Search for OH(A-X) and detection of View the MathML source(B-X) in ultraviolet meteor spectrum

Abe, Shinsuke
Ebizuka, Noboru
Yano, Hajime
Watanabe, Jun-ichi
Borovicka, Jiri

(Citation)
Advances in Space Research,39(4):538-543

(Issue Date)
2007

(Resource Type)
journal article

(Version)
Accepted Manuscript

(URL)
https://hdl.handle.net/20.500.14094/90001255

Search for OH(A-X) and Detection of N_2^+(B-X) in Ultraviolet Meteor Spectrum

Shinsuke Abe

Department of Earth and Planetary Sciences, Faculty of Science, Kobe University, Nada, Kobe 657-8501, Japan.
email: avell@kobe-u.ac.jp

Noboru Ebizuka

Department of Physics, Konan University / RIKEN, Higashi-Nada, Kobe 658-8501, Japan.
email: ebizuka@riken.jp

Hajime Yano

Institute of Space and Astronautical Science, JAXA, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan.
email: yano.hajime@jaxa.jp

Jun-ichi Watanabe

National Astronomical Observatory of Japan, National Institutes of Natural Sciences, NINS, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan.
email: jun.watanabe@nao.ac.jp

Jiří Borovička

Astronomical Institute of the Academy of Sciences, 298 Fricova, Ondrejov 25165, The Czech Republic.
email: borovic@asu.cas.cz

Abstract

An ultraviolet-visible spectrum between 300 and 450 nm of a cometary meteoroid originated from 55P/Tempel-Tuttle was investigated. The spectroscopy was carried out an intensified high definition TV camera with a slit-less 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. N_2^+ temperature was estimated to 10,000 K with a low number density of 1.55×10^5 cm^{-3}. We also discuss the possibility that enhanced emissions

Preprint submitted to Elsevier Science *21 April 2007*

in a meteor and a train around 310 nm are caused by the band head of OH $A^2\Sigma^+ \rightarrow X^2\Pi$. Since cometary dust may have contributed organics and water to the Earth from its early period until now, OH A-X (0,0) must be investigated.

Key words: astrobiology, comets: individual(55P/Tempel-Tuttle), interplanetary medium, meteors, meteoroids, molecular processes

1 Introduction

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

Of particular interest is the question whether meteoroids could have delivered organics and water to the early Earth Jenniskens et al. (2000). Rietmeijer (2002) suggested that the survival of meteoritic compounds would be feasible even at high entry velocities. According this author, cometary meteoroids are aggregates that might include the precursors of the Interplanetary Dust Particles (IDPs) collected in the upper atmosphere. 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 the wavelength of 310 nm. Harvey (1977), Abe et al. (2003a,c, 2004) 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 of 320 - 450 nm meteor emission from a Leonid meteoroid through the investigation of 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, & Schaller (2004a) 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 to identify unknown meteor emissions in ultraviolet region, in particular for understanding the variety of emission phases in meteors and delivery mechanisms of organic matters and content minerals.

2 Observations and data reduction

During the 2001 Leonid maximum, spectroscopic observations were carried out using an Image-Intensified High Definition TV (II-HDTV) cameras in ultraviolet (UV), visible (VIS) and near-infrared (near-IR) wavelength regions (250 - 700 nm). The II-HDTV system consisted of an UV image intensifier (ϕ 18-mm photo-cathode: S20), two relay lenses (f=50mm, F/1.4) and HDTV camera with 2M-pixels CCD. In order to focus precise optical concentration on the wavelength in 250 - 1000 nm, we developed UV lenses of f=30mm,F/1.2 with a field of view of $23^\circ \times 13^\circ$ and wide converter lenses with a field of view of $70^\circ \times 40^\circ$. The HDTV digital imagery has 1920(H) $\times$ 1035(V) pixels that results in 6 times higher resolution than NTSC and PAL standard video system. The recording rate was 29.97 frames (59.94 fields) per second. Spectroscopic observations were performed by the II-HDTV system equipped with a reflection grating, which is 600 grooves per mm, blazed at 330 nm, manufactured by the Richardson Grating Laboratory.

Background stars were removed by subtracting a median frame shortly before or after the meteor spectrum. After flat-fielding and averaging of meteor spectrum, wavelength was determined carefully by means of numerous well-known atomic lines in the meteor emission. Following lines were used for wavelength determination, Fe I(438.4, 373.5, 357.6, 344.1, 323.9 and 302.1nm) Mg I(383.4nm), Mg II(448.1nm) Ca I(422.7nm) and Ca II(393.4 and 396.9nm). 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 $\sim$ 430 nm. The resulting dispersion of the spectrum is 0.37 nm pix^{-1} and FWHM = 1.5 nm in the first order. Since no order-sorting filter was used, it turns out that 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, spectroscopic observation was performed at a high-altitude site in the Nobeyama Radio Observatory of National Astronomical Observatory of Japan (N+35°.93, E138°.48, altitude = 1,340 m). Thanks to excellent observing conditions, clear weather and strong meteor storm activity during the Leonid maximum, its peak activity was well observed around 18:17 UT on November 18, 2001 with the Zenithal Hourly Rate (ZHR) of 3,120 $\pm$ 100, based on reports of the Nippon Meteor Society(Uchiyama, 2002).

3 Results

A detailed spectrum of a Leonid meteor fireball is shown on Fig. 1, which was obtained at 18:58:20 UT on November 18, 2001 within a dust trail ejected by comet 55P/Tempel-Tuttle in 1866 (McNaught & Asher, 1999). Assuming the Leonid radiant (α =+153 °, δ = +22°) and velocity (72 km s^{-1}), the meteor distance R and its altitude H at each frame were inferable. Altitudes to enter our field of view and that of disappearance of this fireball were H = 108.1 km (R = 136.8 km) and H = 80.1 km (R = 124.6 km), respectively. Though the 0th order image was out of the field of view, we could calculate the 0th position on the sky after calibration of pixel-wavelength relationship of the spectrum and distortion of the image, which leaded to few hundred meters accuracy in altitude. The fireball terminated at the altitude of around 82 km. Just before the disappearance of the fireball, a strong enhancement of lines with continuum emissions were detected near the terminal point. Since the enhancement did not persist, within 1/30 sec, intercombination lines is pointed out. The intercombination lines has been observed earlier in the spectra of wakes of bright fireballs (Borovička & Spurný, 1996).

From comparison between meteor emission lines and field-star spectrum, the maximum brightness of the -4th visual magnitude at the standard range of 100 km was derived, which corresponded to a photometric meteoroid mass of $\sim$ 1.8 g estimated by an equation given by Pawlowski et al. (2001). On the assumptions that density is 1.0 or 3.0 g cm^{-3} for this Leonid meteoroid, a diameter of $\sim$15 or $\sim$10 mm is estimated, respectively. All spectral luminosity were normalized at 100 km altitude above the observer. In the later 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 sensitivity calibration is expected the brightest accuracy. Assuming the local thermal equilibrium (LTE), atomic synthetic spectrum was computed by adjusting 5 parameters: temperature T and column densities of 4 atoms (Fe, Mg, Ca, and Na). We made sure that all possible other atoms such as H, N, O, Al, Si, Ti, Cr, Mn, Co, and Ni could be negligible in this wavelength region because these minor emissions blended into strong emission lines due to low resolution spectroscopy. Moreover, no significant contribution of lines of other elements were identified in this spectrum. 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 "main(warm) component", which contains most of the above spectral lines, is T $\sim$ 4,500 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 (Borovička et al., 1999; Trigo-Rodríguez et al., 2003, 2004).

Although overlaps of numerous iron lines prevented us from determining the precise temperature owing to rather low resolution spectroscopy, LTE temperature of 4,100 - 4,700 K for the main spectrum of this Leonid meteor have resulted in all spectrum frames except saturated frames. Thus we applied typical temperatures of 4,500 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 $\times$ 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.

After comparison between observed and synthetic spectra in Fig. 3, we found that these atomic lines could not 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, the SPRADIAN numerical code, which can produce a molecular spectrum at the appropriate temperature and density, was used (Fujita & Abe, 1997). As the result, the best account for two excess bands at 330 and 350 nm was found to be the "First Negative *B*-*X*" band of molecular nitrogen ion N_2^+(1-). Figure 3 shows the model spectrum of N_2^+(1-) with four bands heads (330, 350, 390 and 420 nm) caused by different vibrational states. The model spectrum is wonderfully in complete agreement with the observational spectrum in UV range from 320 to 360 nm. This finding is the first detection of the N_2^+ *B*-*X* molecule in a UV meteor spectrum. The final values of number densities and chemical abundances for this meteor spectrum are summarized in Table 1.

4 Discussion

Smirnov (1967) specified N_2^+ in meteor spectra for the first time. Since then, the presence of the molecular nitrogen ion N_2^+(1-) in meteor spectra was suspected by Millman et al. (1971). Mukhamednazarov & Smirnov (1977) reported the detection of the 427.8 nm (0,1) and the 391.4 nm (0,0) bands in the spectra of faint 3 - 5 magnitude meteors with the aid of intensified TV cameras. However, since the resolution was low ($\sim$ 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 and 3 show clear contribution of Ca I at 422.7 nm and many iron lines which 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 to say that, previous reports could not identify the N_2^+(1-) because it was difficult to detect these bands clearly in VIS region due to overlaps with strong Ca and Fe emissions.

On the other hand, Jenniskens, Laux, & Schaller (2004a) found excessive emissions between 770 and 840 nm with the maximums centered at $\sim$ 789 and $\sim$ 815 nm, which could be caused by the "First Negative *A-X*" band of molecular nitrogen ion N_2^+ Meinel. The evidence of N_2^+ Meinel system was identified in two fireballs (magnitudes of -1 and -7) obtained during the Leonid meteor shower in 2001 and 2002 Leonid Multi-Instrument Aircraft Campaign(MAC) (Jenniskens, 2002; Abe et al., 2003b). Because their un-intensified slit-less 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 abundance (T = 4,400K) of $[N_2^+]/[N_2]$ for the -1 and -7 magnitude fireballs were estimated at 5×10^{-7} and 2×10^{-9}, respectively. In addition to this, a tentative identification of the Fist Negative N_2^+ *B-X* (0,0) band in VIS region was proposed (Jenniskens, Laux, & Schaller, 2004a; Jenniskens et al., 2004b).

Although spectral resolution in our observation was about an order less than Jenniskens' results, we could take full advantage of sensitivity in 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 and (2,0) at 329.3 nm. The Second Positive bands of neutral N_2 molecule was 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 assumption of LTE temperature of 4,500 K (Jenniskens et al., 2000; Jenniskens, Laux, & Schaller, 2004a). The best fit calculation mixed with atomic lines leads to N_2^+(1-) vibrational temperature of 10,000 K. If we assumed the N_2^+ temperature of 4,500 K, the estimated abundance of $[N_2^+]/[N_2]$ leads to $\sim 1 \times 10^{-7}$, which is consistent with results from Jenniskens, Laux, & Schaller (2004a). However, the best fitted spectrum clearly proves that N_2^+(1-) belongs to the "hot component" of T = 10,000 K. Furthermore, another possible evidence for this hot component of assignment of N_2^+ is that the intensity time profiles of N_2^+ and another hot component line of Mg II at 448.1 nm are almost identical.

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 extremely small as 1.55×10^5 cm^{-3}, i.e., $[N_2^+]/[N_2]$ = 1.5×10^{-8}. Few reports have clarified the UV (300 - 350 nm) meteor spectra in the past (Harvey, 1973a,b; Carbary et al., 2003; Jenniskens et al., 2002), and strong features related with 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, Jenniskens, & Laux (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 reflected shock and re-entry 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 re-entry capsules, tends to be in a thermochemical non-equilibrium 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 large meteoroids' vapor cloud. Re-entry speed from interplanetary space is more than 12 km s^{-1} at the altitude of 100 km, which are enough velocity for producing N_2^+(1-) suggested from laboratory experiments (Keck et al., 1959). Therefore, re-entry capsules (meter-size meteoroids) of STARDUST(cometary dust sample return) and HAYABUSA(asteroidal material sample return) directly from the interplanetary space, which will return to the Earth in 2006 January and 2010 June, respectively, will be good opportunities for artificial fireball spectroscopy tests in the future (Yano et al., 2004).

Our spectrum showed high Mg I/Fe I ratio, ~ 11. Mg-rich crystalline olivines were identified as a major mineral component of the dust in the coma of comet P/Halley by the presence of 11.2-11.3 μm peaks in the spectra (Bregman et al., 1987; Campins & Ryan, 1989). The presence of Mg-rich crystalline pyroxene has been confirmed by the detection of the 9.3 μm feature on top of the broad amorphous silicate spectrum in Comet Hale-Bopp (C/1995 01) (Wooden et al., 1999). Our high abundace of Mg/Fe suggested that the high Mg content of cometary dusts can be preserved in relatively large meteoroids. More observed evidences will be needed for further discussion.

Next, let us discuss the subject on another new spectral feature around 310 nm. As mentioned above, several researchers have already pointed out the existence of OH A-X (0,0) band. We investigated other possible lines caused by atomic emissions. According to comparison with synthetic spectrum of atoms, it should be noted that the Mg I at 309.3 and 309.7 nm could certainly contribute to the excess of 310 nm (Fig. 3). If the excess emission above the calculated intensity of Mg I is attributed to OH, the lower limit of OH number density of 1.7×10^{13} cm^{-3} is calculated by the assuming the LTE temperature of 2,000 K. A necessary and sufficient condition of fractional equilibrium temperature for surviving of organics and water was discussed in Jenniskens et al. (2004c).

Abe et al. (2003c, 2004) also obtained UV spectra of meteor persistent train during 2001 Leonid meteor shower in which Abe et al. (2004) identified possible OH A-X emission around 310 nm region. Since the detected OH band in the persistent train was much stronger than in the meteor, the ozon-hydrogen reactions are more likely to occur in the long-lasting train(1). This mechanism is usually considered as Earth's OH airglow namely Meinel band (Meinel, 1955). The atmospheric OH height, $\sim 85km$, is consistent with the emission height of the persistent train. If this mechanism contributes to the persistent train, it seems to be difficult to separate the meteoric effect from other induced atmospheric effects.

$$H + O_3 \rightarrow OH^* + O_2 \quad (1)$$

On the other, the most likely mechanism for emitting OH A-X band in the meteor is caused by the dissociation of water or mineral water in the meteoroid(2).

$$H_2O + h\nu \rightarrow OH^* + H \quad (2)$$

Hydrated mineral phases containing Mg are common and well described in phyllosilicates forming meteorite components (Rubin, 1997), and also they are thought to be common in meteoroids and IDPs (Rietmeijer et al., 2004). In consequence, OH emissions are expected to be detectable and common in meteor spectra produced by hydrated cometary meteoroids like the Leonid members studied here. High resolution and sensitivity and/or statistical analysis of various meteoroids as well as some further explanations of the emission mechanism of OH *A*-*X* band will be needed for future confirmation.

5 acknowledgments

The authors would like to thank Josep M. Trigo-Rodríguez and Vladimir A. Smirnov for their constructive comments and kind advises. This research was supported by the National Astronomical Observatory of Japan of National Institutes of Natural Sciences, the Institute of Space and Astronautical Science of Japan Aerospace Exploration Agency, the Institute of Physical and Chemical Research, and the National Institute of Information and Communications Technology. This study is carried out as a part of "Ground-based Research Announcement for Space Utilization" promoted by Japan Space Forum. This work is partly supported by the 21st Century COE Program "Origin and Evolution of Planetary Systems" under the MEXT.

References

Abe, S., Yano, H., Ebizuka, N., Watanabe J. First Results of High-Definition TV Spectroscopic Observations of the 1999 Leonid Meteor Shower. Earth, Moon, & Planets 82-83, 369, 2000.

Abe, S., Yano, H., Ebizuka, N., Kasuga, T. Sugimoto, M., Watanabe J., Fujino, N., Fuse, T., Ogasawara, R. First results of OH emission from meteor and afterglow: search for organics in cometary meteoroids. In Proceedings of the

Asteroids Comets Meteors 2002 Conference, 29 July-2 August, 2002, Berlin, Germany. Ed.: Warmbein B., ESA SP-500, Noordwijk, 213-216, 2003a.

Abe, S., Yano, H., Ebizuka, N., Sugimoto, M., Kasuga, T., Watanabe, J. Twin Peaks of the 2002 Leonid Meteor Storm Observed in the Leonid MAC Airbone Mission. Pub. of the Astron. Soc. of Japan 55:3, 559-565, 2003b.

Abe, S., Yano, H., Ebizuka, N., Kasuga, T., Sugimoto, M., Watanabe J. UV video spectroscopy of Leonid fireballs and persistent trains. In Proceedings of the 2002 International Science Symposium on the Leonid Meteor Storm, Ed.: Yano H., Abe S., Yoshikawa M., ISAS Report SP-15, Tokyo Press CO., LTD., 149-157, 2003c.

Abe, S., Ebizuka, N., Murayama, H., Ohtsuka, K., Sugimoto, S., Yamamoto, M., Yano,H., Watanabe, J, I., Borovicka, J. Video and Photographic Spectroscopy of 1998 and 2001 Leonid Persistent Trains from 300 to 930 nm. Earth, Moon, and Planets 95, 265-277, 2004.

Borovička, J. A fireball spectrum analysis. Astron. Astrophys. 279, 627-645, 1993.

Borovička, J. Two components in meteor spectra. Planet. Space. Sci. 42, 145-150, 1994.

Borovička, J., Spurný, P. Radiation Study of Two Very Bright Terrestrial Bolides and an Application to the Comet S-L 9 Collision with Jupiter. Icarus 121, 484-510, 1996.

Borovička, J., Stork, R., Bocek, J. First results from video spectroscopy of 1998 Leonid meteors. Meteorit. Planet. Sci. 34, 987-994, 1999.

Bregman, J.D., Witteborn, F.C., Allamandola, L.J., Campins, H., Wooden, D.H., Rank, D.M., Cohen, M., Tielens, A.G.G.M. Airborne and ground-based spectrophotometry of comet P/Halley from 5-13 micrometers. A & A 187, 616-620, 1987.

Campins, H., Ryan, E.V. The identification of crystalline olivine in cometary silicates Astrophys. J. 341, 1059-1066, 1989.

Carbary, J.F., Morrison, D., Romick, G.J., Yee, J.-H. Leonid meteor spectrum from 110 to 860 nm Icarus 161, 223-234, 2003.

Fujita, K., and Abe, T. SPRADIAN, Structured Package for Radiation Analysis: Theory and Application. The Inst. of Space and Astronautical Science Rep. 669, 1-47, 1997.

Harvey, G.A. Spectral Analysis of Four Meteors. IAU Colloq. 13, Evolutionary and Physical Properties of Meteoroids, Ed.: Hemenway C.L., Millman P.M., Cook A.F., NASA SP-319, Washington, D.C., 103-129, 1973.

Harvey, G.A. NASA-LRC Faint Meteor Spectra. IAU Colloq. 13, Evolutionary and Physical Properties of Meteoroids, Ed.: Hemenway C.L., Millman P.M., Cook A.F., NASA SP-319, Washington, D.C., 131-139, 1973.

Harvey, G.A. A search for ultraviolet OH emission from meteors. Astrophys. J. 217, 688-690, 1977.

McNaught, R.H., Asher, D.J. Leonid Dust Trails and Meteor Storms. WGN J. Int. Meteor. Org. 27, 85-102, 1999.

Millman, P.M., Cook, A.F., Hemenway, C.L. Spectroscopy of Perseid Meteor with an Image Orthicon. Canada. J. Phys. 49, 1361-1373, 1971.

Mukhamednazarov, S., Smirnov, V.A. Quantitative analysis of nitrogen band emission 4278 Åin meteor spectra. Astronomical bulletin 11, 101-104, 1977.

Jenniskens, P., Wilson, M.A., Packan, D., Laux, C.O., Kruger, C.H., Boyd, I.D., Popova, O.P., Fonda, M. Meteors: A Delivery Mechanism of Organic Matter to the Early Earth. Earth, Moon, & Planets 82-83, 57-70, 2000.

Jenniskens, P. The 2002 Leonid MAC Airborne Mission: First Results. WGN J. Int. Meteor. Org. 30, 218-224, 2002.

Jenniskens, P., Tedesco, Ed., Murthy, J., Laux, C.O., Price, S. Spaceborne ultraviolet 251-384 nm spectroscopy of a meteor during the 1997 Leonid shower. Meteoritics Planet. Sci. 37, 1071-1078, 2002.

Jenniskens, P., Laux, C.O. Search for the OH ($X^2\Pi$) Meinel Band Emission in Meteors as a Tracer of Mineral Water in Comets: Detection of N_2^+ (A-X). Astrobiology 4, 109-121, 2004.

Jenniskens, P., Schaller, E.L., Laux, C. O., Wilson, M.A., Schmidt, G., Rairden, R.L. Meteors Do Not Break Exogenous Organic Molecules into High Yields of Diatomics. Astrobiology 4, 67-79, 2004.

Jenniskens, P., Schaller, E.L., Laux, C.O., Wilson, M.A., Schaller, E.L. The Mass and Speed Dependence of Meteor Air Plasma Temperatures. Astrobiology 4, 81-94, 2004.

Keck, J.C., Camm, J., Kivel, B., Wentink, T.W. Radiation from Hot Air. Annals of Physics, 7, 1-38, 1959.

Meinel, A.B. OH Emission Bands in the Spectrum of the Night Sky. II. Astrophys. J. 112, 120-130, 1955.

Pawlowski, J.F., Hebert, T.J., Hawkes, R.L., Matney, M.J., Stansbery, E.G. Flux of very faint leonid meteors observed with a 3 m liquid mirror telescope intensified CCD system. Meteorit. Planet. Sci. 36, 1467-1477, 2001.

Rairden, R.L., Jenniskens, P., Laux, C.O. Search for Organic Matter in Leonid Meteoroids. Earth, Moon, & Planets 82-83, 71-80, 2000.

Rietmeijer, F.J.M. Shower Meteoroids: Constraints From Interplanetary Dust Particles And Leonid Meteors. Earth, Moon, & Planets 88, 35-58, 2002.

Rietmeijer, F.J.M., Nuth, J.A.III., Nelson, R.N. Laboratory hydration of condensed magnesiosilica smokes with implications for hydrated silicates in IDPs and comets. Meteorit. Planet. Sci. 39, 723-746, 2004.

Rubin, A.E. Mineralogy of meteorite groups. Meteorit. Planet. Sci. 32, 231-247, 1997.

Smirnov, V. A. Identification of Spectral Lines in Meteors by Means of Laboratory Dispersion Standards. Astronomical magazine, 14, 1316, 1967.

Trigo-Rodríguez, J.M., Llorca, J., Borovička, J., Fabregat, J. Chemical abundances determined from meteor spectra: I Ratios of the main chemical elements. Meteorit. Planet. Sci. 38, 1283-1294, 2003.

Trigo-Rodríguez, J. M., Llorca, J., Fabregat J. Chemical abundances determined from meteor spectra - II. Evidence for enlarged sodium abundances in meteoroids. Monthly Notices of the Royal Astronomical Association 348, 802-810, 2004.

Uchiyama, S. Estimated ZHR Profiles of the 4-Revolution and 9-Revolution Dust Trails during the 2001 Leonid Meteor Storm. WGN J. Int. Meteor. Org. 30, 47-55, 2002.

Viereck, R.A., Mende, S.B., Murad, E., Swenson, G.R., Pike, C.P., Culbertson, F.L., Springer, R.C. Spectral characteristics of Shuttle glow. Geophys. Res. Lett. 19, 1219-1222, 1992.

Wooden, D.H., Harker, D.E., Woodward, C.E., Butner, H.M., Koike, C., Witteborn, F.C. Silicate Mineralogy of the Dust in the Inner Coma of Comet C/1995 01 (Hale-Bopp) Pre- and Postperihelion. Astrophy. J. 517, 1034-1058, 1999.

Yano, H., Yamada, T., Abe, S., Ishihara, Y., Yanagisawa, T., Fujita, K. in JAXA/ISAS Proc., Symposium on Flight Mechanics and Astrodynamics 2003, Ed.: Inatani Y., Sagamihara, Kanagawa, Japan: JAXA/ISAS, 9, 2004.

Table 1
Chemical composition of the Leonid meteor spectrum(t=0.434 s, H=84.1 km)

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=4,500 K)	1.29 (300-450 nm)
OH	$> 1.7 \times 10^{13}$ (T=2,000 K)	0.89 (300-330 nm)
Fe I	5.5×10^{13}	
electron	7.6×10^{13}	
	Abundance	
Mg/Fe = 11	Ca/Fe = 0.1	Na/Fe = 0.03
N_2^+/N_2	$> 1.5 \times 10^{-8}$ (N_2^+: T = 10,000 K, N_2: T = 4,500 K)	
N_2^+/N_2	$\sim 1 \times 10^{-7}$ (N_2^+: T = 4,500 K, N_2: T = 4,500 K)	

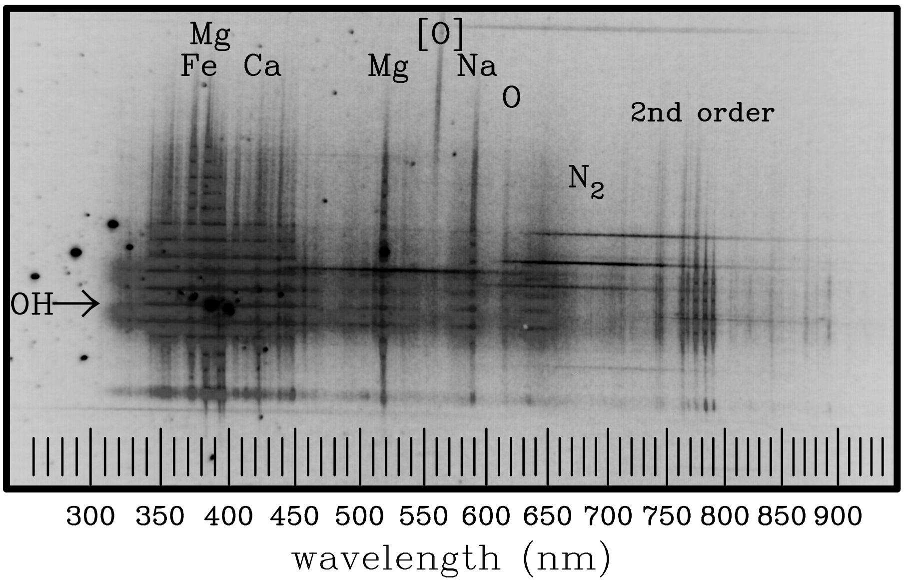

Fig. 1. Raw data of 1st and 2nd order spectrum of 2001 Leonid fireball at 18:58:20 UT on November 18, 2001. This image(the field of view of 23°× 13°) is composed of 15 consecutive frames during the total duration of 0.5 sec. The meteor moved from top to bottom of this image. The dispersion direction is from left to right and parts of the 2nd and 3rd order spectra are on the right. A part of radiation comes from forbidden lines of neutral oxygen known as auroral green line at 557.7 nm. Forbidden green line has an evidently different origin than other lines. First meteors such as Leonids and Perseids form a short-living train caused by this line.

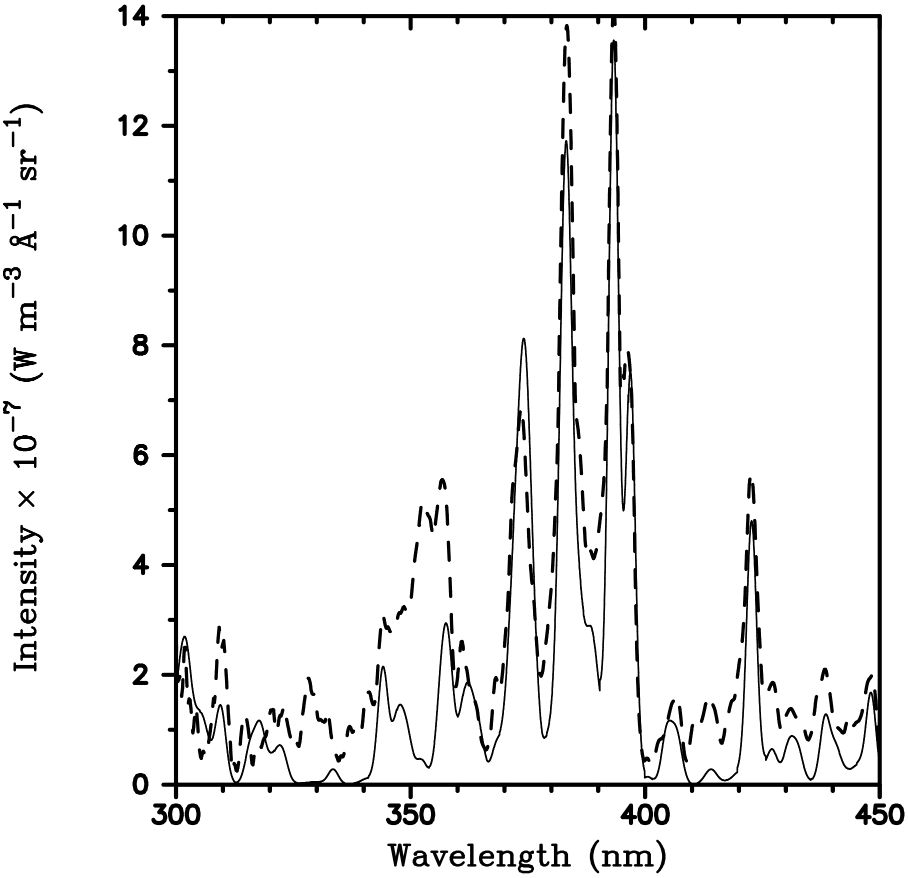

Fig. 2. Observed spectrum (dashed line) compared with synthetic spectrum considering only atoms (solid line). The synthetic spectrum consists of Mg I at 383.8 nm and Ca II at 393.4 and 396.8 nm, Ca I at 422.7 nm and Mg II at 448.1 nm with numerous iron lines. There are unexplained emissions at $\sim$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

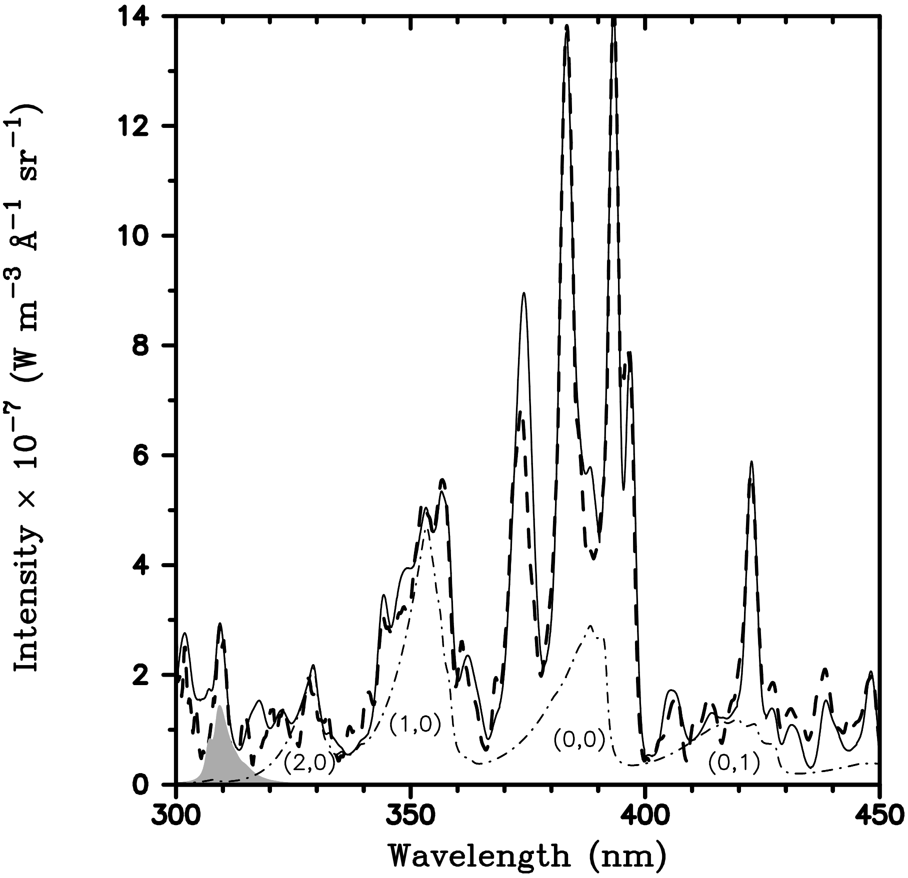

Fig. 3. Observed spectrum(dashed line) compare with synthetic spectrum considering atoms and molecules of N_2^+(1-) with a temperature of 10,000 K (solid line). Dash-dot line indicates N_2^+(1-) at the temperature 10,000 K. The gray filled area near 310 nm shows OH A-X bands.