emission	Number Density (cm^{-3})	Total Flux (10^{-5} W m^{-2} sr^{-1})
N_2^+	1.55×10^5 ($T = 10{,}000$ K)	14.4 (300–450 nm)
N_2	$<1.0 \times 10^{13}$ ($T = 4500$ K)	1.29 (300–450 nm)
OH	$>7.9 \times 10^7$ ($T = 4500$ K)	1.59 (300–330 nm)
Fe I	5.5×10^{13}	…
Electron	7.6×10^{13}	…

Although the spectral resolution in our observation was about an order less than Jenniskens' results, we could take full advantage of the sensitivity in the UV region below 380 nm. It is obvious that the spectrum enhancement around 350 and 330 nm can be explained by band heads of N_2^+ *B*–*X* (1, 0) at 353.4 nm and (2, 0) at 329.3 nm. The second positive bands of the neutral N_2 molecule were not identified in the UV-VIS range, which should contribute as a background. We inferred an upper limit of neutral N_2 of $\sim 1.0 \times 10^{13}$ cm^{-3} by assuming an LTE temperature of 4500 K (Jenniskens et al. 2000; Jenniskens & Laux 2004). The best-fit calculation mixed with atomic lines leads to an $N_2^+(1-)$ vibrational temperature of 10,000 K. If we assume an N_2^+ temperature of 4500 K, the estimated abundance of $[N_2^+]/[N_2]$ leads to $\sim 1 \times 10^{-7}$, which is consistent with the results from Jenniskens & Laux (2004). However, the best-fitted spectrum clearly proves that $N_2^+(1-)$ belongs to the "hot component" of $T = 10{,}000$ K. Figure 3 indicates the synthetic spectrum assuming $T = 4400$ K, which is clearly different from the observed spectrum. Furthermore, another piece of possible evidence for this hot component being assigned to N_2^+ is that the light curves of N_2^+ emission are more similar to ionized Mg at 448.1 nm, which belongs to the hot component, rather than to neutral Mg at 517.8 nm, which belongs to the warm component (Fig. 4).

The $N_2^+(1-)$ system was surprisingly strong; its total flux between 300 and 450 nm was 1.44×10^{-4} W m^{-2} sr^{-1} even when the calculated number density of N_2^+ molecules was ex-

TABLE 2

CHEMICAL ABUNDANCES

Element	Abundance	*T* (K)
Mg/Fe	11	4500
Ca/Fe	0.1	4500
Na/Fe	0.03	4500
N_2^+/N_2	$>1.5 \times 10^{-8}$	
N_2^+		10,000
N_2		4500
N_2^+/N_2	$\sim 1 \times 10^{-7}$	
N_2^+		4500
N_2		4500

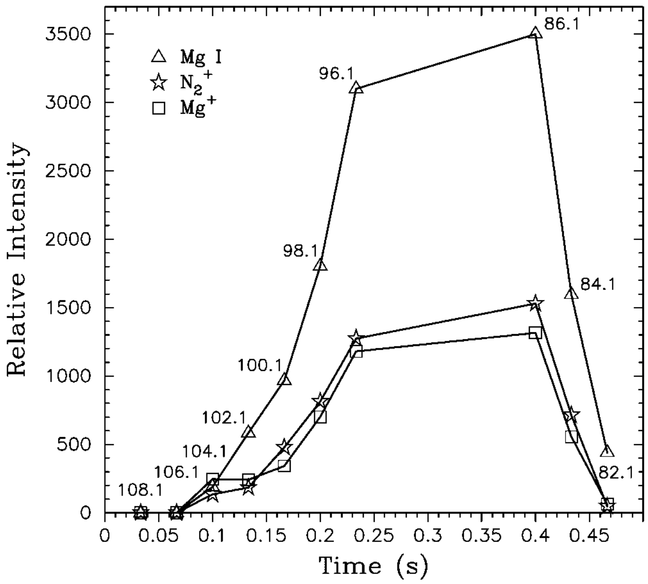

FIG. 4.—Light curves for N_2^+ (353 nm) Mg II (448 nm), and Mg I (518 nm). Time in seconds is on the horizontal axis. The relative intensity in an arbitrary linear scale is on the vertical axis. Altitude (in units of kilometers) at an appropriate time is indicated. Saturated spectra during the meteor flare (t = 0.276–0.400 s, H = 94.1–86.1 km) are omitted.

tremely small as 1.55×10^5 cm^{-3}; i.e., $[N_2^+]/[N_2] = 1.5 \times 10^{-8}$. Few reports have clarified the UV (300–350 nm) meteor spectra in the past (Harvey 1973a, 1973b; Carbary et al. 2003; Jenniskens et al. 2002), and strong features related to $N_2^+(1-)$ had never been reported before. On the other hand, similar features around 350 nm can be seen in spectra of 1999 Leonid meteoroids obtained by Rairden et al. (2000) and in our fireball spectra observed in 2002 Leonids; both were observed during the Leonid MAC. $N_2^+(1-)$ also could be observed in a shock layer of arc plasma heated by the reflected shock and by reentry spacecraft such as the Space Shuttle orbiter (Viereck et al. 1992). The flow in the head and wake regions of a hypersonic object, such as a reentry capsule, tends to be in a thermochemical nonequilibrium state. The most likely scenario of the induced $N_2^+(1-)$ in the meteoroid will result in the effect of large dimensions of high-temperature regions just ahead and behind the meteoroid caused by the large meteoroids' vapor cloud. The reentry speed from interplanetary space is more than 12 km s^{-1} at the altitude of 100 km, which is enough velocity for producing $N_2^+(1-)$ suggested from laboratory experiments (Keck et al. 1959). Therefore, the reentry capsules (meter-size meteoroids) of *Genesis* (solar wind sample return), *S tardust* (cometary dust sample return), and *Hayabusa* (asteroidal material sample return) directly from interplanetary space, which will return to the Earth in 2004 September, 2006 January, and 2007 June, respectively, will provide us with good opportunities to conduct artificial fireball spectroscopy tests in the future (Yano et al. 2004).

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