NARROW-BAND PHOTOMETRY OF COMET C/1995 O1 (HALE–BOPP)

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Abstract. Photometric observations of comet C/1995 O1 (Hale–Bopp) carried out at the Stará Lesná Observatory since February to April 1997 are analyzed and discussed. Emission band fluxes and continuum fluxes are presented, from which the total numbers of molecules in the columns of the coma encircled by diaphragms are calculated. The production rates are estimated from the conventional Haser model. We found that the photometric exponent of dust contribution two months prior perihelion was $n = 5.2$. The photometric exponent n of the cometary magnitude solely to the C_2 emission alone equals 3.3 and that of CN equals 2.5. These values can be explained by a fact that the maximums of production rates of the gases were reached between March 2 and 12 and not at the perihelion as it is valid for dust.

These results are compared with the values of 1P/Halley (1986 III) under the similar conditions, obtained with the same method and instrument. C/Hale–Bopp exhibited 4.1 times more molecules radiating the CN-emission than 1P/Halley in the same column of the coma. The continuum flux of C/Hale–Bopp was also very strong. The ratios (to 1P/Halley) are 94:1 (Cont. 484.5) and 74:1 (Cont. 365.0). The cometary colour was the same as that of the Sun.

Keywords: Narrow-band photometry, comet C/1995 O1 (Hale–Bopp)

1. Comparison Stars and Extinction Changes

Photometric observations of comet C/1995 O1 (Hale–Bopp) carried out at the Stará Lesná Observatory since February to April 1997 are analyzed and discussed. The comet was mostly observed in the pre-perihelion phase during about two months at the ranges of heliocentric and geocentric distances 1.3–0.9 AU and 1.9–1.3 AU, respectively. The observations were performed with a photoelectric photometer installed in the Cassegrain focus of the 600/7500 mm reflector. The measurements were carried out with IHW narrow-band filters CN, C_2, C_3, Cont. 365.0 and Cont. 484.5 and four focal diaphragms – 45, 76, 119 and 196 arc sec in diameter.

The comet passed only rarely in a vicinity of known standard stars. That is why 14 stars, not measured before in IHW filters, had to be used. Their magnitudes were obtained additionally, during September and October 1997, when they could be observed under better conditions – at smaller air masses. The spectral types of selected stars are from F0 to K5 and visual magnitudes in the interval of 3.2–6.7. The magnitudes in narrow-band filters were obtained with respect to the secondary standards HD 22951 and HD 214680 from the list prepared by Osborn et al. (1990).

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Determined magnitudes are not listed here because of lack of place. They can be immediately obtained from the authors.

The bad position of the comet during the whole period of observations caused that the comet was observed at large air masses. The largest air mass at which the comet was measured was 3.47, but that for a comparison star was even 4.50. Air mass was calculated by applying Hardie's polynomial expression (Hardie, 1962).

It is clear that only observations during very transparent nights can be used for further reductions, at such air masses. Therefore, only observations obtained during 8 nights are presented here and observations from 3 nights had to be omitted. The statistical errors of derived coefficients were about 10% during spring period and about 4% in the autumn when the choice was restricted to very good conditions. These variations of atmospheric conditions (accompanied by changes of temperature from -14 °C on February 18 to +6 °C on April 3) precluded an applying of some mean values of the coefficients. That is why the coefficients were determined and used individually for every night.

2. Continuum Fluxes and Colours

To remove the influence of contamination of continuum by C_2-emission, we take interim correction derived (A'Hearn, 1991):

$$m_c(484.5) = m(484.5) + 0.012[m(484.5) - m(514.0)]. \tag{1}$$

The emission band fluxes F_e and continuum fluxes F_c were calculated on the basis of calibrating the filters used, as obtained from various sources and summarized by A'Hearn (1991).

The colour of the cometary material can be represented as the colour excess (Osborn et al., 1990). Following symbols are used: U – 365.0 nm, B – 484.5 nm and ⊙ – the Sun

$$E(U - B) = [m_{\text{comet}}(U) - m_{\text{comet}}(B)] - [m_{\odot}(U) - m_{\odot}(B)]. \tag{2}$$

The solar colour was taken as the average colour of the solar analogs

$$m_{\odot}(U) - m_{\odot}(B) = 1.17 \text{ magnitude.}$$

The continuum fluxes calculated for diameter of the coma equal to 100 000 km obtained by interpolation of the measurements in different diaphragms together with corresponding magnitudes and derived colours of cometary material are given in Table I. The dependences of the continuum fluxes upon the diaphragm diameters were found to be linear with correlation coefficients greater than 0.99.

The continuum fluxes indicate a strong reddening only for the observation on February 23 that can be due to the atmosphere. All the other values tell us that the cometary colour was the same as that of the Sun.

3. Gas Fluxes, Numbers of Molecules and Production Rates

The fluxes of the comet due to the emission features alone are listed in Table I. The underlying continuum was removed. The fluxes due to C_3 alone were too weak and they could not be estimated with an acceptable accuracy.

Usually, the determination of the cometary brightness in chosen diaphragm needs to find the cometary brightness as a function of the focal diaphragm and also to accept some presumptions about spatial distribution of the molecules in the coma. In the case of our measurements of C/Hale–Bopp, the dependences not only of the continuum fluxes but also of the gas fluxes upon the diaphragm diameters are linear with correlation coefficients greater than 0.99. It may be caused by the fact that the giant coma was measured just within a small interval of available diaphragm diameters. Therefore, we can use the linear interpolation for reduction to linear diameter of 100 000 km. The ephemeris data were calculated on the basis of Nakano's orbit (1997).

The coefficients K used for calculating emission band fluxes depend on temperature and are listed in Table I. From the pure molecule emission fluxes F_e, the total numbers M of molecules in the columns of the coma were calculated using the relations given by Boehnhardt et al. (1989). The values of the fluorescence efficiency of the molecules g were adopted as follows:

- for the C_2-molecule from Newburn and Spinrad (1989),
- for the CN-molecule, the dependence on the radial velocity of the comet was taken into account using the tabulated data (Tatum, 1984).

The production rates Q/v were estimated from the conventional Haser's model. The scale lengths of parent (l_p) and daughter (l_d) molecules were taken from A'Hearn et al. (1995).

The values of photometric exponent n defined by the equation

$$M = m_{\mathrm{obs}} - 5 \log \Delta - 2.5n \log r, \tag{3}$$

where m_{obs} was taken as the magnitude corresponding to the linear diameter of the coma of 100 000 km were calculated. We found that the photometric exponent of dust contribution two months prior perihelion is $n = 5.2$. The photometric exponent n of the cometary magnitude solely to the emission of C_2 parent molecules alone equals 3.3 and that of CN equals 2.5. It must be noted that derived slopes need not be characteristic for cometary behaviour due to a short baseline in heliocentric distance used. So, the small difference of values (2.5 versus 3.3) does not enable us to determine if the comet behaviour is in agreement with the view which describes all the gas species of each individual comet by only one photometric exponent as it found Cochran et al. (1992) studied the gas production of 17 comets or in agreement with the view that some comets showed different exponents for different species, as it was found for comet Austin 1990 V (Waniak et al., 1994). On the other hand, the derived differences between dust and gas variations are large, and in spite of short interval of heliocentric distances, look real.

TABLE I

Fluxes, colours, numbers of molecules and production rates. Explanation of the symbols: d – date (day–month), a – diaphragm diameter (arc sec), l – linear diameter (km), r – heliocentric distance (AU), Δ – geocentric distance (AU), $\dot{r}$ – radial heliocentric velocity (km s^{-1}), $F_c(U)$ – continuum flux 365.0 nm (10^{-15} W m^{-2} nm^{-1}), $F_c(B)$ – continuum flux 484.5 nm (10^{-15} W m^{-2} nm^{-1}), $E(U-B)$ – colour (magnitudes), K – emission band flux coefficient (10^{-10} W m^{-2}), F_e – emission band flux (10^{-13} W m^{-2}), g – fluorescence efficiency (10^{-21} W mol^{-1}), M – number of molecules, l_p – parent scale length (km), l_d – daughter scale length (km), Q/v – production rate

d	7 – 2	18 – 2	23 – 2	2 – 3	8 – 3	12 – 3	1 – 4	3 – 4
a	73	82	87	94	99	102	102	100
l	100 000							
r	1.294	1.172	1.121	1.057	1.009	0.981	0.914	0.915
Δ	1.881	1.671	1.582	1.472	1.396	1.358	1.357	1.374
$\dot{r}$	−20.0	−18.2	−17.1	−15.0	−12.8	−11.1	+0.4	+1.6
Continua								
$F_c(U)$	359	860	1210	1950	2820	3720	4480	3900
$F_c(B)$	658	1600	1960	3550	4980	6660	8120	7170
$E(U-B)$	+0.01	+0.02	−0.14	0.00	−0.08	−0.02	−0.01	+0.01
CN-emission								
K	5.40	5.50	5.21	5.25	5.23	5.29	5.10	5.08
F_e	39.0	86.7	99.4	127	202	206	173	169
g	2.457	2.762	2.973	3.320	3.548	3.704	3.071	3.394
log M	32.099	32.293	32.727	32.268	32.395	32.361	32.366	32.323
l_p	$1.3 \times 10^4 r^2$							
l_d	$2.1 \times 10^5 r^2$							
log Q/v	27.436	27.630	27.609	27.605	27.732	27.698	27.703	27.660
C_2-emission								
K	6.81							
F_e	80.1	171	223	336	402	484	516	505
g	45							
log M	32.472	32.613	32.642	32.706	32.698	32.730	32.696	32.698
l_p	$2.2 \times 10^4 r^2$							
l_d	$6.6 \times 10^4 r^2$							
log Q/v	28.145	28.286	28.315	28.379	28.371	28.403	28.369	28.371

TABLE II

Comparison of 1P/Halley and C/Hale–Bopp data

	1P/Halley		C/Hale–Bopp	
Photometric exponents				
Region	n	r [AU]	n	r [AU]
Cont. 365.0	5.0 ± 0.8	1.76–0.94	5.2 ± 0.3	1.29–0.91
Cont. 484.5	5.0 ± 0.4	1.81–0.94	5.2 ± 0.3	1.29–0.91
CN	6.5 ± 0.7	1.76–0.94	2.5 ± 0.6	1.29–0.91
Fluxes				
Region	F_c		F_c	
Cont. 365.0	66.5		4 100	
Cont. 484.5	94.5		7 390	
Logarithm of the number of molecules				
CN	31.749		32.363	

4. Comparison to 1P/Halley

The values of both continuum and gas fluxes show that C/Hale–Bopp was, indeed, one of the brightest comets in history. That is why only 1P/Halley can be a dignified object for comparison. Both the 1P/Halley (Svoreň, 1987) and C/Hale–Bopp (this paper) observations were obtained using the same method and instrument. It enabled us to compare the observations made at the similar heliocentric and geocentric distances. The 1P/Halley observation on January 5, 1986 (a pre-perihelion arc, r = 0.95 AU, Δ = 1.24 AU) and C/Hale–Bopp observations on March 12 and April 1, 1997 were chosen.

Before the comparison, the 1P/Halley data had to be reduced to the same linear diameter of the coma. The adopted linear diameter of 100 000 km corresponds to 111 seconds of arc for 1P/Halley on January 5, 1986. The magnitudes in the calculated diaphragm of 111 arc sec were obtained by logarithmic fit of magnitude – focal diaphragm dependence.

The results listed in Table II show that, in the same column of the coma, C/Hale–Bopp exhibited 4.1 times more molecules radiating the CN-emission than 1P/Halley. The continuum flux of C/Hale–Bopp was also strong. The values reduced to the same geocentric distances show that the ratio is 94:1 (Cont. 484.5) and 74:1 (Cont. 365.0).

The derived values of the photometric exponent n for continuum fluxes are very similar to those of 1P/Halley and the maximum values of continuum fluxes were reached at perihelion. The change of CN magnitude alone (after removing the continuum) is much slower than that of 1P/Halley. These slower changes (the trend for C_2 magnitude is similar) can be explained by large irregularities of the production rates of the gas, e.g. the maximum values in our data were reached between March 2 and 12 and not at perihelion. This is in agreement with sudden outbursts followed by quieter phases.

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