EXPLORATION OF SPECTRA OF PERIODIC COMET 153P/IKEYA–ZHANG

K. I. Churyumov[1], **I. V. Lukyanyk**[1], **L. S. Chubko**[1], **V. V. Kleshchonok**[1], **A. A. Berezhnoy**[4], **V. H. Chavushyan**[2], **L. Sandoval**[3], **A. Palma**[3]

[1] *Astronomical Observatory, National Taras Shevchenko University of Kyiv*
3 Observatorna Str., 04053 Kyiv, Ukraine
e-mail: klim.churyumov@observ.univ.kiev.ua

[2] *Instituto Nacional de Astrofisica, Optica y Electronica, Tonantzintla, Puebla, Mexico*

[3] *Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*

[4] *Moscow State University P. K. Sternberg State Astronomical Institute, Moscow, Russia*

We present preliminary results of study of middle-resolution optical spectra of Comet 153P/Ikeya–Zhang obtained on May 5, 2002 with the help of the 2.12-m reflector of the Guillermo Haro Astrophysical Observatory. Emission lines of the molecules C_2, C_3, CN, NH_2, CO (Asundi and triplet bands), and H_2O^+ are identified in these spectra. On the basis of the intensity distribution along the slit of the spectrograph in C_2, C_3, CN emission lines we determined the velocities expansion and life times of these molecules.

INTRODUCTION

Middle-resolution optical comet spectra obtained with long slit allow one to calculate some physical parameters of cometary neutral atmospheres (escaping velocities of gas in coma, life time of particles, and others), to search for new cometary emission lines, to estimate parameters of gas and dust productivity of comet nucleus, to detect the cometary luminescence continuum of the non-solar nature, and others.

OBSERVATIONS AND DATA REDUCTION

Spectroscopic observations of Comet 153P/Ikeya–Zhang were carried out with the 2.12-m telescope of the Guillermo Haro Observatory in Cananea, Sonora, Mexico, operated by the National Institute of Astrophysics, Optics, and Electronics. The diffraction gratings of the Boller and Chivens spectrographs (long slit and CCD) with a reciprocal dispersion of 3.5 Å per pixel and spectral resolution of 15 Å was used on May 5, 2002. The long slit was orientated along the cometary tail. Grating with 150 l/mm was used. Log of observations of comet is presented in Table 1. A helium-argon lamp was utilized in order to calibrate the spectra for wavelengths.

Table 1. Summary of observations of Comet 153P/Ikeya–Zhang

Starting time, UT	Exposure, s	Wavelengths, Å	Spectral resolution, Å
May 5, 2002, 8:41	1800	3222–6440	15
May 5, 2002, 9:45	1800	3881–7169	11

One comet spectrum in the spectral region from 3222 to 6440 Å and one comet spectrum with the resolution in the spectral region from 3881 to 7169 Å were obtained on May 5, 2002 with the slit spectrograph. The slit of the spectrograph has a width of 2.5 arcsec and a length of 2.5 arcmin. The distance between Comet 153P/Ikeya–Zhang and the Sun was equal to 1.14 AU, the distance between comet and the Earth was 0.42 AU on May 5, 2002. The comet passed the perihelion at 0.51 AU on March 19, 2002. All CCD spectra of 153P/Ikeya–Zhang were processed with the help of the LONG-MIDAS and the Research System IDL computer programs allowing for reductions of the CCD bias level, cosmic ray particles, flat fielding, and night sky contribution. Figures 1–3 show the spectra of Comet 153P/Ikeya–Zhang on May 5, 2002. With the obtained S/N ratios, it is possible to detect emission lines stronger than $2 \cdot 10^{-16}$ erg cm^{-2} s^{-1}Å^{-1}. The accuracy of determination of wavelengths of well-known emission lines is 3 Å.

INTERPRETATION OF RESULTS OF THE INVESTIGATION

The catalogue of the spectral lines in Comet Brorsen–Metcalf [1] and the catalogue of CO optical bands [10] were used for identification of the emission lines in the spectra of Comet 153P/Ikeya–Zhang. In the case of the comet nucleus spectrum on May 5, 2002, 8:41 UT, we found emission lines of the following neutral radicals: 69 of C_2, 15 of NH_2, 3 of CN, 7 of C_3, 20 of CO (Asundi, triplet, and Herman bands), 4 of CH, 2 of H_2O^+, 1 of CH^+. For the comet coma spectrum on May 5, 2002, 8:41 UT, we found emission lines of the following neutral radicals: 71 of C_2, 15 of NH_2, 5 of CN, 7 of C_3, 16 of CO (Asundi and triplet bands), 5 of CH, 1 of NH, 1 of H_2O^+, 2 of CH^+. In the case of the comet nucleus spectrum on May 5, 2002, 9:45 UT, we found emission lines of the following neutral radicals: 73 of C_2, 16 of NH_2, 10 of CN, 3 of C_3, 29 of CO (Asundi, triplet, and Herman bands), 3 of CH, 3 of H_2O^+, 2 of CH^+. The results of this investigation favour the identification of CO triplet, CO Asundi, CO Herman bands, but the numbers do not seem to be quite large enough to rely entirely on the argument of a small statistical probability of 17% for CO triplet, CO Asundi, and CO Herman bands, respectively, that the presence of the observed bands is merely due to chance.

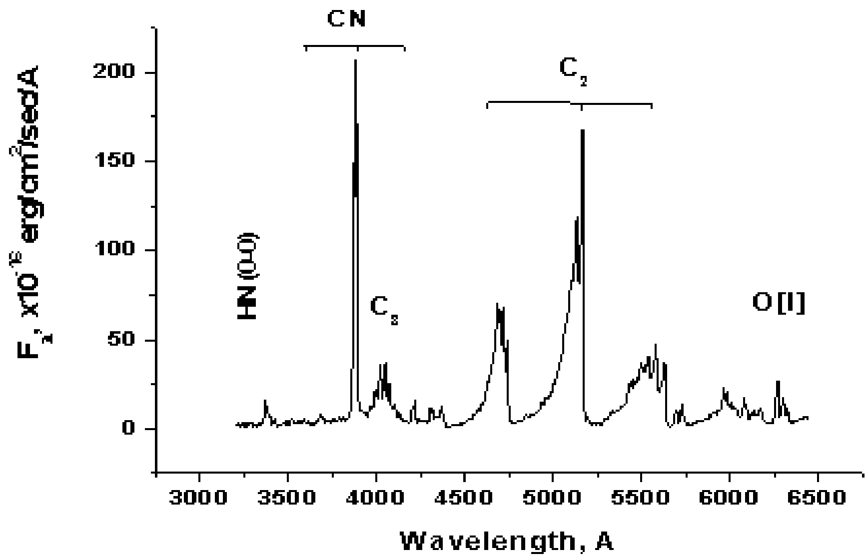

Figure 1. Energy distribution in the spectrum of Comet 153P/Ikeya–Zhang on May 5, 2002 (9:45 UT)

In order to determine some physical parameters of gaseous components of the neutral cometary atmosphere (the gas component expansion u and the lifetime of the particles τ), we built a photometric profiles for the C_2, C_3, and CN emission lines along slit. Then the obtained monochromatic profiles were processed by Shulman's model. Within this model the surface brightness was determined by the following formulas:

$$\log \frac{I(\rho, \phi + \pi)}{I(\rho, \phi)} = 1.72 \frac{\rho}{r_{0c}} \sin \Theta_0 \cos \phi, \tag{1}$$

$$\frac{1}{2}[\log I(\rho, \phi + \pi) I(\rho, \phi)] = const + \log \left[\frac{r_0 k}{\rho} \int_{\frac{\rho}{r_0 k}}^{\infty} K_0(y) dy \right], \tag{2}$$

where $I(\rho,\ \phi + \pi)$ and $I(\rho,\ \phi)$ are brightness surface of emission line along slit, ρ, ϕ are polar coordinates on the picture plane with the polar axis directed to the Sun, $r_{oc} = 2u^2/g$ is characteristic scale of the spheric symmetry region, u is expansion velocity, g denotes acceleration of molecules in the gravity field of the Sun, Θ_o is an angle between the axis z and g-vector, $r_{ok} = u\tau$ is characteristic size of a coma, and $K_0(y)$ is McDonald's function.

The physical parameters for neutral gaseous molecules C_2 (5165 Å), C_3 (4050 Å), and CN (4200 Å), namely, velocity of expansion and lifetime of molecules, are given in Table 2.

One can see from Table 2 that real velocities of expansion of the C_2, C_3, and CN molecules in the coma of Comet 153P/Ikeya–Zhang diverse noticeably from velocity of expansion for gas, determined by Delsemme's formula which gives the values of expansion velocities [6].

Important feature of optical spectra of Comet 153P/Ikeya–Zhang is the presence of weak CO Asundi, triplet, and Herman bands. In spectral region between 3880 and 6440 Å, 5 Asundi, 7 triplet, and 3 Herman bands were

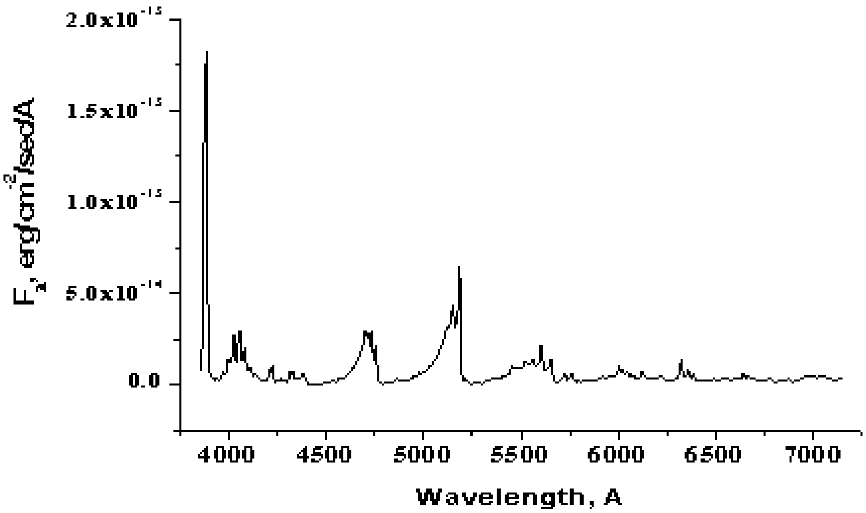

Figure 2. Energy distribution in the spectrum of Comet 153P/Ikeya–Zhang on May 5, 2002 (8:41 UT)

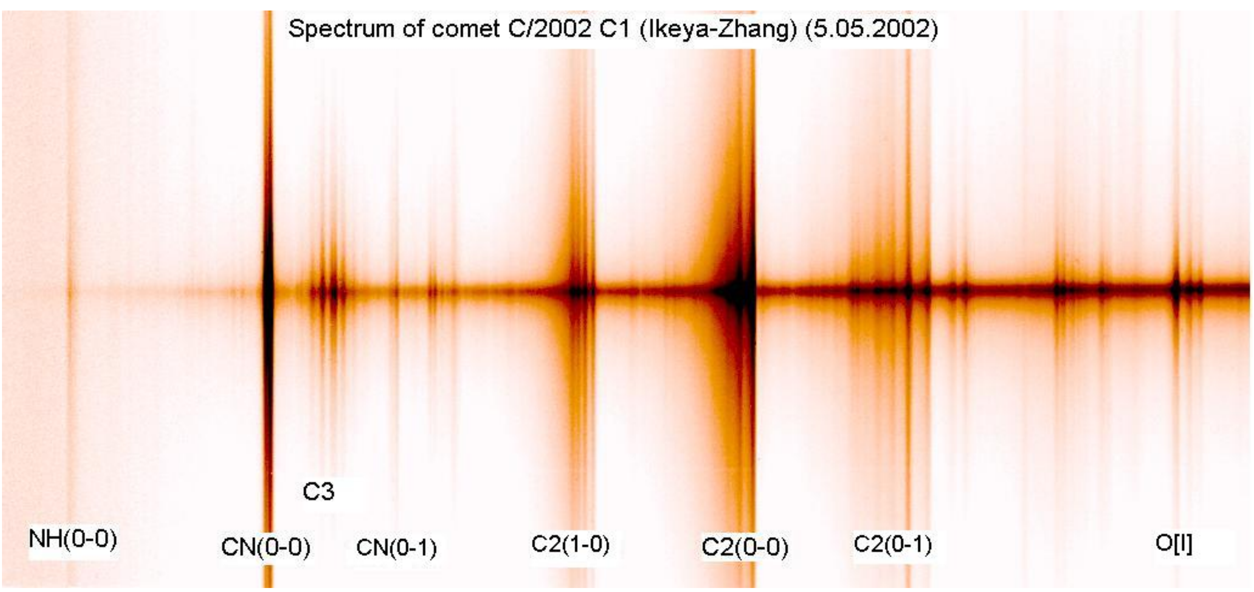

Figure 3. Spectrum of Comet 153P/Ikeya–Zhang on May 5, 2002 (9:45 UT)

Table 2. Physical parameters of neutral gaseous cometary components of C_2, C_3, and CN

Species	Velocity, m s^{-1}	Lifetime, 10^6 s
C_2 (5165 Å)	200.6	3.08
C_3 (4050 Å)	166	0.075
CN (4200 Å)	157	0.06

detected at 8:41 UT on May 5, 2002. At the same time only 3 Asundi, 6 triplet, and 1 Herman bands were detected in coma. This means that a high particle density is required for formation of these emission bands. Besides, 3 Asundi, 7 triplet, and 2 Herman bands were detected near the comet nucleus at 9:45 UT. From 15 bands observed at 8:41 UT, only 7 bands were detected at 9:45 UT. So, intensity of CO optical bands can be changed significantly during tens of minutes. To explain this result, we can assume a short lifetime of CO parent molecule (about $2 \cdot 10^3$ s or less). For analysis of relative intensities of CO optical bands, their Franck–Condon factors were compared. The complete results of Franck–Condon factors calculations are presented in [4]. At given vibrational level of upper electronic state, Franck–Condon factors have maxima for 6–0, 7–1, 8–1, 9–1, 10–2, 11–2, 12–2, 13–2, 14–3, 15–3, 16–3 transitions of Asundi system and for 2–0, 3–0, 4–0, 5–0, 6–0, 7–0, 8–1, 9–1, 10–1, 11–1, 12–2, 13–2, 14–2, 15–3 transitions of triplet system. At given vibrational level of upper electronic state, all transitions with maximal Franck–Condon factors values were observed in Comet 153P/Ikeya–Zhang. This means that relative intensities of observed CO transitions correspond to their Franck–Condon factors values. There is only one exception for transitions from $a'^3\sum^+$, state with $v' = 16$. Franck–Condon factor is maximal for 16–3 transition but only 16–4 and 16–5 transitions were detected. Probably, Franck–Condon factors can not be calculated with accuracy good enough for such high vibrational levels.

From our observations, it is possible to determine that the existence of CO optical bands leads mainly to formation of CO molecules at low vibrational states ($v'' = 0-3$) of $a^3\Pi$ state. In [13] the vibrational temperature (4500 K) for CO $a^3\Pi$ molecules formed during CO_2^+ dissociative recombination and $(a' - a)$, $(d - a)$, $(e - a)$ cascade emission is estimated. This value correspond to a high relative population of only low vibrational levels ($v'' = 0 - 3$). So, our results are in good agreement with experimental data.

Knowing relative intensities of electronic-vibrational transitions and their Franck–Condon factors, it is possible to determine relative populations of vibrational levels of upper electronic state. In Comet 153P/Ikeya–Zhang, the population of vibrational levels of CO molecules at $a'^3\Sigma^+$ and $d^3\Delta$ states is not under thermal equilibrium because even high vibrational levels are high populated. This is in agreement with experimental data [13]. In this work the intensities of 6–0, 7–0, 8–0, 9–0 Asundi, 2–0, 3–0, 4–0 triplet transitions, and 2–0, 3–0 Herman transitions were strong.

At given vibrational level of upper electronic state intensities of electronic-vibrational transitions are proportional to their Franck–Condon factors. There are eight couples of observed transitions from the same upper vibrational level. The comparison between intensities of observed transitions and their Franck–Condon factors shows good agreement.

The first detection of CO bands in optical spectrum of Comet Bradfield 1980t is described in [5], where dissociative recombination of CO_2^+ or HCO^+ is considered as a possible mechanism of origin of these bands. It is also noted that the reactions of dissociative recombination require high electron densities. Fluorescence mechanism can not explain observed intensities of CO Asundi and triplet bands because the excitation rates are too low [11]. CO Asundi and triplet bands were observed in comets Bradfield 1980t in 1981, Scorichenko–George in 1990, WM1 (LINEAR) in 2001 and 2002, and 153P/Ikeya–Zhang in 2002. All these years correspond to high solar activity periods. For all comets, these bands were detected near the nucleus. This can be explained by formation of CO parent molecule in regions near the nucleus where there are high particle densities and high electron concentrations. It is proposed in [5] that an unusual event like outburst can be a reason of CO Asundi and triplet bands formation. During periods of high solar activity the flash and outburst activity of comets is increasing, this correlation supports an outburst hypothesis from [5].

For explanation of CO Asundi and triplet bands intensities in Comet Bradfield 1980t, about $3 \cdot 10^{30}$–$3 \cdot 10^{32}$ parent positive ions are required [5]. During these calculations it was assumed that the rate coefficient of dissociative recombination was about $10^{-7}\,\mathrm{cm^3\,s^{-1}}$ and the mean electron densities were 10^3–$10^5\,\mathrm{cm^{-3}}$. We can make this estimation more carefully because experimental results on CO_2^+ and HCO^+ are available now. Rate constant of CO_2^+ recombination is about $3 \cdot 10^{-7}\,\mathrm{cm^3\,s^{-1}}$. In the recombination the ${}^3\Pi_{3/2}$ CO_2^+ ground state with thermal electrons there is enough energy to populate CO ($a'^3\Sigma^+$, $v' < 11$), CO ($d^3\Delta$, $v' < 6$), and CO ($e^3\Sigma^+$, $v' < 3$). The yields of CO molecules in these states during CO_2^+ recombination are 0.13, 0.081, and 0.017, respectively [13]. These experimental results are in agreement with our observations because Herman bands ($e^3\Sigma^+$–$a^3\Pi$ transition) were much weaker than Asundi and triplet bands in Comet 153P/Ikeya–Zhang. CO_2^+ recombination can not explain origin of high excited vibrational levels of $a'^3\Sigma^+$ and $d^3\Delta$ states. HCO^+ must be refused as a parent CO molecule because HCO^+ recombination can produce only Asundi bands with $v' < 3$ [13]. The HOC^+ recombination is more exoergic process, and it can give rise to emissions from CO (a′, $v' < 17$), CO (d, $v' < 13$), CO (e, $v' < 10$). During HCO^+ recombination Asundi, triplet, and Herman bands were observed [13]. This parent molecule can explain all CO observed bands except for 15–3 triplet band. For formation of 15–3 triplet band, another parent molecule or high speed electrons are required. HCO^+ ion was not detected in comets yet, which means that the concentration of this ion is too low. So, CO_2^+ is the best candidate for CO parent molecule. Formation of high excited vibrational levels of $a'^3\Sigma^+$ and $d^3\Delta$ states can be explained by CO_2^+ dissociative recombination with energetic electrons. The mean electron temperature in pile-up region of Comet Halley is 20 000 K [8], such values of electron temperature is enough for formation of all observed CO bands in Comet 153P/Ikeya–Zhang.

For theoretical estimation of CO production rate during CO_2^+ dissociative recombination, we must estimate the integral

$$N_{\rm theor} = 4\pi\mu k \int [{\rm CO_2^+}][{\rm e}]dr, \qquad (3)$$

where μ is the absolute yield of CO molecules at given electronic state, k is the rate constant, $[CO_2^+]$ is the concentration of CO_2^+ ions, [e] is the electron concentration, and r is the distance from the comet nucleus. Let us assume that $[CO_2^+] \sim r^{-2}$, $[e] \sim r^{-2}$ at $r > r_0$ and $[CO_2^+] \sim r^{-2}$, $[e] \sim r^{-2}$ at $r < r_0$, where $r_0 \sim 3 \cdot 10^8$ cm is the distance between the nucleus and the contact surface. Let us suppose that CO_2^+ and electron densities in Comet 153P/Ikeya–Zhang are the same as in Comet Halley during VEGA flybies. Extrapolating values of CO_2^+ [7] and electron [12] densities from $2 \cdot 10^4$ km to the contact surface, we can derive that $[CO_2^+] \sim 10^3\,{\rm cm}^{-3}$ and $[e] \sim 2 \cdot 10^5\,{\rm cm}^{-3}$ at $r_0 = 3 \cdot 10^8$ cm. Knowing CO absolute yields during CO_2^+ recombination, it is possible to estimate the formation rate of CO molecules at $a'^3\Sigma^+$, $d^3\Delta$, and $e^3\Sigma^+$ electronic states as $4 \cdot 10^{27}$, $3 \cdot 10^{27}$, and $5 \cdot 10^{26}$ mol s^{-1}, respectively.

CONCLUSIONS

On the basis of the intensity distribution along the slit of the spectrograph in C_2, C_3, CN emission lines we determined the velocities of expansion (v) and life times (τ) of these molecules: for C_2 (5165 Å) [201 m s^{-1}, $3.08 \cdot 10^6$ s]; for C_3 (4050 Å) [166 m s^{-1}, $0.075 \cdot 10^6$ s], and for CN (4200 Å) [157 m s^{-1}, $0.06 \cdot 10^6$ s].

Acknowledgements. Authors K. I. Churyumov, I. V. Lukyanyk, and V. V. Kleshchonok thank to the Fundamental Research State Fund of the Ministry of Ukraine for Education and Science (grant 2002) for support of our research in cometary physics area.

[1] *Brown M. E., Bouchez A. H., Spinrad H., et al.* A high-resolution catalog of cometary emission lines // Astron. J.–1996.–**112**, N 3.–P. 1197–1202.

[2] *Churyumov K. I., Kleshchenok V. V., et al.* Identification of Emissions in the Spectrum of Comet C/1989 VI (Skoritchenko–George) Obtained with the 6-m SAO RAS Reflector // Solar System Research.–2001.–**35**, Issue 3.–P. 234–237.

[3] *Churyumov K. I., Luk'yanyk I. V., Berezhnoi A. A., et al.* Optical spectroscopy of comet C/2000 WM1 (LINEAR) at the Guillermo Haro Astrophysical Observatory in México // Earth, Moon and Planets.–2002.–**90**.–P. 361–368.

[4] *Churyumov K. I., Luk'yanyk I. V., Berezhnoy A. A., et al.* Exploration of spectra obtained of comet C/2000 WM1 (LINEAR) // Astron. and Astrophys. Transactions.–2003.–**22**, N 4–5.– P. 625–630.

[5] *Cosmovici C. V., Barbieri C., Bonoli C., et al.* On the identification of CO in the visible spectrum of comet Bradfield 1980t // The Need for Coordinated Ground-Based Observations of Halley's Comet: Proc. of the ESO Workshop, Paris, 29–30 April 1982.–P. 133–387.

[6] *Delsemme A.* Chemical composition of cometary nuclei.–Comets / Ed. L. Wilkening.–Tucson: Univ. of Arizona Press, 1982.–P. 85–130.

[7] *Gringauz K. I., Verigin M. I., Richter A. K., et al.* Quasi-periodic features and the radial distribution of cometary ions in the cometary plasma region of comet P/Halley // Astron. and Astrophys.–1987.–**187**.–P. 191–194.

[8] *Eberhardt P., Krankowsky D., et al.* The electron temperature in the inner coma of comet P/Halley // Astron. and Astrophys.–1995.–**295**.–P. 795.

[9] *Kawakita H., Watanabe J., et al.* Unidentified bands in comet Ikeya–Zhang (C/2002 C1): The correlation between unidentified bands and H_2O^+ // Astrophys. J.–2002.–**574**.–P. L183–L185.

[10] *Krupenie P. H. et al.* The band spectrum of CO.–Washington: National Bureau of Standards, 1966.

[11] *Krishna Swamy K. S. et al.* Fluorescence excitation of CO in comets // Astrophys. J.–1983.–**267**.–P. 882–885.

[12] *Pedersen A., Grard R., Trotignon J. G., et al.* Measurements of low energy electrons and spacescraft potentials near comet P/Halley // Astron. and Astrophys.–1987.–**187**.–P. 297–303.

[13] *Skrypkowski M. P.* Dissociative recombination studies in stationary and flowing afterglows. PhD Thesis.–University of Pittsburg, 1999.–171 p.