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# HELIOCENTRIC DEPENDENCE OF THE SODIUM EMISSION OF COMET 153P/IKEYA-ZHANG

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## ABSTRACT

A low-dispersion spectroscopic monitor of comet 153P/Ikeya-Zhang was carried out from 2002 February through May. The sodium emission was derived mainly during March, when the heliocentric distance of the comet was between 0.511 and 0.764 AU. The number of the produced sodium atoms relative to the total cross section of dust grains follows a power law of $r^{-5.1 \pm 1.0}$, where $r$ is the heliocentric distance. This fact strongly suggests that the sodium is released by a thermal desorption mechanism, not by the photosputtering mechanism from cometary grains. The derived potential barrier for the release of the sodium is 0.49 ± 0.10 eV, which is about half of that in the case of the Moon.

*Subject headings:* comets: individual (153P/Ikeya-Zhang) — interplanetary medium — meteors, meteoroids — Moon

## 1. INTRODUCTION

Sodium is one of the interesting atoms in comets. Historically it has been observed in the tail of some bright comets that appeared in 1960, and it has been suggested that it was included in the meteoritic materials due to the high latent heat derived from the careful consideration by Huebner (1970). In 1980, several spectral observations indicated that the sodium existed in the coma of comets, which were located at around 1 AU from the Sun (e.g., comet 1P/Halley). Moreover, Cremonese et al. (1997) discovered the sodium tail in comet C/1995 O1 (Hale-Bopp) in 1997. This is a new type of cometary tail, which consists of neutral atoms. The formation and the time variation of this sodium tail was well explained by the combination of the strong solar radiation pressure together with the Doppler shift of the solar absorption line of the sodium due to the change of the heliocentric radial velocity of comets (Kawakita & Fujii 1998). The sodium tail was thought to result from the evaporation of the small dust grains (Wilson, Baumgardner, & Mendillo 1998). From a chemical point of view, the dust in cometary nuclei is also thought to be the main repository of the sodium (Rietmeijer 1999).

However, a major problem in the origin of the sodium from comets has not been clarified until now. It is the mechanism of the release of the cometary sodium. We do not know how to release the sodium from the cometary dust particles. On the other hand, intensive research on the sodium atmosphere of the Moon and Mercury have been performed so far. Although the main mechanism of sustaining the sodium atmosphere in the Moon appears to be photosputtering desorption (Yakshinskiy & Madey 1999), there is little or no consensus about the dominating mechanism, owing to many difficulties, such as interference of the bright bodies, time variation, and finite structure of the atmosphere with definite spatial distribution. Fortunately, cometary sodium can be studied simply because we can regard the sodium produced by small grains under different conditions of the solar flux because of the time variation of the heliocentric distance of the comets due to the orbital motion. We tried to utilize the cometary orbital motion as a variable condition in the natural experiment for inspecting the variation of the sodium production. A long-term monitor of the sodium on the comet will be a key to solving the unknown mechanism of the sodium release from cometary dust particles.

Here we present our result of a spectroscopic monitor of comet 153P/Ikeya-Zhang, mainly focusing on the heliocentric dependence of the sodium, and propose that the thermal desorption is the major mechanism for the release of the sodium from cometary grains.

## 2. OBSERVATION

Comet 153P/Ikeya-Zhang was discovered on 2002 February 1 (Ikeya & Zhang 2002). One of our authors (M. Fujii) carried out a low-resolution spectroscopic monitor of comet 153P/Ikeya-Zhang from 2002 February through May, by using a 28 cm Schmidt-Cassegrain telescope at the Fujii-Bisei Observatory, which was located at Okayama prefecture, Japan (N34°.67, E133°.55, $H = 400$ m). A low-dispersion spectrograph, of which spectral coverage is 450–700 nm, was used together with an electric cooled CCD camera (type ST-6, Santa Barbara Instrument Group). The size of the slit is $7''.4 \times 420''$, and the spectral resolution ($\lambda/\Delta\lambda$) is about 450 at 550 nm. The slit was put on the optical center of the coma through all observations.

Among the obtained data, the sodium emission was recognized from February 20 through April 12 as shown in Figure 1. The range of the heliocentric distance was between 0.764 and 0.511 AU. The observational parameters are shown in Table 1.

## 3. REDUCTION AND ANALYSIS

The observed spectra were reduced by a standard procedure (TWODSPEC and ONEDSPEC) built in the IRAF astronomical software package provided by NOAO. Since our spectro-

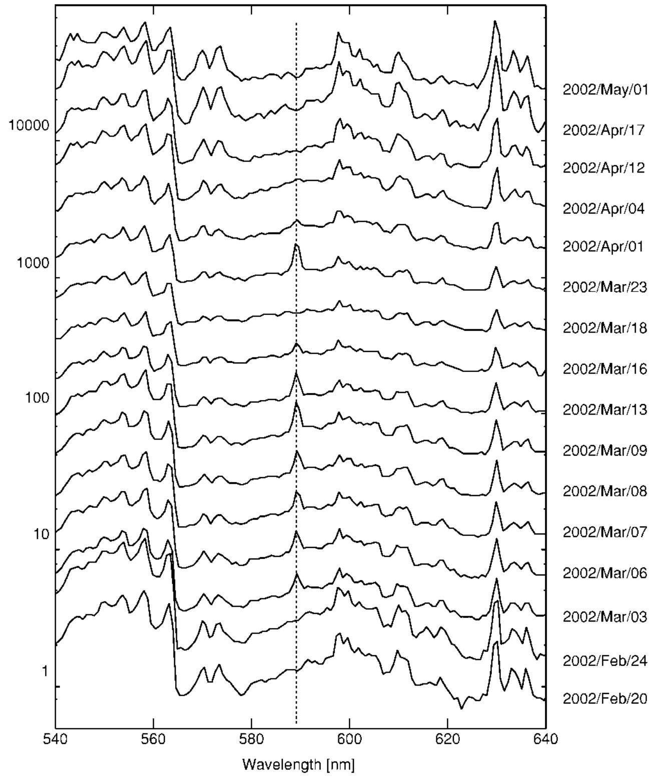

FIG. 1.—Spectra of comet 153P/Ikeya-Zhang during our monitoring. The lowest spectrum is on 2002 February 20.4 UT, and the spectra lie in order of date, from bottom to top (see Table 1). The vertical axis is logarithmic, and it shows the flux in arbitrary units. Sky background signals have been subtracted. Cometary sodium D line emissions are recognized at 589 nm on the dotted line.

graph has a long slit, both a cometary spectrum and the sky background spectrum can be obtained simultaneously. The cometary signals are collected from the near nucleus region, 7″.4 within the length of 35″.8 at the sky. The spectrum of the sky background region far from the nucleus by between 119″ and 149″ is also extracted and was used for the subtraction applied to the cometary spectrum.

A cometary spectrum consists of cometary gaseous emissions and the reflected sunlight by cometary dust grains. The reflected sunlight is subtracted using the solar analog spectrum of which the Moon was used in this study. In this process, we assumed the albedo of cometary dust as a quadratic function of the wavelength, where the five emission-free regions in the cometary spectrum were fitted.

Unfortunately, the sodium D lines at 589 nm are contaminated by the weak $C_2$ emission band (Swan band, $\Delta v = -2$). In order to avoid this contamination, we use the template spectrum of the $C_2$ Swan band ($\Delta v = -2$), which is obtained from the observations on April 17.8 and May 1.6 when the sodium emission was not recognized in our data. After the $C_2$ template spectrum is subtracted, the flux of sodium emission at 589 nm (in units of ergs $\mathrm{cm^{-2}\ s^{-1}}$) is measured for each date.

The continuum was also estimated at 580 nm (in units of ergs $\mathrm{cm^{-2}\ s^{-1}\ nm^{-1}}$) by fitting the derived quadratic function mentioned above to the data at the emission-free regions such as 480, 525, and 625 nm, in order to avoid the contamination of the gaseous emissions at this wavelength.

Here we concentrate on the ratio of the sodium to continuum flux. This is done mainly because the sodium is thought to be released from the cometary grains; the ratio of the sodium emission to the continuum should be an excellent index of the sodium production. Moreover, we deal with this ratio partly because of the difficulty of determining the absolute flux of the sodium emission from our observation. The strength of the emission line depends both on the emission mechanism of sodium D lines and on the production mechanism of sodium atoms. The emission mechanism of sodium D lines is well known as a fluorescence, which depends strongly on the incident solar flux at 589 nm for the comets. This flux to the comets varies by the Doppler effects by the relative velocity caused by the orbital motion of the comet. Furthermore, the reflected sunlight depends also on the scattering efficiency at a phase angle of the comet. Therefore, we correct the sodium-to-continuum ratio where the heliocentric radial velocity is 0 km $\mathrm{s^{-1}}$, by using the data shown in Figure 2, and the phase angle is 50°. The correction of the phase effect is based on the data by Mason et al. (2001). The change of the flux ratio corrected by these effects is shown in Table 2. The final value after these corrections should be proportional to the ratio of the number of sodium atoms to the total cross section of dust particles at each observation epoch.

The major factor of the error in such measurements comes from the background subtraction including the atmospheric so-

TABLE 1
OBSERVATIONAL LOG

| Observation Date (UT) | Exposure Time (s) | $r$ (AU) | $\Delta$ (AU) | Phase Angle (deg) | Heliocentric Radial Velocity (km $\mathrm{s^{-1}}$) | Remarks |
|---|---|---|---|---|---|---|
| 2002 Feb 20.4 ...... | 980 | 0.792 | 1.307 | 49.0 | −28.21 | No Na emission |
| 2002 Feb 24.4 ...... | 1446 | 0.728 | 1.243 | 52.7 | −27.04 | Na emission |
| 2002 Mar 3.4 ....... | 1832 | 0.626 | 1.121 | 61.7 | −23.07 | Na emission |
| 2002 Mar 6.4 ....... | 980 | 0.588 | 1.065 | 66.7 | −20.30 | Na emission |
| 2002 Mar 7.4 ....... | 1210 | 0.577 | 1.045 | 68.6 | −19.19 | Na emission |
| 2002 Mar 8.4 ....... | 1022 | 0.566 | 1.026 | 70.5 | −17.99 | Na emission |
| 2002 Mar 9.4 ....... | 906 | 0.556 | 1.007 | 72.5 | −16.69 | Na emission |
| 2002 Mar 13.4 ...... | 920 | 0.524 | 0.928 | 81.3 | −10.53 | Na emission |
| 2002 Mar 16.4 ...... | 570 | 0.511 | 0.868 | 88.4 | −5.03 | Na emission |
| 2002 Mar 18.4 ...... | 906 | 0.507 | 0.829 | 93.2 | −1.14 | No Na emission (Swings effect) |
| 2002 Mar 23.4 ...... | 990 | 0.518 | 0.735 | 104.0 | 8.48 | Na emission |
| 2002 Apr 1.4 ....... | 930 | 0.599 | 0.594 | 113.9 | 21.17 | Na emission |
| 2002 Apr 4.4 ....... | 930 | 0.638 | 0.556 | 113.7 | 23.73 | Na emission |
| 2002 Apr 12.8 ...... | 540 | 0.764 | 0.473 | 105.8 | 27.77 | Na emission |
| 2002 Apr 17.8 ...... | 480 | 0.845 | 0.439 | 97.8 | 28.78 | No Na emission |
| 2002 May 1.6 ....... | 1434 | 1.079 | 0.406 | 69.1 | 29.29 | No Na emission |

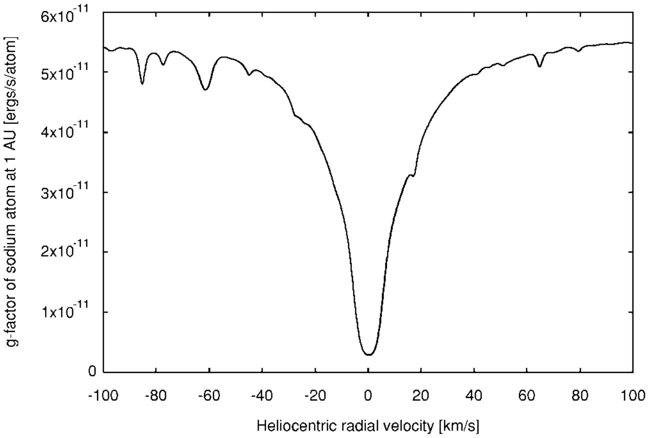

FIG. 2.—Variation of the applied $g$-factor at 1 AU for the sodium atom with heliocentric radial velocity. We applied $r^{-2}$ low to obtain the $g$-factor at $r$ AU.

TABLE 2

FLUX RATIOS

| Observation Date (UT) | $r$ (AU) | Na/Continuum[a] | Deduced Na/Continuum[b] |
|---|---|---|---|
| 2002 Feb 20.4 ...... | 0.792 | ... | ... |
| 2002 Feb 24.4 ...... | 0.728 | 2.882 ± 0.89 | 0.193 ± 0.06 |
| 2002 Mar 3.4 ....... | 0.626 | 10.47 ± 0.42 | 0.724 ± 0.03 |
| 2002 Mar 6.4 ....... | 0.588 | 11.16 ± 0.89 | 0.810 ± 0.06 |
| 2002 Mar 7.4 ....... | 0.577 | 10.96 ± 0.55 | 0.833 ± 0.04 |
| 2002 Mar 8.4 ....... | 0.566 | 10.98 ± 0.44 | 0.875 ± 0.04 |
| 2002 Mar 9.4 ....... | 0.556 | 15.02 ± 0.45 | 1.243 ± 0.04 |
| 2002 Mar 13.4 ...... | 0.524 | 11.23 ± 0.22 | 1.313 ± 0.03 |
| 2002 Mar 16.4 ...... | 0.511 | 7.113 ± 0.28 | 2.156 ± 0.06 |
| 2002 Mar 18.4 ...... | 0.507 | ... | ... |
| 2002 Mar 23.4 ...... | 0.518 | 14.66 ± 0.44 | 2.714 ± 0.11 |
| 2002 Apr 1.4 ....... | 0.599 | 6.278 ± 0.25 | 0.794 ± 0.04 |
| 2002 Apr 4.4 ....... | 0.638 | 5.214 ± 0.21 | 0.622 ± 0.02 |
| 2002 Apr 12.8 ...... | 0.764 | 1.844 ± 0.13 | 0.190 ± 0.01 |
| 2002 Apr 17.8 ...... | 0.845 | ... | ... |
| 2002 May 1.6 ....... | 1.079 | ... | ... |

[a] The ratio between the measured sodium emission and the estimated continuum flux at 580 nm.

[b] The corrected ratio for a heliocentric radial velocity and the phase angle (see text).

dium emission and the $C_2$ template spectrum. Because we used the long slit, the error for the sky contribution should be small. However, the $C_2$ template spectrum may be reconsidered in the future. The independent data given by Cremonese et al. (2002) indicated sodium emission in their high-dispersion spectroscopic observation on 2002 April 20, while we could not recognize it in our observations on both April 17.8 and May 1.6. This implies that our $C_2$ template spectrum for the subtraction may include very weak sodium emission or that the sodium production increased temporally around 2002 April 20. If the sodium emission exists in our $C_2$ template spectrum made from the data on April 17.8 and May 1.6, it may lead us to a lower sodium flux measurement.

In order to subtract the molecular emissions around 589 nm, it is better to use the synthesized spectrum of $C_2$ as well as $NH_2$, $H_2O^+$, and so on. Such spectral synthesis is still ongoing, and a further treatment is beyond the scope of this Letter.

## 4. RESULTS AND DISCUSSIONS

Figure 3 shows the heliocentric dependence of the derived ratio of the sodium emission relative to the continuum emission. It is clearly shown that the quantity of the sodium increased with the smaller heliocentric distance. When the data are fitted by a simple power law of the $r^k$ function, where the $r$ denotes the heliocentric distance in units of AU, the derived value of the power index $k$ is $-5.1 \pm 1.0$.

This dependence is steeper than expected if we assume the photosputtering on the dust particles to be the main mechanism of the sodium production, where the expected power index should be $-2$. On the other hand, such steep heliocentric dependence can be explained by the thermal desorption mechanism as proposed for the main mechanism of the sodium production at the subsolar point of the Moon (Sprague et al. 1992). This is a reasonable result, as shown below.

The possible mechanisms for supplying sodium atoms from the Moon or Mercury's surface are thought to be solar wind sputtering, micrometeoroid impacts, thermal desorption, and photosputtering (Smyth & Marconi 1995).

Although we have no consensus on the dominating mechanism for sustaining the tenuous atmosphere of the Moon, we are able to concentrate on the latter two mechanisms. The solar wind sputtering is thought to be a small contribution, after careful observational tests (Mendillo, Baumgardner, & Wilson 1999). The impact of the micrometeoroids is definitely one of the important factors for the Moon. The enhancement of the sodium was actually detected during the impacts of Leonid meteors in 1999 (Smith et al. 1999). However, another trial for detecting such enhancement resulted in failure during the 1999 Quadrantid meteor shower (Verani et al. 2001). This difference may be caused by the different impact velocity of meteor showers (Carbognani & Cremonese 2002). Anyway, it may be important, but not so dominating all the time. Therefore, we can concentrate on two mechanisms: thermal desorption and photosputtering desorption. Considering the spatial distribution of the sodium around the Moon, Sprague et al. (1992) concluded that two mechanisms are roughly compatible, and at the subsolar point, thermal desorption is dominating rather than the photosputtering desorption. If we consider the dust grains in the coma of comets, it is well thermalized by the possible fast rotation together with the small size.

Therefore, the dust particles will be effectively thermalized similar to the subsolar point of the Moon. This is consistent with the derived result from our observation.

The thermal desorption rate of a sodium atom from a dust grain is proportional to $e^{-D/kT}$, where $D$ is an energy potential

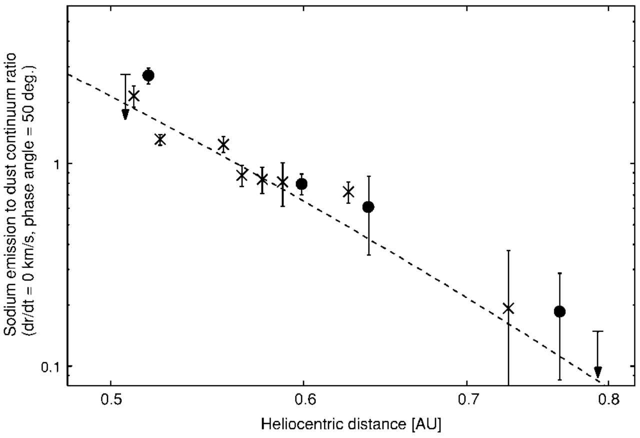

FIG. 3.—Heliocentric dependence of the sodium emission relative to the continuum emission of comet 153P/Ikeya-Zhang. The crosses are the values in the preperihelion, and the circles in the postperihelion. Each error bar shows a $\pm 3\ \sigma$ error level. See text for an explanation of the fitted curve.

barrier for the release the sodium atom from the dust grain surface, $k$ is Boltzmann's constant, and $T$ is the temperature of dust grains (Sprague et al. 1992). The corrected sodium-to-continuum ratio should be proportional to the thermal desorption rate in this case. Here we assume the temperature of the dust grains is equal to the color temperature ($T_{\rm color}$) obtained in infrared observations. The color temperature is usually represented by $ST_{\rm bb}$, where $S$ is a superheat and $T_{\rm bb}$ is an equilibrated blackbody temperature (Mason et al. 2001). The typical value of $S$ is usually between 1.0 and 1.4 for comets. Although the infrared observation was not reported during the period of our observation, Lyke et al. (2002) measured thermal flux, which resulted in the blackbody color temperature of 270 ± 15 K at the heliocentric distance of 1.423 AU. The derived superheat is 1.15 ± 0.06, which is within the average value for comets (Mason et al. 2001). We can regard the superheat of this comet as the normal, not the exceptional, value, as in the case of comet C/1995 O1 (Hale-Bopp), which showed an extremely large superheat of about 1.6–1.7. Using $T_{\rm bb} = 280/\sqrt{r}$, we can expect that the corrected sodium-to-continuum ratio is proportional to $e^{-(D/S)\sqrt{r}/(280k)}$, where $D/S$ can be regarded as a free parameter. When we apply the superheat $S$ to be 1.15 as derived from the color temperature by Lyke et al. (2002), the potential barrier $S$ is 0.49 ± 0.10 eV for comet 153P/Ikeya-Zhang as the result of a least-squares fit as shown in Figure 3.

It should be noted that this value is about half of that in the case of the Moon. Sprague et al. (1992) derived $D$ as 1.1 eV for the Moon. This leads to the important implication that sodium is easily produced from the cometary grains rather than the Moon's surface. It may be natural because the cometary grains included in the cometary nuclei are thought to be primordial compared with the surface grains of the Moon, which have been exposed to the strong solar radiation for a long time.

In this study, we assume implicitly the same spatial distribution of both the sodium and the dust particles because we deal with a limited region, 35″.8 at the photocenter, for deriving the flux ratio. However, it is expected that they are different owing to the large difference of the radiation pressure effect between them. If the ratios in the outer and inner portions are different, there may be a systematic error to the deduced ratios because the corresponding linear scale at the comet changes with the geocentric distance. In order to estimate this effect, we separately reduced the ratios for several different aperture lengths along the slit. For example, the ratios measured by 24″ and 48″ for the March 9 data show a 10% difference. Although this suggests that the sodium is more concentrated than the cometary dust particles, it is comparable to the error of the measurements. As shown in Figure 3, the heliocentric variation derived is well fitted by a single curve, including the data taken in both the pre- and postperihelion phases, while the geocentric distance decreased steadily with time by a factor of 2. This also suggests that there is no serious effect, at least in this study, from the difference of the spatial distribution of the sodium and of the dust particles within the measured scale. The measured sodium-to-continuum ratio can be regarded as representative of the whole comet, and the heliocentric dependence can therefore be taken as measuring an intrinsic property.

Although the sodium production is well explained by the thermal desorption in the case of this comet, we did have only one example for a limited range of the heliocentric distance. The sodium emission of comets has a wide variety both on the heliocentric range and on the strength of the emission. Therefore, we should collect many samples in order to clarify comprehensive pictures on cometary sodium for the future.

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## REFERENCES

Carbognani, A., & Cremonese, G. 2002, A&A, 394, 723

Cremonese, G., Boattini, A., Capria, M. T., De Sanctis, M. C., D'Abramo, G., & Buzzoni, A. 2002, IAU Circ. 7914

Cremonese, G., et al. 1997, ApJ, 490, L199

Huebner, W. F. 1970, A&A, 5, 286

Ikeya, K., & Zhang, D. 2002, IAU Circ. 7812

Kawakita, H., & Fujii, M. 1998, ApJ, 502, L185

Lyke, J. E., Kelley, M. S., Jackson, D. C., Gehrz, R. D., & Woodward, C. E. 2002, IAU Circ. 7921

Mason, C. G., Gehrz, R. D., Jones, T. J., Woodward, C. E., Hanner, M. S., & Williams, D. M. 2001, ApJ, 549, 635

Mendillo, M., Baumgardner, J., & Wilson, J. 1999, Icarus, 137, 13

Rietmeijer, F. J. 1999, ApJ, 514, L125

Smith, S. M., Wilson, J. K., Baumgardner, J., & Mendillo, M. 1999, Geophys. Res. Lett., 26, 1649

Smyth, W. H., & Marconi, M. L. 1995, ApJ, 443, 371

Sprague, A. L., Kozlowski, R. W. H., Hunten, D. M., Wells, W. K., & Grosse, F. A. 1992, Icarus, 96, 27

Verani, S., Barbieri, C., Benn, C. R., Cremonese, G., & Mendillo, M. 2001, MNRAS, 327, 244

Wilson, J. K., Baumgardner, J., & Mendillo, M. 1998, Geophys. Res. Lett., 25, 225

Yakshinskiy, B. V., & Madey, T. E. 1999, Nature, 400, 642