NARROWBAND PHOTOMETRY OF COMET OKAZAKI–LEVY–RUDENKO 1989r

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(Received 10 June, 1992)

Abstract. The results of the photoelectric photometry with the narrowband CN, C_3, C_2 and Blue Continuum (BC) IHW interference filters are presented. Observations were carried out with a set of diaphragms of different effective radii. On the base of the Haser model the production rates of the radicals have been obtained. The CN and C_2 molecules scale lengths (3.4×10^5 km and 8.5×10^4 km respectively for 1.0 AU heliocentric distance) have been also derived. The dust continuum spectrum is negligibly low in comparison with the molecular one, which stay in agreement with the results of other observations of comet Okazaki–Levy–Rudenko.

1. Observations

Photometric observations of comet Okazaki–Levy–Rudenko were performed in October and November 1989 at the Cracow Observatory and at the Observational Station in the Bieszczady Mountains. Table I contains information about the photometric systems. Despite the fact that the original IHW filters were used, their transparence curves were obtained anew for different angles of light incidence. Thus, the transparence curve for the given filter and for the convergent light beam corresponding to the given telescope have been constructed. The central wavelengths $-\lambda_0$ and FWHM of the filters presented in Table I are referred to these curves.

The observations were performed as follows. Brightnesses of the central part of the cometary coma were measured with a set of circular diaphragms of different effective radii. Absolute flux calibration was achieved by observations of comparison stars. The comparison stars may be divided into two classes; primary and secondary standards. Magnitudes of the secondary standards referred to the narrowband filters were obtained observationally from the primary standards, i.e. from stars with published spectrophotometry (Breger, 1976). Their spectra were constructed by last-square fitting of the theoretical spectra given by Kurucz (1979) to the monochromatic magnitudes contained in the Breger's catalogue; our primary standards system has better than 0.05 magnitude agreement with Osborn's (1990) photometric system. Table II presents the magnitudes of the primary and secondary standards.

Magnitudes of the comet were corrected for atmospheric extinction. Extinction coefficients in the standard UBV system were obtained for each night and the narrowband filter coefficients were calculated assuming an exponential dependence between the extinction coefficient and the light wavelength. Because of the large

Earth, Moon, and Planets **59**: 229–237, 1992.

TABLE I

Photometric systems (telescopes and interference filters)

Telescope	Filter	λ_0 [Å]	FWHM[Å]
Refractor	CN	3868	43
	C_3	4055	73
Reflector	BC	4855	66
	C_2	5144	84

Refractor – refractor placed at the Observational Station in the Bieszczady Mountains, $D = 203$ mm, $F = 3000$ mm. Reflector – Cassegrain telescope placed at the Cracow Observatory, $D = 500$ mm, $F = 6670$ mm.

TABLE II

Narrowband filter magnitudes of all the primary and secondary standards and nights when the actual cometary comparison stars were used

BS or HD	m (CN)	m (C_3)	m (BC)	m (C_2)	Nights when the standard was used
Primary standards (Breger)					
BS 3454	3.915	3.874	4.196	4.201	
BS 4983	5.175	4.874	4.452	4.360	Nov. 04.2, 13.1
BS 5191	1.516	1.488	1.782	1.797	
BS 5235	3.637	3.336	2.874	2.780	Nov. 13.1
BS 5351	4.071	4.013	4.153	4.135	
BS 5404	4.818	4.548	4.223	4.124	
BS 5447	5.010	4.748	4.639	4.498	Oct. 24.2, 24.7, 25.7, 28.2, 28.7, 29.1
Secondary standards					
BS 5229	6.303	5.986	–	–	Oct. 24.2, 29.1
BS 5255	–	–	5.853	5.705	Nov. 04.2
BS 5304	5.722	5.403	4.978	4.903	Oct. 24.2, 24.7, 25.7, 26.7, 28.7, 29.1
BS 5374	–	–	6.630	6.432	Oct. 20.7
HD 124587 HD 124588 *	–	–	6.983	6.850	Oct. 23.7

* Double star with separation 1″.71 between components.

zenith distances at which the cometary observations were performed, the air masses were taken from Bemporad's formulas (Schoenberg, 1929) with air temperature and pressure taken into account. The brightness contributions from stars comprised in the same diaphragms as the comet were checked up observationally and their influence on the cometary brightness was found negligible. Table III gives the results of observations – extra atmospheric fluxes of the comet in the narrowband filters for different apertures. Errors of these results do not exceed 7% of the flux, and are mostly due to the poorly known extinction coefficients and their strong variability in the region of the sky near the horizon.

TABLE III

Results of the observations

UT Date 1989		z [deg]	r [AU]	Δ [AU]	F [ergs cm^{-2} s^{-1}]				
					CN Filter				
Mth	*d*	Diaphragm radius [arc min] =			1.06	1.76	2.71	3.54	5.15
10	24.143 ÷ 0.169	75.6 ÷ 81.0	0.755	1.184	3.01 E-09	5.38 E-09	6.11 E-09	7.98 E-09	9.99 E-09
10	24.700 ÷ 0.710	70.9 ÷ 73.0	0.749	1.174	1.71 E-09	3.04 E-09	3.74 E-09	4.26 E-09	5.36 E-09
10	25.701 ÷ 0.710	72.1 ÷ 74.1	0.739	1.156	1.42 E-09	3.14 E-09	3.10 E-09	4.89 E-09	6.12 E-09
10	28.156 ÷ 0.166	74.1 ÷ 76.2	0.715	1.109	2.20 E-09	3.16 E-09	5.82 E-09	6.40 E-09	7.02 E-09
10	28.691 ÷ 0.720	73.3 ÷ 79.5	0.710	1.099	2.92 E-09	5.00 E-09	5.98 E-09	6.71 E-09	7.81 E-09
10	29.119 ÷ 0.167	72.9 ÷ 83.0	0.706	1.090	1.98 E-09	3.13 E-09	4.29 E-09	5.51 E-09	–
11	13.113 ÷ 0.189	61.6 ÷ 79.5	0.643	0.764	7.26 E-09	1.54 E-08	2.02 E-08	2.45 E-08	3.10 E-08
					C_3 Filter				
Mth	*d*	Diaphragm radius [arc min] =			0.99	1.85	2.72	3.60	5.37
10	28.720	79.5	0.710	1.098	–	2.77 E-10	–	–	–
11	13.158 ÷ 0.167	66.8 ÷ 69.1	0.643	0.764	2.21 E-10	3.34 E-10	5.30 E-10	8.10 E-10	7.56 E-10
					BC Filter				
Mth	*d*	Diaphragm radius [arc min] =			0.30	0.37	0.58	0.73	1.02
10	20.750 ÷ 0.762	77.0 ÷ 79.5	0.794	1.241	–	–	5.56 E-11	6.30 E-11	7.16 E-11
10	23.723 ÷ 0.781	74.4 ÷ 85.8	0.760	1.191	2.47 E-11	3.68 E-11	5.07 E-11	6.44 E-11	7.24 E-11
10	25.712 ÷ 0.747	74.0 ÷ 81.2	0.739	1.155	2.51 E-11	2.92 E-11	4.71 E-11	5.81 E-11	6.49 E-11
10	26.711	74.9	0.729	1.137	–	3.12 E-11	–	–	–
10	28.708 ÷ 0.737	76.5 ÷ 82.3	0.710	1.093	–	3.57 E-11	5.88 E-11	6.52 E-11	8.97 E-11
11	04.133 ÷ 0.190	64.2 ÷ 77.3	0.664	0.964	9.55 E-11	9.47 E-11	1.26 E-10	–	–
					C_2 Filter				
Mth	*d*	Diaphragm radius [arc min] =			0.30	0.37	0.58	0.73	1.02
10	20.745 ÷ 0.760	76.0 ÷ 79.1	0.794	1.241	–	–	8.58 E-10	1.01 E-09	1.16 E-09
10	23.721 ÷ 0.779	73.9 ÷ 85.3	0.760	1.191	3.82 E-10	5.04 E-10	7.32 E-10	9.37 E-10	1.10 E-09
10	27.709 ÷ 0.744	73.4 ÷ 80.6	0.739	1.155	3.49 E-10	4.86 E-10	7.11 E-10	8.97 E-10	1.07 E-09
10	26.708 ÷ 0.716	74.3 ÷ 76.0	0.729	1.137	–	4.28 E-10	5.82 E-10	–	–
10	28.705 ÷ 0.748	75.9 ÷ 84.4	0.710	1.093	3.15 E-10	4.89 E-10	8.24 E-10	9.84 E-10	1.16 E-09
11	04.142 ÷ 0.181	64.7 ÷ 77.0	0.664	0.964	3.64 E-10	6.37 E-10	1.18 E-09	–	–

z; zenith distance of the comet. *r;* comet-Sun and comet-Earth distances. *F;* observed extra atmospheric flux in the appropriate filter.

2. Numbers of the Molecules

As the first step the subtraction of the cometary continuum radiation from the molecular emissions must be done. Unfortunately, only one filter, Blue Continuum, has provided information about the dust radiation of the comet. Since a reflectivity gradient (Jewitt and Meech, 1986) cannot be determined in this situation, the assumption must be accepted, that the continuum spectrum of the comet is identical with the Solar spectrum. As one can see the nonzero contribution to the radiation in the Blue Continuum filter is given by the short-length "wing" of the C_2 0–0 band. In order to eliminate this parasitic contribution the mean profile of the C_2 0–0 band from the spectroscopic observations of comets Encke (Newburn and Spinrad, 1984) and Kohoutek (A'Hearn, 1975) has been taken into consideration. The common result of these reductions is that the continuum emission of comet Okazaki–Levy–Rudenko is negligible, especially in comparison with the strong CN and C_2 emissions. The previous assumption about the reflectivity gradient may cause only small errors of the narrowband fluxes, not exceeding 5%. The fact that comet Okazaki–Levy–Rudenko is a gassy comet with a very weak dust continuum radiation was confirmed by other observations (Eaton *et al.*, 1991; and Brooke *et al.*, 1991).

The next step was to convert the fluxes observed in the narrowband filters into the fluxes emitted in the profiles of the molecular emissions. The profiles of the emission features were taken from the "mean" cometary spectrum basing on the spectrophotometric observations of comet Kohoutek and comet Enke (see above). Then the resultant fluxes were converted into the numbers of molecules contained within cylinders of radii corresponding to the photometer apertures. For C_2 and C_3 radicals the formula taken from the paper of Millis *et al.* (1982) was used; namely,

$$\log N = \log F + 27.499 + 2 \log r\Delta - \log g \, ; \qquad (1)$$

where N is the number of molecules, F is the observed (and converted as has been mentioned previously) flux in ergs $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, r and Δ are the heliocentric and geocentric distances of the comet in AU and g is the fluorescence efficiency per molecule at the distance 1 AU in (cgs units). The numbers of C_2 and C_3 molecules were computed using the $\log g$ equal to -12.657 and -12.00 respectively. In the case of the CN radical the numbers of molecules were obtained according to Tatum's tables (Tatum, 1984) with the Swings effect taken into account.

3. Radical Production Rates and Their Scale Length

The Haser model (Haser, 1966) was used to determine the molecule production rates and to investigate the scale lengths for CN and C_2 radicals. The model assumes purely radial molecular coma outflow, with a velocity independent of the distance between the given point and the cometary nucleus. A spherical symmetry of the gas production rate and the outflow velocity has been also assumed. The classical Haser model is represented by the equation

$$n(d) = \frac{Q}{4\pi d^2 v} \frac{\gamma_d}{\gamma_d - \gamma_p} (\exp(-d/\gamma_d) - \exp(-d/\gamma_p)) \, , \qquad (2)$$

where $n(d)$ is the number density of the molecules in cm^{-3}, dependent on the distance d between the given point in the coma and the nucleus (in cm), Q is the production rate in s^{-1}, v is the expansion velocity of the molecular coma, γ_p and γ_d are the scale lengths for the parent and daughter (CN, C_2, C_3) molecules (in cm) respectively. The Haser model is too far from reality in many points but is still used because of its simplicity. For our investigations it is fully adequate in view of the low precision of the photometric data obtained from observations near the horizon. The second reason is that the amount of observational data per one

TABLE IV

Haser model parameters and the number production rates of the radicals

UT date 1989		r [AU]	Q/v [10^{26} km^{-1}]		
			CN	C_3	C_2
Mth	d				
10	20.7	0.794	–	–	9.24 (±0.33)
10	23.7	0.760	–	–	7.73 (±0.18)
10	24.2	0.755	3.20 (±0.10)	–	–
10	24.7	0.749	1.78 (±0.03)	–	–
10	25.7	0.739	1.71 (±0.12)	–	6.80 (±0.12)
10	26.7	0.729	–	–	5.60 (±0.47)
10	28.2	0.715	2.09 (±0.13)	–	–
10	28.7	0.710	2.45 (±0.08)	0.22	6.27 (±0.27)
10	29.1	0.706	1.50 (±0.22)	–	–
11	04.2	0.664	–	–	6.03 (±0.80)
11	13.1	0.643	4.40 (±0.16)	0.19 (±0.03)	–
			γ_p^0 [km] = 1.6 10^4	3.1 10^3	1.6 10^4
			$n_p = 1.5$	2.0	2.0
			γ_d^0 [km] = $\underline{3.4 \pm 0.3\ 10^5}$	1.45 10^5	$\underline{8.5 \pm 1.3\ 10^4}$
			$n_d = 2.0$	2.0	2.0

The model parameters obtained by the authors in the adjustment procedure are underlined.

night is too small to use more sophisticated models e.g. Combi model (Combi, 1988). The production rates and scale lengths for CN and C_2 were determined as follows: As the number of apertures is not great and the observational material is of low precision the computations of the scale lengths for each night were not successful. In this situation the dependence between the scale length and the heliocentric distance of the comet was expressed by the commonly used formula

$$\gamma_p = \gamma_p^0 r^{n_p}, \qquad \gamma_d = \gamma_d^0 r^{n_d}; \tag{3}$$

where γ_p^0 and γ_d^0 are the parent and daughter scale-lengths for the heliocentric distance r equal to 1.0 AU, n_p and n_d are the indices describing this dependence. The values of the indices n_p and n_d were adopted from literature (Cochran 1985, Combi and Delsemme, 1986) and the scale lengths γ_p^0 and γ_d^0 were found using the best observational material for the CN (nights: Oct. 24.2, 24.7, 28.7, 29.1, Nov. 13.1) and C_2 radicals (nights: Oct. 23.7, 25.7, 28.7). The theoretical value of the number of molecules in each aperture was obtained as follows. From equation (2) the two-dimensional number density in the plane perpendicular to the line of sight was computed and then it was integrated with the photometric profile of the aperture. These profiles were obtained observationally by photometric scans of a star moving along the aperture diameter at different position angles. The appropriate computations were performed minimizing the discrepancies (expressed by log) between the numbers of the molecules obtained theoretically and observationally, where the parameters to be found were the scale lengths γ_p^0, γ_d^0 and the reduced production rate Q/v for each night. The first runs of the

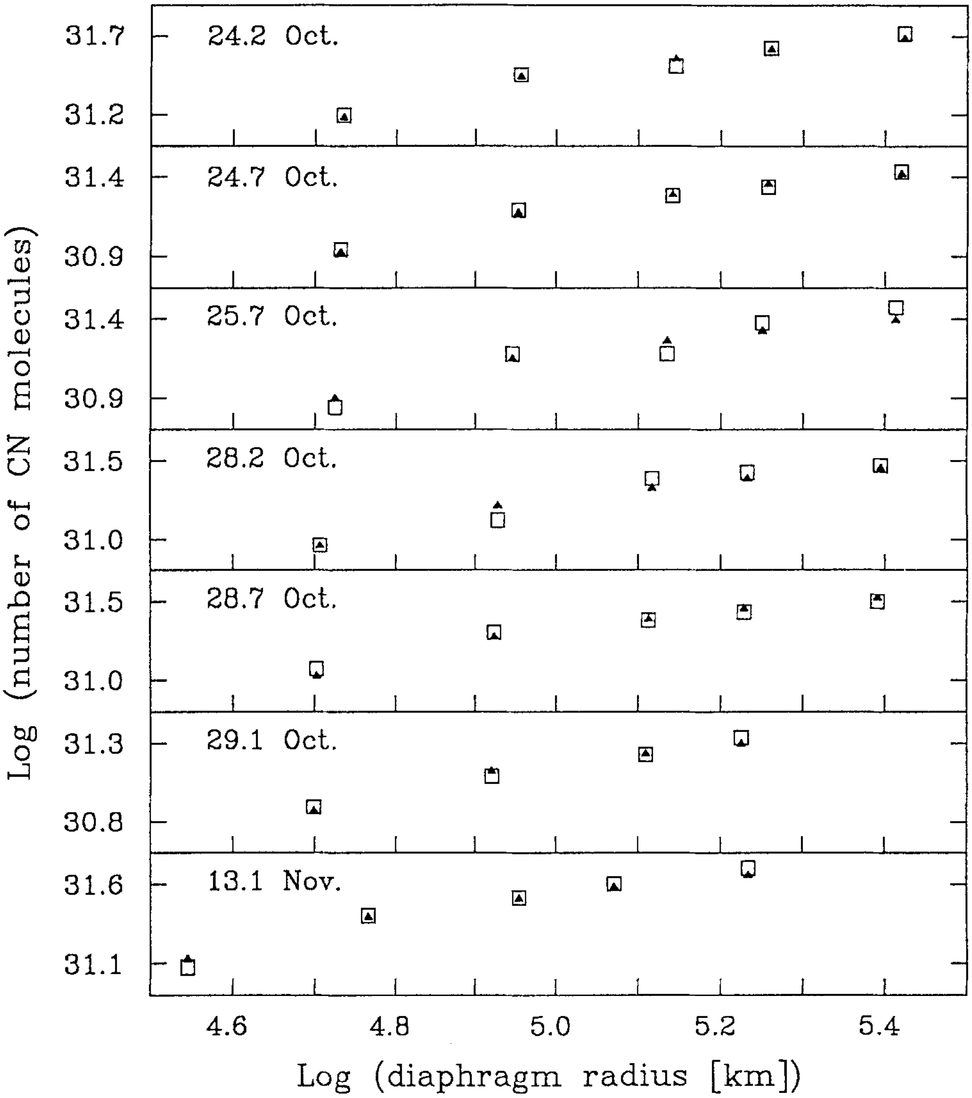

Fig. 1. Numbers of CN molecules contained in the cylinders corresponding to the apertures of different radii. Open squares – observationally obtained, filled triangles – computed from the model.

optimization procedure revealed, that the parent scale length γ_p^0 cannot be computed and its value must be taken from literature. In the computations the different values of γ_p^0, n_p and n_d taken from the papers of Cochran (1985) and Combi and Delsemme (1986) were examined and only their best combinations were used in the determination of γ_d^0 and the production rates. For the C_3 molecule only production rates were determined basing on the Haser model parameters given by Cochran (1985).

The results of the computations are given in Table IV, which contains the values

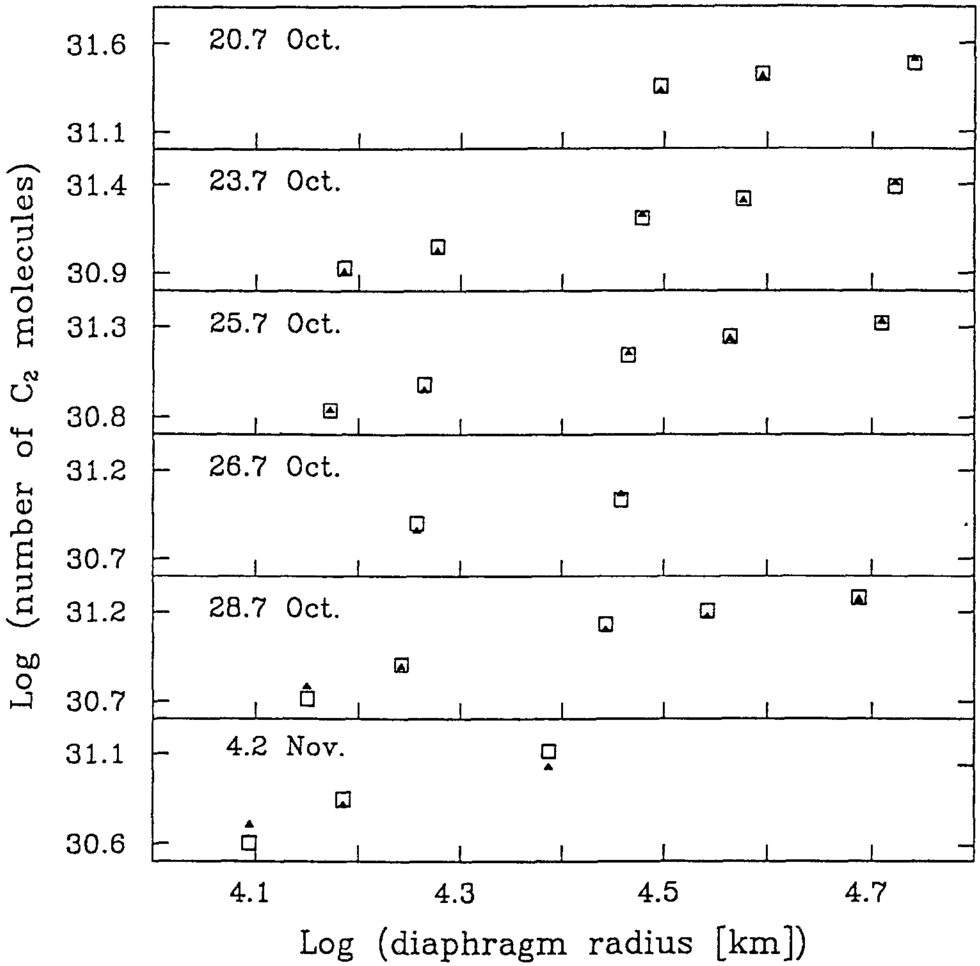

Fig. 2. Numbers of C_2 molecules contained in the cylinders corresponding to the apertures of different radii. Open squares – observationally obtained, filled triangles – computed from the model.

of Haser model parameters both taken from literature and those obtained by the authors (underlined in the table) and the molecular production rates (Q/v) for each night. The theoretically computed and observed numbers of molecules in different apertures are compared in Figure 1 for CN and Figure 2 for C_2 and the heliocentric distance dependencies of the production rates of radicals are presented in Figure 3. A quite good agreement between the observed and computed numbers of molecules is visible, especially taking into consideration the low precision of the photometric data. The obtained values of the parameter γ_d^0 for CN and C_2 are not too far from those obtained previously for other comets; 1.1 or 1.2×10^5 km for CN and 3.0×10^5 km for C_2 respectively. The errors of the production rates presented in Table IV are only the r.m.s. errors of the optimization procedure and the systematic errors submitted by the standardization proced-

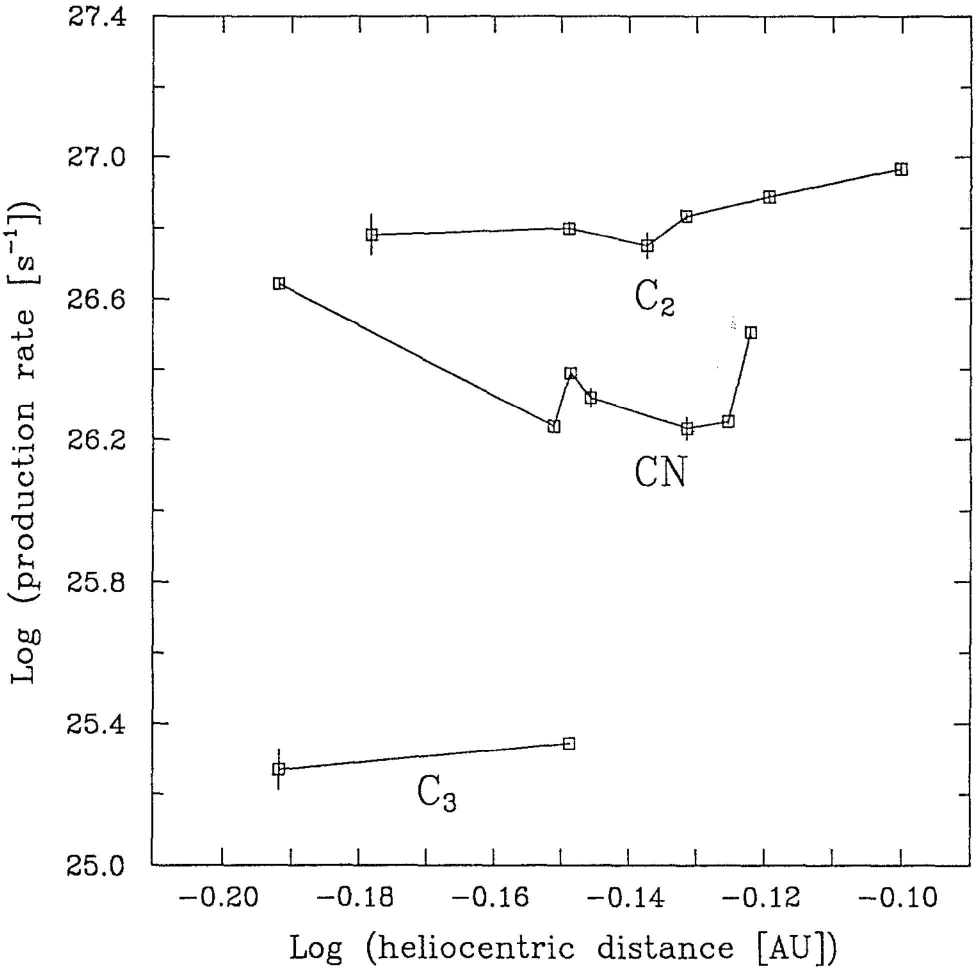

Fig. 3. CN, C_3 and C_2 molecules production rates versus heliocentric distance of the comet. *Notes:* 1.0 km s^{-1} was assumed for the outflow velocity of the molecules. Error bars visualize only the r.m.s. errors of the optimization procedure.

ure must be taken into account in order to obtain the real errors of the production rate. The rapid transitions of the CN production rate, which can be seen in Figure 3 are hardly real because it is difficult to expect any variations of so short a scale since the time of passage, when the edge of the maximal aperture is reached, is not less than tens of hours (for the canonical value of the radial velocity of the molecules 1.0 km s^{-1}). These changes may be explained by the errors originating in the process of the absolute flux calibration. Only long-term trends of the production rates can be treated as fully real results.

4. Conclusions

The photometric observations of comet Okazaki–Levy–Rudenko with narrowband interference filters and a set of apertures of different radii allowed to study the scale lengths γ_d^0 (for heliocentric distance of 1.0 AU) for CN and C_2 and the production rates of radicals. The main results may be summarized as follows.

(i) The continuum spectrum is negligibly low in comparison with the molecular emissions.

(ii) The determined values of the γ_d^0 parameters for the CN and C_2 molecules (3.4×10^5 and 8.5×10^4 km) are similar to those obtained earlier for other comets.

(iii) Comet Okazaki–Levy–Rudenko is very similar to Comet Kohoutek (comparable production rates of CN, C_2 and C_3 at similar heliocentric distances) (Newburn, 1984).

(iv) The C_2 production rate is greater than the CN production rate which is a common result for comets at heliocentric distances lower than 1.5 AU.

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