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UV video spectroscopy of Leonid fireballs and persistent trains

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Abstract: Cometary meteoroids are considered as one of the best candidates to have supplied organic compounds to the Earth in the early stage of its history. However, there had been no observational evidence to support this hypothesis until recently. Thus we conducted spectroscopic observations of the 2001 Leonid meteor shower by using intensified HDTV cameras equipped with a reflective grating which covers 300-700 nm wavelength range. In order to minimize the effect of air extinction near 300 nm, the observations were performed at a high elevation, i.e., the Subaru Telescope Hawaii observatory (h=4,100 m) and Nobeyama Radio Observatory (h=1,340 m) of National Astronomical Observatory of Japan. Spectral features of hydroxyl radicals in the cometary meteoroids were clearly observed. In this paper, we show the first result of detection of OH emission from the ground and discuss on the origin of the discovered OH A-X (0,0) band.

1. INTRODUCTION

Comets are the surviving bodies since the genesis of our solar system. They are thought to be remnants of planetesimals at the edge of the protoplanetary disk that could not grow into planets. Comets spend almost all their time at great distances from the Sun. As comets are heated by sunlight near its perihelion, the materials on the parent body are sublimated. Meteor emission originates from a mixture of atoms and molecules ablated from the meteoroid itself as well as from the surrounding air.

When the meteoroid penetrates into the Earth's atmosphere, it is gradually heated by collisions with air atoms and molecules until the particle evaporate individual compounds in order of sublimation temperature (Bronshten (1983)). The process of mass loss by a meteoroid is

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known as "ablation". The ablation process enables remote observations to measure the constituent parts of the meteoroids. Interplanetary dust particles (IDPs) represent grains small enough to be gently decelerated in the upper atmosphere without melting. At 4 Gyr ago, the Earth would have been accreting $2 \times 10^8 kg\,yr^{-1}$ of organics from IDPs, which were estimated by Chyba and Sagan (1997). Of all exogenous sources of organic matter, only IDPs were considered (Anders et al. (1989); Chyba and Sagan (1997)). The delivered mass of organics matter from meteors are estimated to $2 \times 10^9 kg\,yr^{-1}$ (Jenniskens et al. (2000)). Meteors, solid particles larger than about diameter of 100 μm and smaller than about 1 m, are potentially efficient sources of extra-terrestrial organics which come from comets.

Fig. 1: 1999 Leonid Meteor Storm. Composite of meteor image displays about 200 Leonid meteors were obtained within 1 minute. FOV is $60^\circ \times 34^\circ$ Zenith Hourly Rate ZHR 4,100 at 02:02 UT on November 18, 1999 (Abe et al. (2000); Jenniskens et al. (2000)).

Every 33 years, or thereabouts, the Leonid meteor shower occurs when Earth's path crosses the tilted orbit of Comet Tempel-Tuttle (55P/Tempel-Tuttle). Through detailed meteor observations and analysis of their interaction with the Earth's atmosphere, physical and chemical properties of cometary meteoroids can be studied. Moreover, organic molecules thought to be delivered to the Earth even today. However, there had been no observational evidence to support this hypothesis until recently. Meteor storm (Fig. 1) is the best chance to search for organics because of the high detectable probability in the narrow field of view for the precision spectroscopic observations. Leonid MAC (Leonid Multi-Instrument Aircraft Campaign) is NASA's first astrobiology mission to learn how extraterrestrial materials may have been brought to the Earth at the time of the origin of life (Jenniskens and Butow (1999)). From 1999 Leonid storm (1999 Leonid MAC), we searched for the (0,0) band of $B^2\Sigma^+ \longrightarrow X^2\Sigma^+$ transition of the CN molecule around 388 nm. CN emission was not detected significantly above the blends of metal atom lines caused by neutral FeI, MgI at 382, 383 nm and ionized CaII at 392, 395 nm, not even at the higher altitudes where metal atom lines are less dominant (Abe et al. (2000)). The upper limit abundance of CN relative to Fe, [CN/Fe] =0.03 is reported (Rairden et al. (2000)). The purpose of this paper is to search for new emission lines related with cometary organics in ultra-violet region.

Two-cannel photometric measurements of emission at OH wavelength in Perseid and alpha-

Capricornid spectra were reported (Harvey (1977)). However, the source of the emission remains unknown. On the other hand, OH emission of 1997 Leonid was observed by the UV spectroscopic observations from the space satellite (Jenniskens et al. (2002)). But the data are noisy and there can be potentially large residuals arising from the imperfect subtraction of the background air-glow. Spectroscopic observations of 2001 Leonid meteor storm were carried out using a intensified HDTV camera equipped with a reflective grating covering 300 - 700 nm wavelength range. Hydroxyl radical in the cometary meteoroids was observed in fireballs and persistent trains. A good knowledge of the relationship between meteors and comets is needed for understanding of the cometary volatiles. In this paper, we show the first detection of OH A-X (0,0) emission from the ground-based observations and discuss about the origin of the discovered OH.

2. OBSERVATIONS

During the 2001 Leonid maximum, Visual-UV (250 - 800 nm) spectroscopic observations were carried out using two II-HDTV (Image-Intensified High Definition TV) cameras. The II-HDTV was composed of a large diameter image intensifier along with a 1-inch 2M-pixel FIT CCD. HDTV has a longer scanning line (25.86 Fs of visible line time) and a higher video line count (1080 visible lines) with higher sampling frequency (74.25 MHz which get cut in half, 30MHz, because of the Nyquist theorem) that will result in a lot higher resolution than normal digital video. Moreover, HDTV digital can possible to record in 10-bit which is 4 times higher dynamic range than previous video systems. The intensified high definition TV technique increases the number of TV lines from about 525 (NTSC) to 1080, 6 times higher resolution than normal digital video camera, and has higher 10-bit dynamic range, 4 times higher dynamic range than previous video systems. For a given field of view (23°×13°), The intensified HDTV system is more sensitive than conventional intensified CCD cameras. Meteors as faint as 8th magnitude and stars of 11th magnitude can routinely be observed even with a wide 37° × 21° field lens (Watanabe et al. (1999); Abe et al. (2000)). Our spectroscopic observations were performed by the intensified HDTV camera equipped with a transmission grating with 500 grooves per mm, blazed at 330 nm, made by the Richardson Grating Laboratory (Ebizuka et al. (1998)). The effective spectral sensitivity of the UV-VIS-II-HDTV including atmosphere extinction was constructed by measuring a number of spectra of bright main-sequence stars in the observing field. Fig.2 indicates the sensitivity curve of the UV-II-HDTV. This system is sensitive in 300–700 nm range, with the maximum sensitivity at 390 nm. Spectral resolution of this system is R=300, which means the resolution is about 1.0 nm at 300 nm. Detailed of our instruments are given in Kasuga et al. (2003).

In order to prevent air extinction owing to mainly aerosol scattering in the ultra-violet wavelength near 300 nm, spectroscopic observations were performed at high-altitude observing sites, Subaru Telescope at the summit of Mauna Kea Hawaii (height = 4,139 m) and Nobeyama Radio Observatory at Nagano prefecture (height = 1,340 m), which are operated by the National Astronomical Observatory of Japan (NAOJ), respectively. Thanks to excellent observing conditions, clear weather and wonderful meteor storm during the Leonid maximum. In Japan, the peak activity was observed around 18:15 (UT) on November 19, 2001 with a peak Zenithal Hourly Rate (Z.H.R.) in naked eye of 3,000 based on report of Nippon Meteor Society (NMS) and IMO (International Meteor Organization) (Arlt et al. (2001); Ogawa and Uchiyama (2001)).

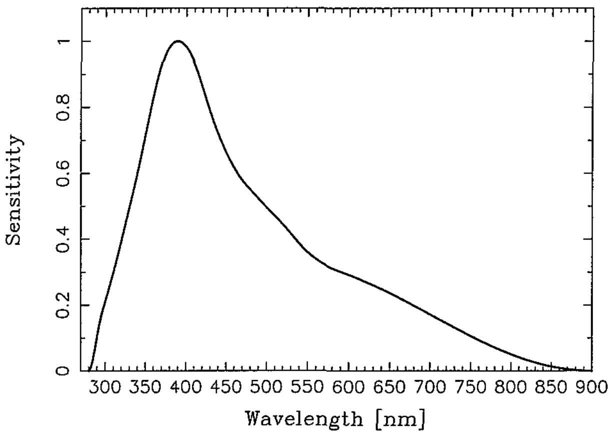

Fig. 2: Spectral sensitivity curve of the UV-VIS-II-HDTV system including the atmosphere extinction.

3. RESULTS

3.1 Leonid fireball

Here, we report on the first UV spectroscopic observations using intensified high-definition TV from the ground. From both observational stations, we confirmed around 310 nm band emissions from the fireballs and the meteor trains respectively. The results shown here are based on the detailed analysis of a high-quality spectrum of a Leonid fireball and a persistent train. The excellent Leonid fireball spectrum was observed at 17:07:38 UT on November 18. Fig.3 shows the composite spectrum image of the fireball obtained by the UV-II-HDTV. The 0th order image is out of the left side of the frame. The dispersion direction is from right to left and a part of the 2nd order spectra is on the right part. Fig.4 indicates the time series of spectrum calibrated by the system sensitivity in UV-VIS(300–700 nm) range. Some spectra seem to be flat at the highest point because of saturation. The HDTV image consists of 30 frames or 60 interlaced fields per second, more detailed rate is 29.97 frames or 59.94 fields per second. The time step of Fig.4 means the spectrum of each field. However, the integration time of the field spectrum is 1/30 sec the same integration time as the frame spectrum. Assuming the local thermodynamic equilibrium (LTE) in the meteor emission, excited temperature of $4,500 \pm 300K$ has been measured by using atomic Fe lines in short wavelength range from 370 to 550 nm.

A bright afterglow was seen at the end of the bright flares. The afterglow shows an immediate sharp increase and rapid drop with a period of 0.13 sec. The duration time of this afterglow is shorter than the afterglow spectrum of a 1999 Leonid fireball over a period of a few seconds(Borovička et al. (2000); Borovička et al. (2002)). We can only assume from the sense of the duration time that the second peak was caused by another emission mechanism, such as "recombination" of free electrons generated by the meteor plasma. Fig.5 shows the two emission phase spectra of afterglow(upper) and meteor(lower), respectively. Mg(518, 553,448 nm) and Ca(422 nm) emissions show a significant increase. It remains an unsettled question what cause the second emission. However, we may leave the details to discuss on the mechanism in this paper.

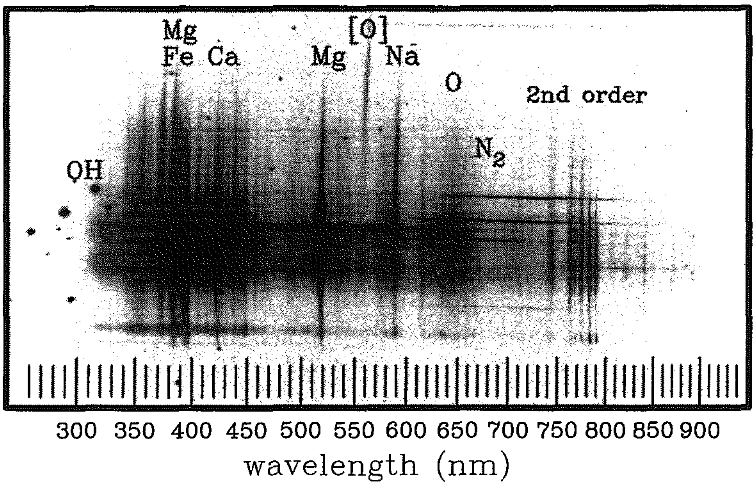

Fig. 3: Composite HDTV spectrum of 2001 Leonid fireball. Duration time of this spectrum image is 0.53 seconds.

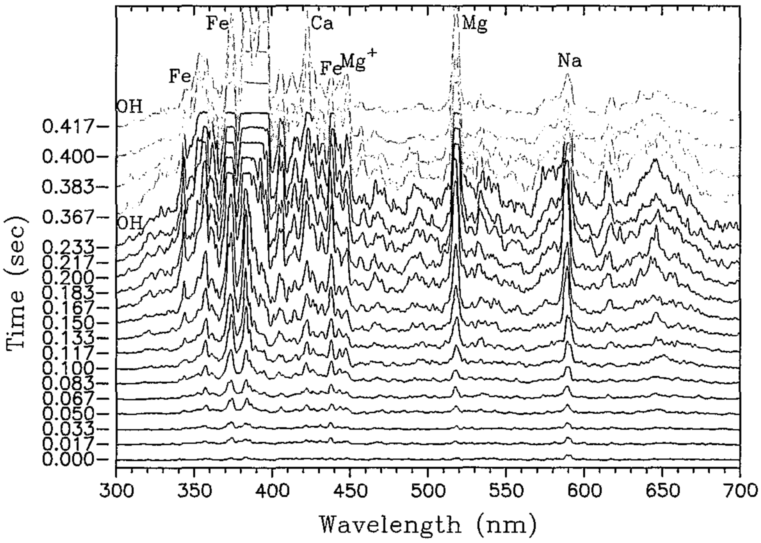

Fig. 4: Time series of 2001 Leonid fireball spectrum in UV and VIS region (300-700nm). Strong saturated spectra around the flare point of the meteor were omitted.

3.2 Leonid persistent train

Meteor persistent train is a luminous cloud formed by meteor which persist long after the disappearance of the parent meteor. It is considered that the clouds consist of a mixture of atoms and molecules ablated from the meteoroid itself as well as from the surrounding Earth's atmosphere. Magnesium and iron are the most dominant atoms in the early stage (a few seconds ~ 30 sec) of the persistent train, so called "after glow", while sodium is also rich in the after glow (Abe (2001)). One Leonid of magnitude -10 appeared at 16:47:24 UT on November 18 and this meteor left the long-lived train, which was visible by naked eye for more than 30

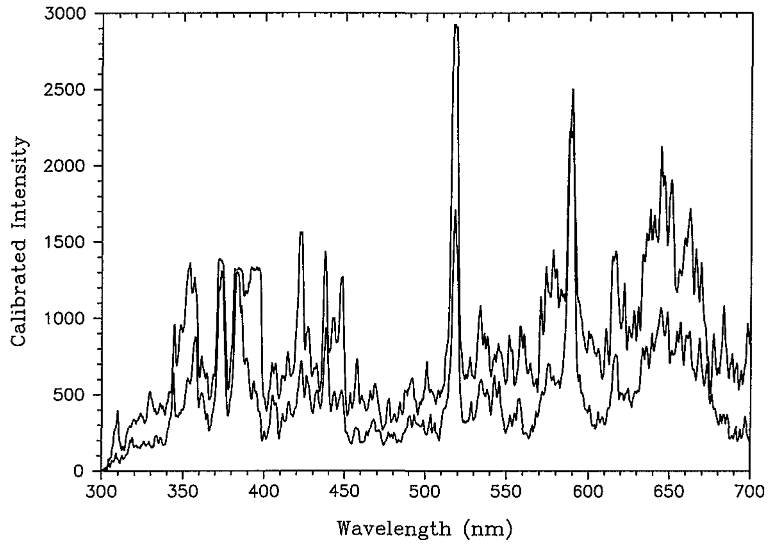

Fig. 5: Afterglow spectrum(upper; T=0.417 s) with meteor phase spectrum(lower; T=0.167 s). Mg, Ca and continuum components enhanced at the afterglow.

minutes. The exposures started from 10 seconds after the meteor's disappearance. In this spectrum, we discovered the OH A-X (0,0) band. The hydroxyl radical radiates strongly in the ultra-violet between 305 and 310 nm. Fig. 6 shows the observational meteor train spectrum in 300–350 nm range compared with synthetic spectrum of OH A-X (0,0) band. The identified iron lines in the train imply an excitation temperature of $\sim 1,000K$. In the synthetic spectrum, the excited temperature is set of 1,000 K and the spectrum is convolved by Gaussian of 0.5 nm FWHM. The spectrum is normalized to 30.0 at the maximum intensity. The position of observed band heads of 305–315 nm are similar to that of calculated. 334, 343 and 347 nm features are caused by atomic Fe lines.

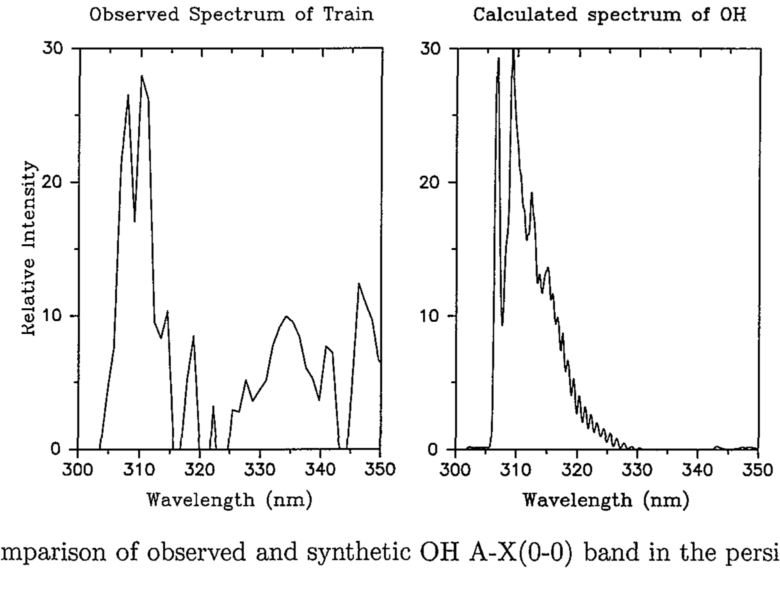

Fig. 6: Comparison of observed and synthetic OH A-X(0-0) band in the persistent train.

4. DISCUSSION

Fig.7 indicates a set of time series UV spectrum after the meteor flare point. There exists a band feature around 305–310 nm. At this point, we cannot give a clear interpretation for the source of the band emission. However, the calculated profile of OH A-X (0,0) band agrees very well with the observed profile of the meteor persistent trail. Such comparisons for the (0,0) band arising from $A^2\Sigma^+ \longrightarrow X^2\Pi$ transitions of OH molecules have also been carried out for various comets. The most abundant species in comets is H_2O, which dissociates to the most abundant radicals OH and H. Central to this issue is the problem of the origin of the discovered OH. It offers the key to an understanding of the exogenous sources of organic matter to the early Earth. It will be useful to make a distinction between several possibilities of the origin of the OH molecules.

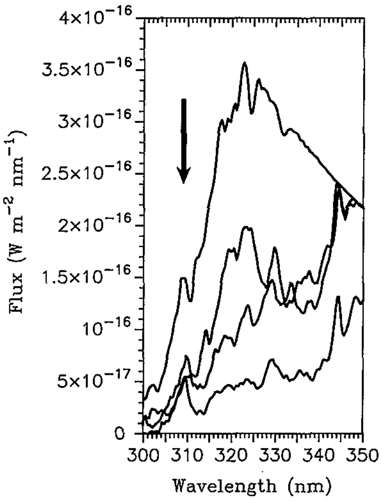

Fig. 7: Time series of 2001 Leonid fireball spectrum in UV region (300-400nm). The spectrum is calibrated by the system sensitivity. The curved feature(upper-right) is caused by the results of saturated spectrum divided by the system sensitivity.

- Assuming the mother molecule of OH is H_2O, water content in the atmosphere at $\sim 100\,km$ is supposed to be about several tens ppm. However, explained OH content at $\sim 100\,km$ is less than 1 ppm. Thus, it is hard to say that the origin of OH is H_2O in the upper atmosphere.

- OH abundance in the high altitude atmosphere ($100\,km$) cannot explain the strong OH emission in the meteor spectrum. Therefore, the OH emissions from meteors may account for the extra-terrestrial source. Otherwise, the following can be considered as one of the example reaction in the upper-atmosphere, $O_3 + H \longrightarrow OH^* + O_2$.

- Water ice is not expected to survive in the meteoroids for a long time. This spectrum represents the evidence that presence of hydrous silicate minerals may be condensed in hydrated mineral.

- Cometary meteoroids can contain significant mineral water or OH such as in hydrate chondrites (Saponite and Serpentine (Rietmeijer (2002))).

- OH number density at the height of 80 km is 10^6 cm^{-3} form the space observation of CRISTA-SPAS satellite (Conway et al. (1999)). Atmospheric OH at the lower altitude can be excited by meteor interaction with the atmosphere.

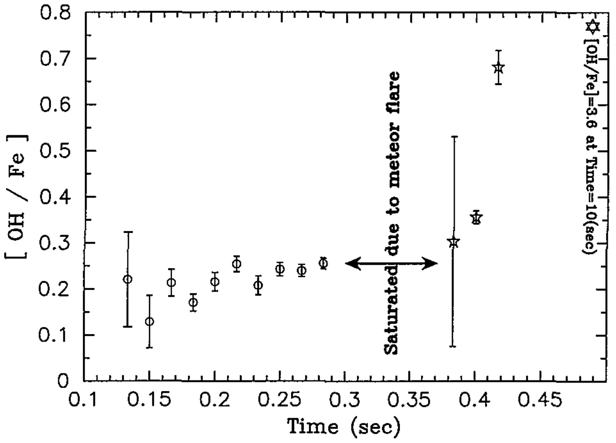

Fig. 8: Time evolution of [OH/Fe] in the Leonid fireball and persistent train spectra.

Fig.8 shows the time evolution of a [OH]/[Fe] ratio in the Leonid fireball compare with the ratio in the persistent train. Before the meteor flare, the [OH]/[Fe] ratio is steady at 0.2 or a slight increase. While there is marked increase in the [OH]/[Fe] ratio after the flare. The ratio is 0.36 (T=0.400 s) and 0.68 (T=0.417 s). The [OH]/[Fe] ratio in the persistent train indicates 3.6 (T=10.0 s) which is shown in the same figure. In the following, it shall be assumed that an immediate sharp enhancement of the [OH]/[Fe] ratio at the late stage of the fireball is resulted from the excitation of atmospheric OH. However, the existence of the OH emission at the early stage came from meteoroids itself.

Amorphous carbon globules were discovered within the structure of the Tagish Lake meteorite. The observed globules have apparent diameters of 140–1700 nm and some globules contain saponite flakes (Nakamura et al. (2001)). This result helps account for the result of our discovered OH. That is to say, the same protective place exist in the meteor and primitive organics would have served very well to protect by some shielding effects. Assuming this hypothesis, meteors are candidates to explain the exogenous veneer of pre-biotic organics on the early Earth as well as meteorites or IDPs. In particular, to evaluate feasibility of emission mechanism and origin of the discovered OH, we will observe 2002 Leonid meteor shower from observational aircraft in the Leonid MAC. Further observational results from the 2002 Leonid meteor storm will be appeared in the forthcoming paper.

On the other hand, the identification of asteroidal spectra classes with specific meteoritic types is still in controversy. MUSES-C sample return mission become available for comparison with ground-based telescopic database(Fujiwara et al. (1999)). However, there are no plans to send spacecraft to every asteroids and comets. Therefore, observations of meteors from different showers with different parent bodies can be used to some motivations for future explore missions. In particular, ultraviolet spectra of meteors entering the Earth's atmosphere is very important for understanding the ratio of more volatile elements such as carbon, oxygen and nitrogen to the refractory components of meteors. There is a large "iron-free" window predicted to be observable in the 115–215 nm UV region(Achal et al. (1986)). I would like to propose a new approach to search for volatiles and amino acid precursors(Kobayashi et al. (1995)) in the cometary meteoroids using the iron-free window. However, the meteor radiation at wavelength short-ward of ~ 310 nm is absorbed by the Earth's atmosphere. Therefore, the space is the next observational platform of the meteor spectroscopy in the near future.

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