Astronomical and Astrophysical Transactions (*AApTr*), 2014, Vol. 28, Issue 3, pp. 293–306,
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Spectroscopic study of comet 9P/Tempel 1

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Received 13 March, 2013

We present the results of exploration of the spectra of comet 9P/Tempel 1, observed on Mount Pastukhov (Russia). The observations took place 2.5 months before collision of the copper nosed impactor of the Deep Impact spacecraft. The physical parameters of C_2, C_3 and CN molecules in the near nucleus region of the cometary atmosphere of 9P/Tempel 1 were determined. The presence of the cometary luminescence continuum (non-solar origin) in the spectra of the comet was confirmed.

Keywords: Comets; Composition; Comet 9P/Tempel 1; Spectroscopy

1 Introduction

The main goal of the present paper is to help to establish a unique description of the physico-chemical nature of comet 9P/Tempel 1 during the very favorable apparition of 2005 ($\Delta = 0.71$ AU in 2005 May 3).

Comet 9P/Tempel 1 has been known for a rather long time. It belongs to the Jupiter family of comets with a 5.5 years period. The continuum prevails in the visible part of its spectrum; this is indicative of the high dust component part in the cometary coma. Special attention of observers to the comet was attracted in connection with the space experiments Deep Impact (July 4, 2005) and New Exploration of Tempel 1 (or NExT flyby of opportunity mission, February 15, 2011). The collision of the copper nosed impactor with the cometary nucleus occurred in the course of the first experiment; that led to the considerable dust and gas emission with the subsequent flare of cometary brightness [1]. This is the first time a comet is visited twice by

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two different probes. Spectrophotometric observations in the visible are essential to determine the composition of the coma.

The middle-resolution optical spectra of the comet, obtained with the long slit, allowed computing some physical parameters of the cometary neutral atmospheres (expansion velocities of the gas in coma, the lifetime and scale length of species), by fitting the profiles with appropriate models [2–3, 4–5], to detect the cometary luminescence continuum of non-solar nature [6–13].

2 Observations and data reductions

The spectra of the short-period comet 9P/Tempel 1 were collected at the Special Astrophysical Observatory of the Russian Academy of Sciences (RAS) on March 14–15, 2005 (Mount Pastukhov, Nizhny Arkhyz, Northern Caucasus, Russia). The observation circumstances are given in Table 1.

Table 1 Observational data for comet 9P/Tempel 1.

Date	r, AU	Δ, AU	Phase angle, deg	Z, deg	Exposure, sec	Flux standard
2005 March 15	1.85	0.91	14.6	43	600	BD+75d325

The SCORPIO equipment (Spectral Camera with Optical Reducer for the Photometric and Interferometric Observations) installed in the prime focus of the 6-m BTA telescope was used for this purpose. The necessary technical details can be found at http://www.sao.ru/hq/lsfvo/devices/scorpio/scorpio.html, or in [14]. The focal reducer SCORPIO was used with the long slit. The length of the slit was 2 arcmin (79,200 km at the distance of the comet), its width was 1 arcsec (660 km at the same distance). The resolving power of the spectrograph was 10 Å, the dispersion was 2.1 Å/pixel. The signal-to-noise ratio was 30 for the middle part of the spectral range. The slit was oriented along the tail direction.

The nucleus was projected on the slit center. Altogether, four cometary spectra were collected for analysis. The observed spectral range was 3700–7500 Å. Simultaneously we obtained images in filter V (CWL = 5470 Å, equivalent width EW = 790 Å) with the following parameters: scale 0.357×0.357 arcsec/pixel, binning 2×2, CCD camera 1024×1046 pixels. Image pixel size corresponds to a linear size 470× 470 km. At the moment of observations the comet had the following photometric magnitudes: B = 16.5, V = 15.8, R = 15.5, I = 15.3.

Observed material was processed with software specially created by the developers of SCORPIO. All necessary corrections and reductions were taken into account (the bias correction, the dark subtraction, the flat-field division, the subtraction of the night-sky spectrum, the wavelength calibration using the known lamp spectrum). The Doppler effect was taken into account by the wavelength correction caused by geocentric comet radial velocity. The reference spectrum was used for recalculation of the intensity in absolute units.

An example of the 9P/Tempel 1 spectrum is given in Fig. 1.

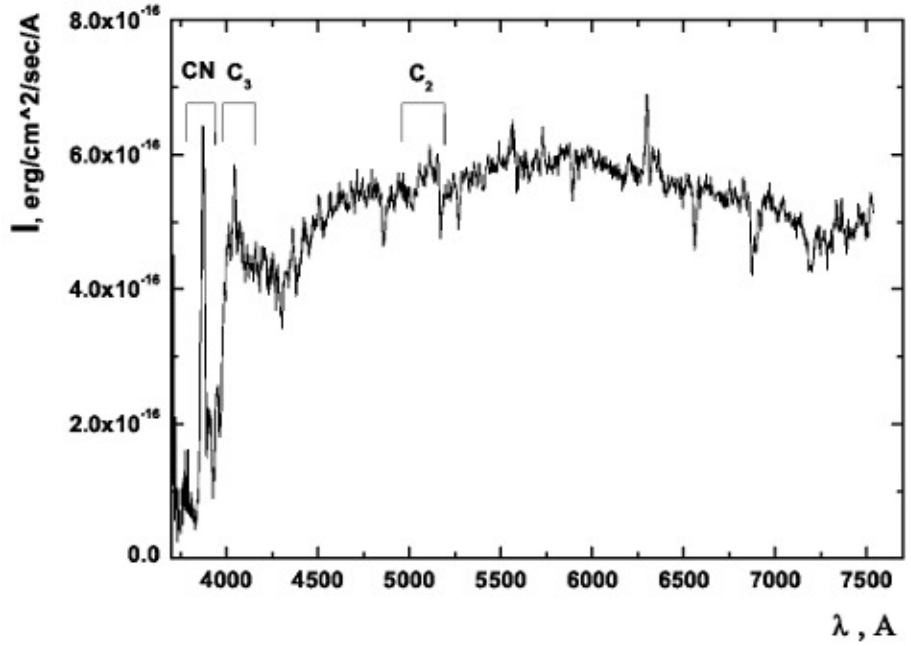


Figure 1 Energy distribution in the spectrum of comet 9P/Tempel 1. The positions of the studied bands are indicated.

3 The physical parameters of comet 9P/Tempel 1

The theory of the neutral cometary atmospheres has been developed in several stages. Firstly, Mokhnasch [15–17], Wallace [18], Riives [19] and Haser [4, 5] succeeded in the determination of certain basic parameters, which underlie any complete model. Then, Gnedin and Dolginov [20] and Shulman [2, 3] lifted the theory to a higher level, but the calculations involved were too complicated to have won much favour for interpreting the observations of comets.

Haser's model is one of the most often used in processing the observed surface-brightness profiles. Characteristic scales for this model as a rule are taken from [21]. Recently, several attempts have been made, at the cost of certain complications, to avoid the most serious shortcomings of Haser's model while retaining its intuitive character. Combi [22] used an artificial example to allow for the non-radial motion of the daughter molecules: the radicals were assumed to be ejected perpendicularly to the direction in which the parent molecules were travelling. Festou's "vectorial" model [23] presupposed an isotropic escape of radicals relative to the moving centre of mass, but Festou gave only an algorithm for calculation, discouraging the "vectorial" model from being widely applied.

Shulman's model (see [2, 3]) is little known among specialists of the world mainly because it has been published only in Russian. The authors of the present paper provide the translation of his model into English (see References). Also we present the summary of Shulman's model for the practical interpretation of observations of

comets. The advantage of that model is the small number of parameters and simplicity of usage when interpreting observations. It should be also noted that unlike the other above mentioned models, it takes into consideration the asymmetry of the cometary atmosphere, caused by the solar wind pressure. In this model the processes of creating daughter molecules and some kinds of parent molecules are not taken into account.

This model, together with the traditionally used Haser's model, was applied for the study of 9P/Tempel 1. Several investigators noted that the comet is dusty.

We obtained an estimate of $Af\rho$ value using the method described by Farnham et al. [24] for the region which corresponds to the filter GC:

$$Af\rho = \frac{q_{\rm GC} r^2 \Delta F_{\rm GC}}{\theta}, \tag{1}$$

where r and Δ are, respectively, the heliocentric and geocentric distances to the comet in AU, θ is the aperture diameter in arcsec, $q_{\rm GC} = 1.341{\times}10^{17}$ is a conversion factor for GC filter, $F_{\rm GC}$ is the wavelength-averaged flux measured through the GC filter for a circular diaphragm.

Since we are dealing with spectroscopic (not photometric) observations, we have to take into account the difference between the area sizes of the circular diaphragm and the slit when determining the $F_{\rm GC}$ value:

$$F_{\rm GC}^{'} = \frac{F_{\rm GC}^{''} \pi d}{4 n m_y} = 1.18 \times 10^{-15} \frac{\rm erg}{\rm cm^2\,s\,\AA}, \tag{2}$$

where $F_{\rm GC}^{''}$ is the wavelength-averaged flux within the spectral domain that corresponds to GC filter, $d = 1$ arcsec is the width of the slit, $m_y = 0.357$ arcsec/pixel is the image scale along the slit, $n = 2$ pixels is the width of the region along the slit in pixel on the nucleus of the comet. After using these values our final estimate is $Af\rho = 247$ cm. For instance, Milani et al. [1] give the value $Af\rho = 230$ cm which characterizes the intensity of the continuous spectrum for comet Tempel 1.

The total rate of the gas release by the cometary nucleus is about $2{\times}10^{28}$ molecules $\sec^{-1}$ [25]. This means that the comet is quite dusty. Feaga et al. [26] indicate that this comet has a strong non-isotropic emission and an effect that was especially strong during the inbound portion of its trajectory [27]. Correspondingly, the asymmetries in the coma that are produced by jets will completely dominate any effects produced by the solar radiation pressure. Nevertheless, an analysis of the V images with an exposure of 30 sec that were obtained simultaneously with spectroscopic observations (see Fig. 2) does not reveal any well-expressed structures (jets). This enables one to apply the model of quasi-isotropic central source (i.e., Shulman's model).

To obtain the model parameters one needs to study the dependence of the molecule column density upon the distance from the nucleus. For this one can use monochromatic images, as the long-slit spectra too. The section of the long-slit spectrum along the dispersion is the intensity distribution with wavelength. The same, but across the dispersion, gives us the spatial distribution of monochromatic intensity.

For our purposes we used molecular bands of C_2 ($d^3\Pi_g - a^3\Pi_u(0,0)$), CN ($B^2\Sigma^+ - X^2\Sigma^+(0,0)$) and C_3 ($A^1\Pi_u - X^1\Sigma_g^+$).

First of all we determined the continuum level using the adjusted spectral regions of the studied emission bands. After that it was subtracted from the intensity of

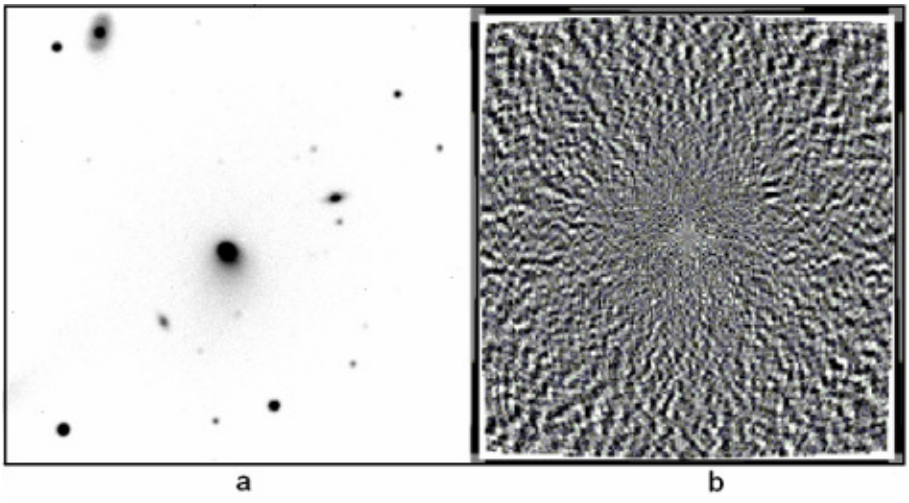


Figure 2 Image of 9P/Tempel obtained in V filter (a), and image obtained in filter V using the numerical filter of [28] (b), that demonstrates the absence of any well-expressed structures in the head of this comet.

the emission bands. The spatial profiles for investigated molecules were built by integrating the intensity within the width of the bands showed in Fig. 3.

Monochromatic spatial profiles of C_2, C_3, CN molecules obtained in this way for each spectrum were then analyzed within Shulman's model.

The logarithms of asymmetry and averaged line brightness profile [29] are:

$$\log \frac{I(\rho, \varphi + \pi)}{I(\rho, \varphi)} = 1.72 \frac{\rho}{r_{0c}} \sin \theta_0 \cos \varphi, \tag{3}$$

$$\frac{1}{2} \log \left[I(\rho, \varphi + \pi I(\rho, \varphi) \right] = const + \log \left[\frac{r_{0k}}{\rho} \int\limits_{\frac{\rho}{r_{0k}}}^{\infty} K_0(y) dy \right], \tag{4}$$

where ρ, φ are the polar coordinates in the picture plane with the polar axis directed to the Sun; θ_0 is the phase angle of the comet; $r_{0k} = v \cdot \tau$ is the characteristic scale of a molecule path; τ is the lifetime of a molecule; $r_{0c} = 1/2 a \tau^2$ is a characteristic scale of the region of the spherical symmetry; a is the radiation acceleration of molecules; $K_0(y)$ is the McDonald's function.

By making a special selection of r_{0k} and r_{0c} values we were seeking for the best agreement between the observed and calculated spatial profiles using the least squares method.

Acceleration of the molecules a in the solar radiation field was calculated using the following formula:

$$\log a = 11.303 + \log g - \log m - 2 \log r, \tag{5}$$

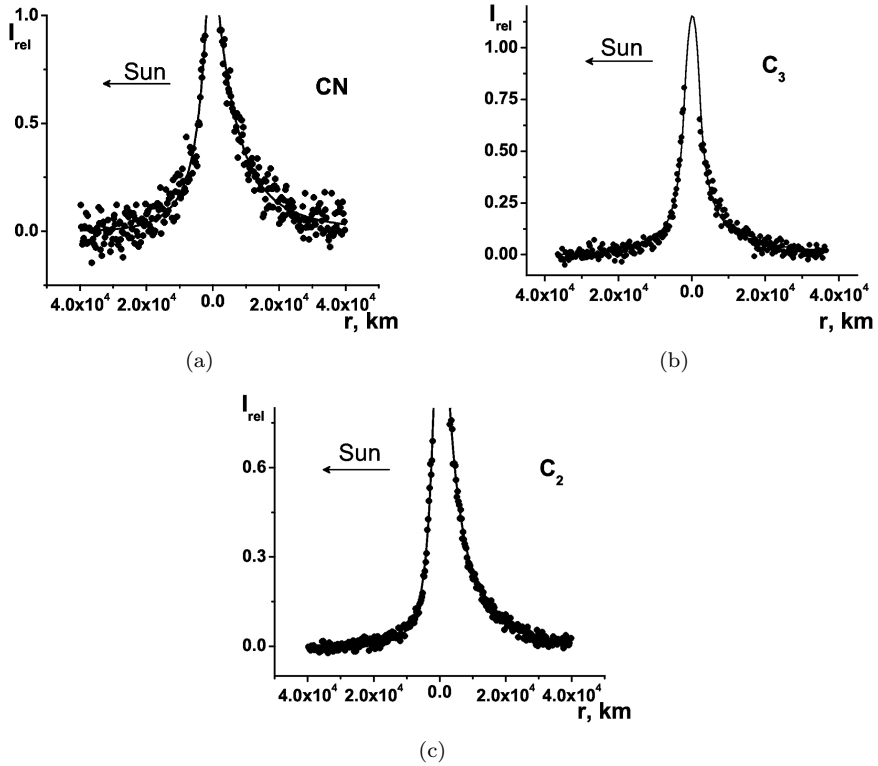


Figure 3 Photometric profiles for the C_2(a), C_3(b) and CN (c) emission lines along the slit for comet 9P/Tempel 1. Dots represent the observed profile; continuous line, the calculated profile based on Shulman's model.

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

Species	Shulman's model		Haser's model			
			Our		Cochran* [21]	
	V, km/s	τ, 10^5 s	L_{parent}, $\times 10^3$ km	L_{daughter}, $\times 10^5$ km	L_{parent}, $\times 10^4$ km	L_{daughter}, $\times 10^5$ km
C_2	0.43 ± 0.25	0.16 ± 0.1	1.24 ± 0.8	0.12 ± 0.05	8.56	4.11
C_3	0.26 ± 0.15	1.4 ± 0.8	0.92 ± 0.7	0.32 ± 0.14	1.06	4.96
CN	0.34 ± 0.21	1.1 ± 0.7	6.3 ± 4.9	0.21 ± 0.10	5.82	0.1

where g is a sum factor of fluorescence for all the bands of a given molecule expressed in erg/s, m is the mass of a molecule in atomic units, r is the heliocentric distance of

*Path values of the molecules from [21] recalculated on the heliocentric distance 1.85 A.U. for 9P/Tempel 1.

a comet. In this formula g comes from the tables of [30] and [31] with velocity and heliocentric distance of the comet being taken into account (Swings effect). Using the asymmetry of observed profiles and averaging the brightness (least squares method), one can estimate parameters r_{0k} and r_{0c}. After that, one can calculate v and τ.

The evaluated physical parameters (averaged for the four spectra), namely, the expansion velocity, the lifetime and scale length of the parent and daughter molecules of neutral gaseous molecules of C_2(5165 Å), C_3(4050 Å, "Swings group") and CN (4200 Å) are given in Table 2. Accuracy of the model results is characterized by a standard deviation from the mean value.

From Table 2 one can see that the path values in Haser's model for our data and data of [21] differ. From our point of view it could be caused by the fact that for the determination of the path value Cochran's data are relevant for almost pure gaseous comets, while 9P/Tempel 1 is a highly dusty comet.

From the Haser's model spatial scales one can estimate the lifetime of molecules. As usual, for this aim velocities of 1 km/s are used. Nevertheless, it is clear that these velocities should vary with heliocentric distance of a comet, as well as they should decrease with distance. It is also completely understandable that these velocities should be different for different species. Even if velocities of the parent molecules in the outflowing gas of cometary nucleus are the same, after disruption of those parent molecules their daughter fragments may have different velocities. Shulman's model takes into account the molecule acceleration caused by solar radiation, and this enables one to determine the characteristic size of the region of spherical symmetry using the observed asymmetry. This gives one the possibility of determining the more reliable velocities of molecules.

In Haser's model velocities and lifetimes cannot be divided. They are entering as a combination in the scale length. Moreover, only one set of characteristic path values for one molecule is used despite the fact that there could be many ways to create observed molecules. Therefore, it is not surprising that the lifetimes based on Shulman's model can differ from those obtained in Haser's model.

4 Search for the cometary luminescence continuum in the spectra of comet 9P/Tempel 1

The luminescence continuum was first detected in the spectrum of comet 1P/Halley by G. Nazarchuk, who found two broad features with a maximum of intensity near 3950 Å and 5100 Å, respectively [32]. These features were part of the scattered solar continuum. A dust component in the cometary atmosphere gives a continuous spectrum as the result of the scattering of the solar spectrum by dust particles.

In the present paper, the spectra of comet 9P/Tempel 1 were investigated in order to determine the real level of the non-solar-origin continuum in the spectral region of 3500–6000 Å. In the high resolution spectra of several comets, it has been noticed that the equivalent widths of the main Fraunhofer lines are smaller than in the solar spectrum (Fig. 4). Such phenomenon is connected to a presence of an additional component of the continuous spectrum in the cometary radiation. The luminescence of organic cometary particles can work as a source of that additional radiation. The

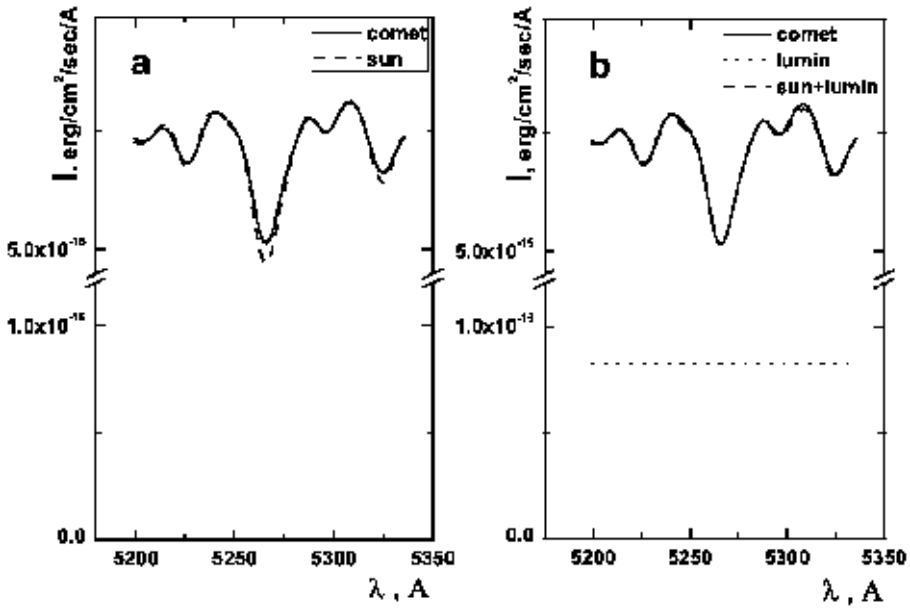


Figure 4 Sketch showing the detection of the luminescent continuum in the cometary spectrum: a) the standard method of determination of the level of the reflected solar spectrum, b) the solar continuum level taking into account the luminescent continuum of the cometary dust radiation.

spatial distribution of that source has a very strong concentration toward the cometary nucleus.

Effect of the light scattering cannot explain the observed level of the additional continuum (according to the developers of SCORPIO its level is about a few percent, private communication). Additional argumentation of its existence could be the following: the depths of the Fraunhofer lines in the spectrum of the solar light scattered in the atmosphere (the spectrum of the dawn sky) correspond to the calculated depths.

It should be also noted that this effect is not observed in all comets. For instance, Churyumov and Kleshchonok [7] noticed the absence of the luminescence continuum in comet C/1996 B2 (Hyakutake), while all steps of analysis were the same as in this work.

Unfortunately, the luminescence has a wide spectrum without significant features that complicates the identification of radiating material. Thus, the cometary spectrum $I_{\rm com}$ consists of three components:

$$I_{\rm com}(\lambda) = I_{\rm e}(\lambda) + I_{\rm s}(\lambda) + I_{\rm l}(\lambda), \tag{6}$$

where $I_{\rm e}$ is the intensity of cometary emission spectrum, $I_{\rm s}$ is intensity of the solar spectrum reflected by cometary dust, $I_{\rm l}$ is intensity of cometary luminescent radiation.

The spectral regions without strong emission lines were selected for the determination of the level of the luminescent continuum. In this case it is quite natural to

consider that $I_e \approx 0$. For those regions of the spectrum, it was adopted that the luminescent continuum level has no variation. Thus, for the selected regions of the cometary spectrum, the following approximation is valid:

$$I_{com}(\lambda) = kI_f(\lambda) + I_l, \tag{7}$$

where $I_f(\lambda)$ is the intensity in the known solar spectrum which is calculated taking into account the spectral resolution of the cometary spectrum and its discontinuity, k is the factor that characterizes the reflective ability of cometary dust, and I_l is the intensity of the luminescent continuum. In practice, parameters k and I_l are selected so that to obtain the best fit to the cometary continuum region (Fig. 4). Gathering data on the level of the luminescent continuum for different spectral regions provides the possibility to study the behavior of the luminescent continuum in the whole cometary spectrum.

The following procedure was applied to obtain the solar continuum. First of all we obtained the instrumental profile using the narrow line. A set of appropriate, not blended lines of moderate intensity was selected from the lamp spectrum. This set was used to determine the dispersion curve. All lines were normalized, and then the mean profile was obtained. The instrumental function of the spectrograph, $s(\lambda)$, was derived from the mean profile using the normalization condition $\int_0^\infty s(\lambda)d\lambda = 1$. This instrumental function includes the resolving power, as well as the effect of the discreteness of the photodetector. After that, we can calculate intensities in the solar spectrum for each pixel of the cometary spectrum using the convolution of the high-resolution solar spectrum $I_f(\lambda)$:

$$I_f(\lambda_i) = \int_{\lambda_i-\Delta\lambda}^{\lambda_i+\Delta\lambda} i_f(t)s(t)dt, \tag{8}$$

where the half-width of the integration range was selected from the condition that the instrumental function at the edges of the interval should be less than 0.001.

Intensity of the luminescence continuum (in percent relative to the solar continuum) was found from (7) by determining the ratio I_l/kI_f, where the mean intensity of the Fraunhofer spectrum was obtained in spectral regions free of strong absorption lines. The equivalent widths of Fraunhofer lines were not investigated.

The technique we used for studying the luminescent continuum in spectra of comet 9P/Tempel 1 is the same as the one described by Churyumov et al. [33], p. 106 (Fig. 5). Essentially, as an initial solar spectrum we used the high-resolution solar spectrum atlas published by Kurucz et al. [35]. We reduced this initial solar spectrum to the given spectrograph spectral resolution by convolution with a real instrumental profile obtained from the calibrating lamp spectrum. Then we subtracted the reduced initial solar spectrum from the cometary one to obtain a purely emission cometary spectrum. The resulting spectrum is interpreted as a combination of two components: the solar reflected and a fluorescent continuum from the comet. We assume that the latter radiation here is due to the luminescence of cometary dust.

For comet 9P/Tempel 1, the level of the luminescent continuum is 30% of the level of the total cometary continuum with the maximum near 5250 Å.

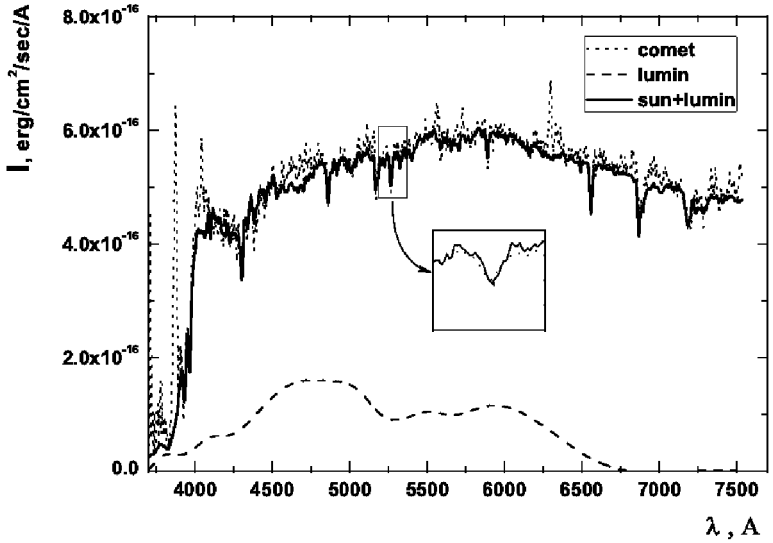


Figure 5 Spectrum of comet 9P/Tempel 1. The components of spectrum: dotted line, combined cometary spectrum; dashed line, luminescence spectrum; continuous line, cometary spectrum without emissions (the sum of the Fraunhofer spectrum and luminescence spectrum). Boxed, the zoomed fragment of the spectrum which demonstrates the quality of cometary continuous spectrum rebuilding.

Another support of the existence of the luminescence continuum comes from comparison of the cometary spectra for the nucleus region and at the edge of the slit, where cometary emissions are absent (here we expect to have a pure scattered solar radiation). Provided there is no contribution from the luminescence radiation, we have to register the same depths of the Fraunhofer lines in both spectra (both are exposed at the same time and at the same device). The cometary spectra (upper part; for convenience, the emission lines are removed) and the solar spectrum (lower part) exposed with SCORPIO are given in Fig. 6.

As is seen in Fig. 6 the depths of the Fraunhofer lines in the cometary spectrum differ from those in the solar spectrum. Therefore, both the suggested methods and the direct comparison show the presence of the luminescent continuum in the spectrum of comet 9P/Tempel 1. This can be caused by the luminescence of comet organic species, which are present in the cometary dust particles. As it was shown by Nazarchuk and Chorny [36], there could also be the following alternative sources of the cometary luminescence continuum radiation in the optical region: 1) the continuous spectrum of the C_2H radical, which arises under the photolysis of the C_2H_2 molecule [37] (it is beyond the scope of our paper to calculate the concentration of C_2H); 2) the sputtering of water ice particles at temperatures below 100 K by electrons with energy between 20 and 300 eV; 3) the photoluminescence of Lonsdaleite crystals, which are white grains of diamonds and can be included in the composition of graphite particles; 4) the ordinary scattering by silicates as well as their Roentgen luminescence; 5) the photoluminescence of polycyclic aromatic hydrocarbons (PAHs).

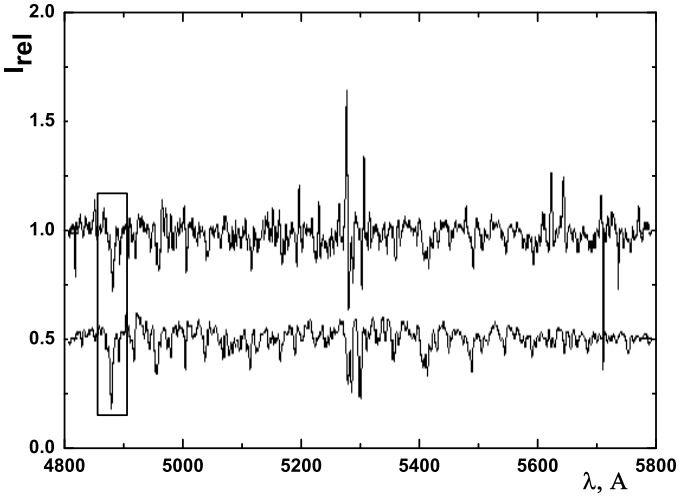


Figure 6 The spectra of comet 9P/Tempel 1 (upper part, emission lines are removed) and the solar spectrum (lower part). Demonstrated in the box is the difference in depths of the selected line at various distances from the cometary nucleus. This effect cannot be explained by an influence from the weak cometary emissions, because, for example, in the red part of the spectrum it is not seen.

Analysis [36] shows that the possible contribution of sources 2, 3 and 4 is very small. Source 1 can contribute to the continuum with a maximum at 5100 Å. As to the features at 6300, 5250 and 4500 Å, source 5 (photoluminescence of small PAHs – anthracene $C_{14}H_{10}$, pyrene $C_{16}H_{10}$, chrysene $C_{18}H_{10}$, tetracene $C_{18}H_{12}$, and some other PAHs) is probably the most important.

5 Conclusion

On the basis of analysis of the comet 9P/Tempel 1 spectra exposed on March 14–15, 2005, the energy distributions and brightness profiles in the selected emission lines along the spectrograph slit were constructed. Some physical parameters of the selected molecules of the neutral cometary atmosphere (particle outflow velocities, lifetimes and scale length of the parent and daughter molecules CN, C_2 and C_3) were determined.

The spectra of comet 9P/Tempel 1 were investigated in order to determine the real level of the non-solar-nature continuum in the spectral region of 3500–6000 Å. We believe that, in the spectra of comet 9P/Tempel 1, we detected the real luminescence cometary continuum, which is caused by the luminescence of organic species incorporated in cometary dust particles (CHON-particles). For comet 9P/Tempel 1, the level of the luminescent cometary continuum is 30% of the level of the total cometary continuum with the maximum intensity near 5250 Å. This situation should improve upon further analysis and with future additional data.

Acknowledgements

KIC is thankful for financial support provided by FAPESP (Fundação de Amparo á Pesquisa do Estado de São Paulo) under contract No. 08/58366-2 during his visit to the University of São Paulo.

References

[1] G.A. Milani, Gy.M. Szabó, G. Sostero *et al.* Photometry of comet 9P/Tempel 1 during the 2004/2005 approach and the Deep Impact module impact, *Icarus*, 191:517–525, 2007.

[2] L.M. Shulman. Distribution of neutral matter density in the cometary atmosphere, *Astrometry and Astrophysics*, 11:26–30, 1970 (in Russian) (translation into English in www.astro.iag.usp/p̃icazzio/shulman).

[3] L.M. Shulman. Dynamics of Cometary Atmosphere. The Neutral Gas, Naukova Dumka, Kiev. 242, 1972 (in Russian) (translation into English in www.astro.iag.usp/picazzio/shulman).

[4] L. Haser. Distribution d'intensite dans la tete d'une comete, *Bull. Acad. R. Belg.* 43:740–750, 1957.

[5] L. Haser. In Nature et Origine des Cometes, *Mem. 8 Soc. R. Sci. Liege*, (5) 12:233, 1966.

[6] Churyumov, K.I., Kleshchenok, V.V., Vlassyuk, V.V. 1994. Spectral observations of comet P/Schaumasse (1992X) with the 6-meter telescope BTA. *Pisma v Astronomicheskij Journal*, 20, 76–77, Moscow.

[7] K.I. Churyumov, V.V. Kleshchonok. *Odessa Astronomical Publication*, 12:258–260, 1999.

[8] I.V. Luk'yanyk, K.I. Churyumov. Observations of comet C/2001 A2 (linear) with the multipupil fiber spectrograph. *Earth, Moon and Planets*, 90:177–183, 2002.

[9] K.I. Churyumov, I.V. Luk'yanyk, V.L. Afanasiev, A.V. Moisseev, Exploration of the comet 19/P Borrelly spectra obtained with the MPFS and Scorpio of 6-m Telescope on Aug. 2001. *Proceedings of Asteroids, Comets, Meteors – ACM 2002.* Ed. Barbara Warmbein. Noordwijk, Netherlands: ESA Publications Division, 657–660, 2002.

[10] I.V. Luk'yanyk, K.I. Churyumov, V.L. Afanasiev, A.V. Moiseev. Observation of spectra and monochromatic images of comet C/2001 A2 (LINEAR). *Proceedings of Asteroids, Comets, Meteors – ACM 2002.* Ed. Barbara Warmbein. Noordwijk, Netherlands: ESA Publications Division, 717–720, 2002.

[11] E. Picazzio, A.A. de Almeida, K.I. Churyumov *et al.* The optical spectroscopy and near infrared observations of comet C/2000 WM1 (Linear) in December, 2001 in Chile and Brazil, *Earth, Moon and Planets*, 90:23–32, 2002.

[12] E. Picazzio, A.A. de Almeida, K.I. Churyumov *et al.* A high spectral resolution atlas and catalogue of emission lines of the comet C/2000 WM1 (LINEAR). *Adv. Space Res.*, 10:312–322, 2006.

[13] L.S. Chubko, K.I. Churyumov, V.L. Afanasiev, I.V. Luk'yanyk, V.V. Kleshchonok. Comparison of the spectra of the comets 9P/Tempel 1 and C/2004 Q2 (Machholz). *Deep Impact as a World Observatory Event: Synergies in Space, Time, and Wavelength. ESO Astrophysics Symposia*, 197–200, 2009.
[14] V.L. Afanasiev, A.V. Moiseev. The SCORPIO universal focal reducer of the 6-m telescope, *Astronomy Letters*, 31:193–203 (translated from *Letters in Astronomical Journal*, 31:214–225, 2005).
[15] D.O. Mokhnasch. *Byull. Inst. Teor. Astron. Akad. Nauk SSSR*, 6:269, 1956.
[16] D.O. Mokhnasch. *Astron. Zh.*, 35:605, 1958 [*Sov. Astron.*, 2:560, 1959].
[17] D.O. Mokhnasch. *Dokl. Akad. Nauk SSSR*, 120:1228, 1958 [*Sob. Phys. Dokl.*, 3:492].
[18] L.V. Wallace and F.D. Miller. Isophote configurations for model comets, *Astron. J.*, 63:213, 1958.
[19] V.G. Riives. *Publ. Tartu. Astrofiz. Obs.*, 33:281, 1960.
[20] Yu.N. Gnedin, A.Z. Dolginov. Particle distribution in a comet head. *Astron. Zh.* 43:181 [*Sov. Astron.*, 10:143], 1966.
[21] A.L. Cochran. A re-evaluation of the Haser model scale lengths for comets. *Astron. J.*, 90:2609–2614, 1985.
[22] M.R. Combi, A.H. Delsemme. Neutral cometary atmospheres. I – an average random walk model for photodissociation in comets, *Astrophys. J.* 237:633, 1980.
[23] M.C. Festou. The density distribution of neutral compounds in cometary atmospheres. I – Models and equations, *Astron. Astrophys.* 95:69–79, 1981.
[24] T.L. Farnham, D.G. Schleicher, M.F. A'Hearn. The HB narrowband comet filters: standard stars and calibrations, *Icarus*, 147:180, 2000.
[25] T.L. Farnham, C.M. Lisse, M.F. A'Hearn, *et al. Bull. Am. Astron. Soc.*, 36:1126, 2010.
[26] L.M. Feaga, M.F. A'Hearn, J.M. Sunshine *et al.* Asymmetries in the distribution of H_2O and CO_2 in the inner coma of Comet 9P/Tempel 1 as observed by Deep Impact, *Icarus*, 190: 345–356, 2007.
[27] D.G. Schleicher. Deep Impact's target Comet 9P/Tempel 1 at multiple apparitions: Seasonal and secular variations in gas and dust production, *Icarus*, 190:406–422, 2007.
[28] S. Larson, Z. Sekanina. Coma morphology and dust-emission pattern of periodic Comet Halley. I – High-resolution images taken at Mount Wilson in 1910, *Astron. J.*, 89:571–578, 1984.
[29] V.L. Afanasiev. Physical features of neutral coma of comet Abe, 1970g, *Problemy kosmicheskoy fiziki*, 9:120–129, 1974 (Translation into English in http://www.observ.univ.kiev.ua/index.php?mod=pages&page=afanasiev).
[30] D.G. Schleicher. The fluorescence efficiencies of the CN violet bands in comets, *Astron. J.*, 140:973–984, 2010.
[31] M.F. A'Hearn, Comets, ed. L. Wilkening, Univ. Arizona Press, Tucson, 1982.
[32] G.K. Nazarchuk. Luminescencing dust particles in the atmosphere of comet Halley, 1982i, *Kiev Comet Circular*, 372:2, 1987.
[33] K.I. Churyumov, V.V. Kleshchenok, V.V. Vlassyuk. Spectral observations of comet P/Schaumasse (1992X) with the 6-meter telescope BTA. *Pisma v Astronomicheskij Journal*, 20:76–77, 1994.
[34] K.I. Churyumov, V.V. Kleshchonok, F.A. Mussaev, I.F. Bikmaev, G. Galazutdinov. Observations of high resolution spectra of Ccomet Hale-Bopp (C/1995 O1) at the SAO of the RAS. *Earth, Moon and Planets*, 78:105–110, 1997.

[35] R.L. Kurucz, I. Furenlid, J. Brault, L. Testerman. Solar flux atlas from 296 to 1300 nm. National Solar Observatory, Sunspot, New Mexico, 1984.
[36] G.K. Nazarchuk, G.F. Chorny. Luminescence of organic molecules in the Halley comet. In IAU Symposium 160, Lunar and Planetary Institute, Houston, USA, 233, 1993.
[37] W.M. Jackson, X.L. Yang, X. Shi, A.L. Cochran. The temporal changes in the emission spectrum of comet 9P/Tempel 1 after Deep Impact, *Ap. J.*, 698:1609–1619, 2009.