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CN, NH_2, and dust in the atmosphere of comet C/1999 J3 (LINEAR)

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Abstract. Comet C/1999 J3 (LINEAR) was observed with 2 m telescope of the Pik Terskol Observatory on September 19, 1999. Narrow-band CCD images of the CN, NH_2, and dust atmospheres were recorded with the Two-Channel focal reducer of the Max-Plank-Institute for Aeronomy. The distributions of the CN and NH_2 molecules in the comet atmosphere were fitted with a Monte Carlo model. For the CN atmosphere the best agreement between observed and calculated surface profiles was reached with the CN photodissociation lifetime $\tau(\mathrm{CN}) = 1.5\times10^5$ s and with the parent photodissociation lifetime $\tau(\mathrm{CN}_{\mathrm{parent}}) = 3.2\times10^4$ s. This result indicates that HCN is the main source of the CN radicals in the atmosphere of comet C/1999 J3 (LINEAR). Regarding the NH_2 radicals, there is no doubt that NH_3 is the dominant source of this species in the comet atmosphere. The lifetimes $\tau(\mathrm{NH}_2) = 1.0\times10^5$ s for NH_2 and $\tau(\mathrm{NH}_{2\ \mathrm{parent}}) = 5.0\times10^3$ s for its parent are close to theoretical calculations. The gas-production rates of CN, $Q(\mathrm{CN}) = 3.8\times10^{25}$ mol s^{-1}, and NH_2, $Q(\mathrm{NH}_2) = 6.9\times10^{25}$ mol s^{-1} have also been determined. The appearance of the comet and the obtained data show that the comet is a gaseous one. The $Af\rho$ values are 21.6 cm for the blue spectral window and 23.4 cm for the red one. The normalized spectral gradient of the cometary dust is low, 4.0% per 1000 Å. The ratio $\log((Af\rho)_{443}/Q(\mathrm{CN})) = -24.25$ indicates a very low dust to gas ratio as well.

Key words. comets: individual: C/1999 J3 (LINEAR) – molecular processes – methods: numerical

1. Introduction

Comet C/1999 J3 (LINEAR) was discovered by the LINEAR team on May 12, 1999. The new object was initially identified as an asteroid. Its cometary nature was later revealed by observers at Klet Observatory in the Czech Republic. According to the orbital elements the comet has a period of ~63 000 years and is not a “new” comet. It passed its perihelion on September 20, 1999 and reached a magnitude of 7.5 in the middle of October.

2. Observations and data reduction

Observations of comet C/1999 J3 were made with the the 2m telescope of the Pik Terskol Observatory on September 19, 1999, one day before the comet's perihelion passage. The heliocentric and geocentric distances of the comet were 0.977 AU and 0.983 AU respectively. The Two-Channel focal reducer of the Max-Planck-Institute for Aeronomy equipped with CCD detectors (Jockers 1997) was used to study the comet's atmosphere. The observed sky fields were 7.8 × 7.8 arcmin with a pixel size of 1.0 arcsec and 7.8 × 5.2 arcmin with a pixel size of 0.8 arcsec in the blue and red channels, respectively. The interference filters IF390 ($\lambda_0 = 389.4$ nm, $FWHM = 10.5$ nm) and IF662 ($\lambda_0 = 662.1$ nm, $FWHM = 5.9$ nm) were chosen to isolate the emissions of the CN and NH_2 molecules. The underlying dust continua were determined from observations through interference filters IF642 ($\lambda_0 = 641.6$ nm, $FWHM = 2.6$ nm) and IF443 ($\lambda_0 = 443.2$ nm, $FWHM = 4.4$ nm). More details on the observed data can be found in Table 1.

The original CCD frames were bias subtracted, flat-fielded and cleaned of cosmic events. Star trails were also removed from the comet images. The night sky level was estimated from the parts of the sky field not covered by the cometary coma and was subtracted. The cometary counts were converted to an absolute intensity scale using

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Table 1. Log of observations.

Date (UT) September, 1999	Exposure s	Aperture size arcmin	Pixel size arcsec	Interference filter Designation	 λ_0, Å	 $FWHM$, Å	 Species
19.004	600	7.8 × 7.8	1.0 × 1.0	IF390	3894	105	CN
19.014	600	7.8 × 7.8	1.0 × 1.0	IF443	4432	44	Dust
19.004	600	7.8 × 5.2	0.8 × 0.8	IF662	6621	59	NH_2
19.014	600	7.8 × 5.2	0.8 × 0.8	IF642	6416	26	Dust

observations of the standard star 15 UMa. Its flux was taken from Voloshina et al. (1982).

Cometary images obtained through the interference filters IF390 and IF662 contain the CN and NH_2 emissions as well as dust continuum. Therefore, in order to study the distribution of these molecules in the atmosphere of comet C/1999 J3 the dust continuum must be removed. This is done by subtraction of the appropriately scaled continuum images from the images containing emission and dust. The continuum scaling factor k can be calculated taking into account the wavelength dependence of the solar spectrum and the effect of the reddened cometary continuum

$$k = \frac{F^{\odot}_{\rm m+d}}{F^{\odot}_{\rm d}} \left[1 + \frac{(Af\rho)_{642} - (Af\rho)_{443}}{\lambda_{642} - \lambda_{443}} \cdot \frac{\lambda_{\rm m+d} - \lambda_{\rm d}}{(Af\rho)_{\rm d})}\right]. \quad (1)$$

Here the subscripts 642 and 443 refer to the interference filters IF642 and IF443 and the subscripts m+d and d to the interference filters used for observation of the molecule and the adjacent dust continuum (i.e. 390 and 443 for CN and 662 and 642 for NH_2). $F^{\odot}$ denotes the solar flux convoluted with the transmission curve of the filter indicated in the subscript, λ is the wavelength, and $(Af\rho)$ the corresponding albedo-filling factor-distance product (see Sect. 4.3).

The solar spectrum was taken from Arvesen et al. (1969).

Preliminary results of these observations have been published recently (Korsun & Jockers 2000).

3. Model

For the analysis of our data we use a random walk model which is based on the Monte Carlo simulation. Such a model regarding the movement of a test particle in a collision environment has been discussed in detail by Cashwell & Everett (1959). The basic ideas of this model have been adapted by Combi and co-authors to explain the formation of cometary neutral comae. The details of the algorithm were described by Combi & Delsemme (1980) and Combi & Smyth (1988).

The fundamental equation of this model is as follows. If $p(x){\rm d}x$ is the probability of x lying between x and $x+{\rm d}x$ and if it is known that x always is in the range $a \le x < b$, i.e. $\int_a^b p(x'){\rm d}x' = 1$ then a properly distributed random value of x is found by solving

$$R_i = \int_a^x p(x'){\rm d}x'. \quad (2)$$

The random number R_i is uniformly distributed in $0 \le R_i < 1$.

First of all we must define a background environment in which we trace the test particles. Because water molecules dominate in cometary atmospheres, their spatial distribution can serve this purpose. The number density of the water targets $n(\rho)$ is written as

$$n(\rho) = \frac{Q(\rm H_2O)}{4\pi v_{\rm H_2O}} \frac{1}{\rho^2}, \quad (3)$$

where ρ is the radial distance from the nucleus, $Q(\rm H_2O)$ the water production rate, and $v_{\rm H_2O}$ the water outflow velocity. We take the $1/\rho^2$ dependence without exponential factor according to the discussion of Combi & Smyth (1988). In our calculations we use as a model parameter $Q(\rm H_2O) = 1.6 \times 10^{28}\ s^{-1}$ (Jockers et al. 2000). For the water outflow velocity we used the in situ measurements by Giotto in the atmosphere of Comet Halley (Lämmerzahl et al. 1987). We assumed that the outflow velocity of the investigated parent molecules is the same as for water.

Because around the time of our observations comet C/1999 J3 did not show a brightness variability other than the monotonic dependence on heliocentric distance, we assume that the molecular production rate is constant. So, an individual parent molecule is released from the nucleus at the time

$$t_i = R_i\, T_{\rm F}. \quad (4)$$

Here $0 \le R_i < 1$ is a random number and $T_{\rm F}$ is the time interval from $t = 0$ to the moment of observation. If the nucleus is an isotropic source of the gas, the outflow direction of the molecule has uniform probability. Then the spherical polar angles ϕ_i and θ_i can be calculated from

$$\phi_i = 2\pi R_i, \qquad \cos(\theta_i) = 1 - 2R_i. \quad (5)$$

The above three random numbers and the assumed outflow speed completely specify the initial trajectory of the parent molecule.

The parent molecule has a finite photodissociation lifetime $\tau_{\rm p}$ after which it dissociates into simple fragments, daughter molecules, at the time

$$t_{\rm p} = t_i - \tau_{\rm p} \ln(R_i). \quad (6)$$

The initial trajectory of the daughter molecule is determined by the vector sum of the parent radial velocity plus some additional velocity of the radical, caused by the energy excess when the parent photodissociates. The direction of this additional velocity is random in the frame of the parent molecule. Further movement of the radical is controlled by the bulk distribution of the H_2O molecules which represent the dominant component of cometary atmospheres. The radical collides with water targets and its post-collision trajectory is determined by the energy and momentum balance equations. Elastic molecule-molecule collisions are assumed here. The collision path length in the water atmosphere is highly dependent on radial distance as the bulk density of the water decreases quickly (see Eq. (3)). We use here Eq. (10) from Combi & Smyth (1988).

We follow the trajectory of the radical from collision to collision until the time of observation T_{F} or until the time t_{d}, when the daughter molecule photodissociates in the solar radiation field. The photodissociation life time of the daughter fragment t_{d} is given by

$$t_{\mathrm{d}} = t_{\mathrm{p}} - \tau_{\mathrm{d}} \ln(R_i), \tag{7}$$

where R_i is a new random number. To build a model atmosphere with satisfactory statistics we trace 5×10^7 particles in our calculations.

Additionally, we take into consideration the solar radiation pressure on the daughter molecules. To be compared with observations, the calculated cometary atmosphere is projected on the sky plane as it was seen by the observer.

4. Results

4.1. Time scales

We compared the observed surface distribution of the analyzed species with the calculated model. The Chi-square goodness-of-fit test has been adopted for this purpose.

CN molecule. Although CN is the second species which was detected in comets, so far there is no agreement among researchers regarding the nature of its parent. The most plausible hypothesis is that the HCN molecule is the major contributor to this radical in the cometary atmosphere. This molecule is stable and observed in comets. HCN is sufficiently abundant to represent the main parent molecule of CN (Ziurys et al. 1999). Additionally, recent comparison of the morphology of HCN and CN in Comet Hale-Bopp evidences that some CN jets are produced by HCN jets (Woodney et al. 1998). Nevertheless, there is probably a secondary source of CN radicals in cometary atmospheres. A likely candidate for this secondary source is dust (A'Hearn et al. 1995), however, C_2N_2, as suggested by Festou et al. (1998), is also possible.

From this discussion it seems reasonable to start our model calculations assuming that the photochemical reaction

$$\mathrm{HCN} + h\nu = \mathrm{H} + \mathrm{CN} \tag{8}$$

produces most of the cometary CN. The main destruction mechanism of CN is also photolysis:

$$\mathrm{CN} + h\nu = \mathrm{C} + \mathrm{N}. \tag{9}$$

Theoretical predictions of the photodissociation time scales for many cometary species under solar irradiance have been provided by Huebner & Link (1999). Solar photo rate coefficients and excess energies for dissociation and ionization are calculated both for low and high solar activity. According to Huebner & Link (1999) the lifetimes for HCN and CN at 1 AU amount to 7.94×10^4 s and 3.15×10^5 s at low solar activity and to 3.19×10^4 s and 1.34×10^5 s at high solar activity.

We satisfactorily fitted the observed CN atmosphere with a model having lifetimes of 1.5×10^5 s for CN and 3.2×10^4 s for its parent. Figure 1 shows observed and modeled isophotes of CN with the observed CN atmosphere as background. Profiles along and perpendicular to the solar and anti-solar direction are presented as well.

At the time of our observations (September 1999) the Sun was close to the maximum of its activity. There is excellent agreement between observed and calculated data. We conclude that the assumption of HCN as parent molecule of CN is consistent with our observations.

The moderate distortion of the CN atmosphere in the tail direction is caused by the solar radiation pressure which accelerates the CN molecules tailwards. An acceleration $a = 0.3\ \mathrm{cm\,s^{-2}}$ provides the best fit of our models. This value agrees with the data of Boice (1990).

NH_2 molecule. Previous observations of the NH_2 surface brightness distribution in comets were mainly derived from long-slit spectra. Because the NH_2 emission bands are weak and in many cases blended with features of other species, it is very difficult to interpret the observations. Tegler & Wyckoff (1989) have proposed that NH_3 is the parent of NH_2. Later, this was supported by other researchers (Krasnopolsky & Tkachuk 1991; Tegler et al. 1992; Korsun 1995; Kawakita & Watanabe 1998). Theoretical calculations of the lifetimes for NH_2 and its parent have been provided by Allen et al. (1987), Tegler et al. (1992), Van Dishoeck (1992, cited as private communication in Feldman et al. 1993), and Huebner & Link (1999). According to Huebner & Link (1999) there are several ways to produce NH_2 from NH_3. In the solar radiation field the reaction displayed below is dominant.

$$\mathrm{NH_3} + h\nu = \mathrm{NH_2}(\mathrm{X}^2\mathrm{B}_1) + \mathrm{H}. \tag{10}$$

The NH_2 molecules are destroyed by the solar radiation field via

$$\mathrm{NH_2} + h\nu = \mathrm{NH} + \mathrm{H}. \tag{11}$$

About 96% of NH_2 is produced in the cometary atmosphere by reaction (10). At low solar activity the lifetimes of NH_3 and NH_2 are 5.65×10^3 s and 4.65×10^5 s and at high solar activity 5.00×10^3 s and 2.94×10^5 s.

We interpret here observations of the two-dimensional NH_2 atmosphere. Previously this was only done by Tegler et al. (1992). Our computed surface profiles are in reasonably good agreement with the observed ones, if we adopt the theoretical values for the time scales of NH_2, $\tau(\mathrm{NH_2}) = 1.0 \times 10^5$ s, and $\tau(\mathrm{NH_{2\ parent}}) = 5.0 \times 10^3$ s for

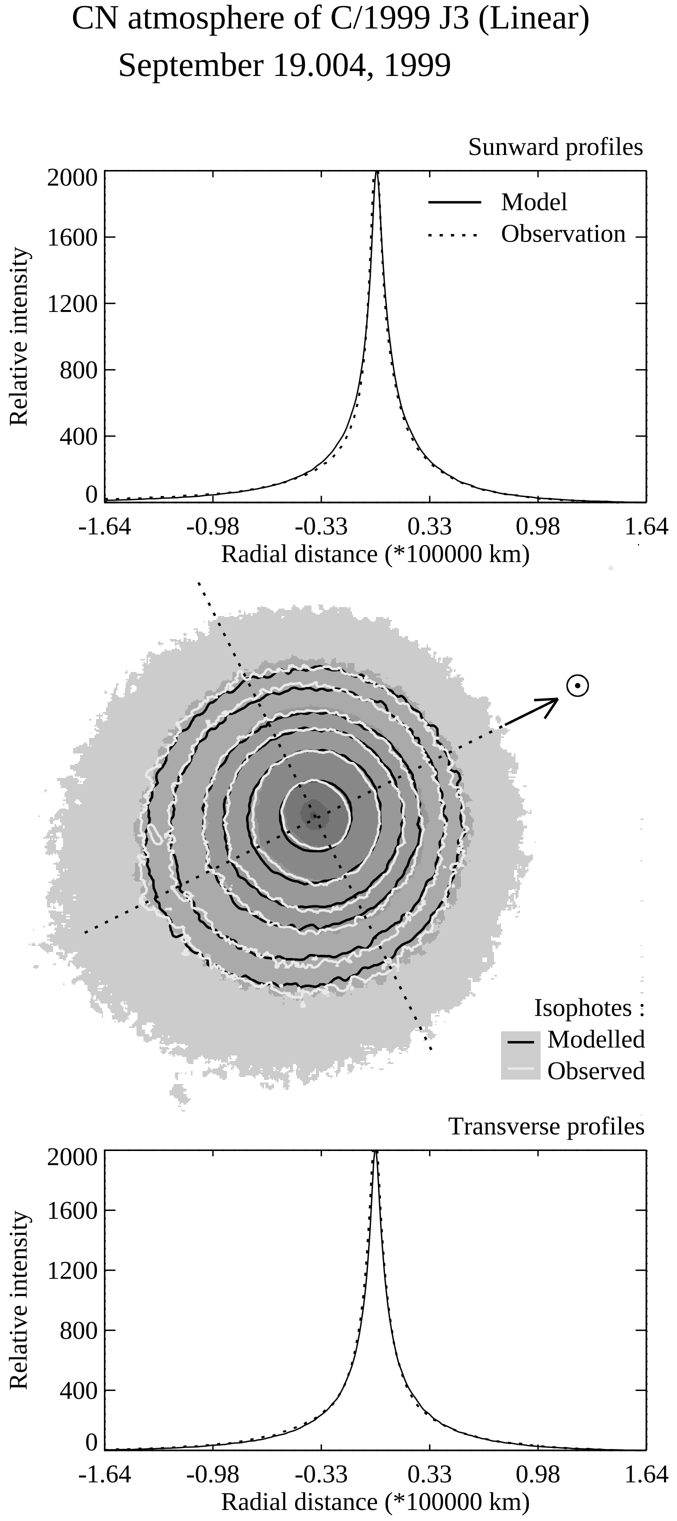

Fig. 1. Modelled and observed isophotes and radial profiles of the CN atmosphere. The zero point of radial distance is placed at the brightest point. Positive values are toward the Sun. Radial profiles are averaged across a lane of 5″ width.

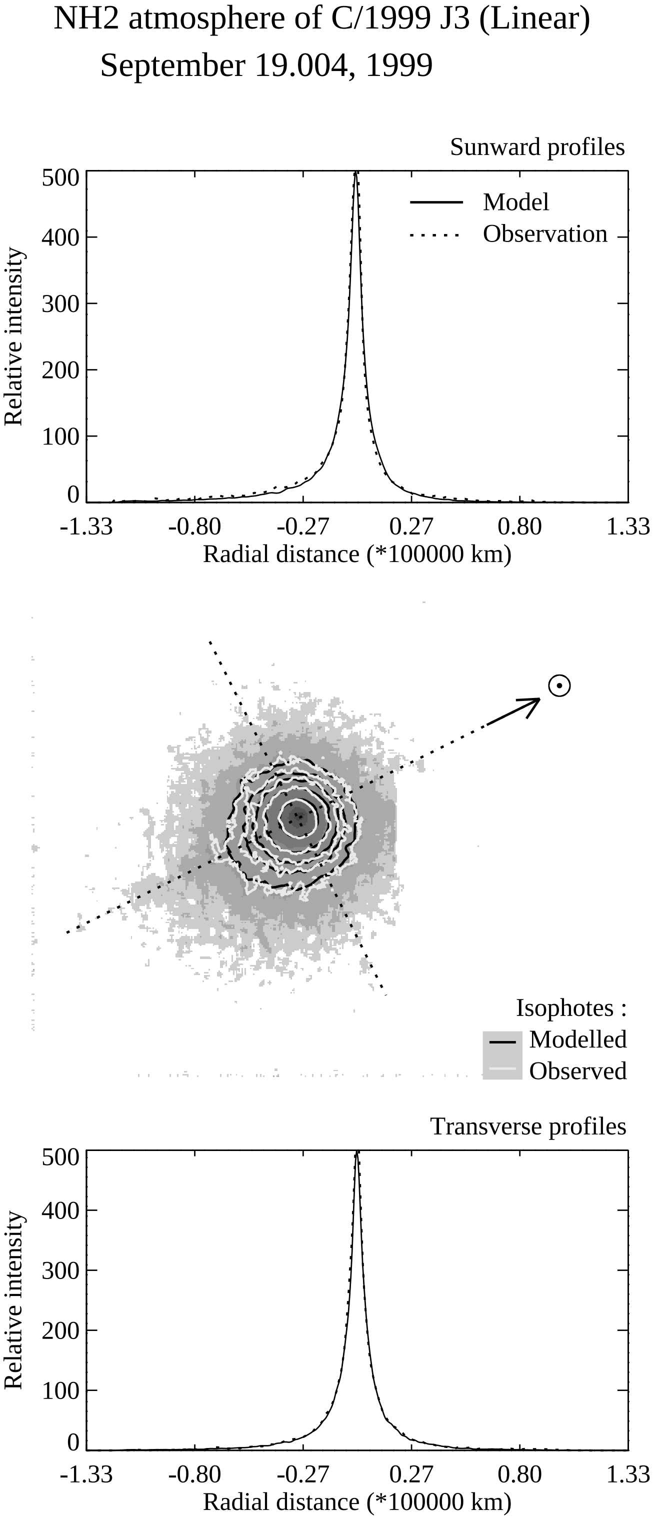

Fig. 2. Modelled and observed isophotes and radial profiles for the NH_2 atmosphere. The zero point of radial distance is placed at the brightest point. Positive values are toward the Sun. Radial profiles are averaged across a lane of 4″ width.

its parent, the NH_3 molecule. We conclude that NH_3 is probably the dominant source of NH_2 in the coma of comet C/1999 J3 (LINEAR). Figure 2 shows the comparison of the model and observed data. A tailward acceleration of the NH_2 molecules by the solar radiation pressure $a = 0.27$ cm s^{-2} (Boice 1990) was taken into account and leads to a satisfactory description of the sunward distortion of the observed coma.

4.2. Gas production rates

If we know the amount of molecules $N_{\rm mod}$ used in the Monte-Carlo model, and the model production rate, $Q_{\rm mod}$, then the total gas production rate of the modeled species, $Q_{\rm obs}$ [mol s^{-1}] can be expressed as

$$Q_{\rm obs} = \frac{N_{\rm obs}}{N_{\rm mod}} Q_{\rm mod}, \tag{12}$$

where $N_{\rm obs}$ [mol] is the total number of molecules observed in the cometary coma. It is determined from the observations using the relation between the total number of observed molecules and the total flux in the observed molecular transition $F_{\rm obs}$ [erg cm^{-2} s^{-1}]

$$N_{\rm obs} = \frac{4\pi\Delta^2 F_{\rm obs}}{g}. \tag{13}$$

Here Δ [cm] is the geocentric distance of the comet and g [erg s^{-1} mol^{-1}] the fluorescence efficiency factor (g–factor) of the observed band. g is assumed to vary with heliocentric distance as r^{-2}.

The g-factor of CN has been computed by Schleicher (A'Hearn et al. 1995). We used the value of 2.4×10^{-13} erg s^{-1} mol^{-1} valid for a heliocentric velocity of comet C/1999 J3 (LINEAR) at the moment of observation of -0.5 km s^{-1}. From our model parameters $N_{\rm mod}$ and $Q_{\rm mod}$ and Eq. (12) we get $Q({\rm CN}) = 3.8 \times 10^{25}$ mol s^{-1}.

To determine the gas production rate for NH$_2$ we have used the revised g-factor for the (0, 7, 0) band derived by Kawakita et al. (2001), 2.29×10^{-15} erg s^{-1} mol^{-1}. As a result we find the NH$_2$ production rate $Q({\rm NH_2}) = 6.9 \times 10^{25}$ mol s^{-1}.

The water production rate for this comet has been determined by Jockers et al. (2000) from H$_2$O$^+$ observations using MHD similarity law. The value of 1.6×10^{28} mol s^{-1} was found.

Comparison with our data shows that $Q({\rm CN})/Q({\rm H_2O}) = 0.24\%$ and $Q({\rm NH_2})/Q({\rm H_2O}) = 0.43\%$. If the number of NH$_2$ molecules in the cometary atmospheres accounts for 96% of NH$_3$ (see Sect. 4.1) then $Q({\rm NH_3})/Q({\rm H_2O}) = 0.45\%$ in comet C/1999 J3 (LINEAR). These results agree with values obtained previously for a number of comets. CCD spectroscopy of 39 comets suggests that $Q({\rm CN})/Q({\rm H_2O})$ varies between 0.11% and 0.30% (Fink & Hicks 1996). Our ammonia abundance of 0.45% is comparable with the values derived from recent direct measurements in the radio range of comet C/1996 B2 (Hyakutake), 0.6%, and comet C/1995 O1 (Hale-Bopp), 0.7% (Bird et al. 1997). Previous determinations of the ammonia abundance derived from observations of NH$_2$ in the visual wavelength range yield values from 0.05% to 0.20% (Fink & Hicks 1996; Wyckoff et al. 1991). They must be corrected in accordance with the revised g-factors of NH$_2$.

4.3. Dust

As we have CCD frames taken in two different cometary dust continuum windows we can estimate the dust production rate and dust color of the comet C/1999 J3. It has become customary to determine the $Af\rho$ product to characterize the dust coma of a comet (A'Hearn et al. 1984). This value is proportional to the dust production rate and is independent of the projected distance ρ from the cometary nucleus if the cometary continuum brightness follows a ρ^{-1} law. The albedo – filling factor – distance product $Af\rho$ is defined as

$$Af\rho = \frac{(2r\Delta)^2}{\rho}\frac{F_{\rm com}}{F_{\rm sun}}. \tag{14}$$

Here r [AU] is the comet's heliocentric distance, Δ [cm] is the comet's geocentric distance, ρ [cm] is the radius of aperture at the comet, $F_{\rm com}$ [erg cm^{-2} s^{-1}] is the measured cometary flux in continuum, and $F_{\rm sun}$ [erg cm^{-2} s^{-1}] is the solar flux at 1 AU. As in Sect. 2 the solar flux has been taken from the rocket measurements by Arvesen et al. (1969) and convoluted with the transmission curves of our interference filters IF443 and IF642.

Because the aperture of the CCD chip is larger than the size of the detectable cometary dust coma, and Eq. (14) is valid only if the cometary continuum brightness follows a ρ^{-1} law, we determine an effective radius, $\rho_{\rm eff}$, in our calculations. It is obtained by analyzing the slope of the average dust brightness profiles where it follows a ρ^{-1} law. As a result, we derive $(Af\rho)_{443} = 21.6$ cm for the blue continuum window and $(Af\rho)_{642} = 23.4$ cm for the red continuum red window. $Af\rho$ data have been obtained for many comets and show a wide scatter (Storrs et al. 1992; A'Hearn et al. 1995). The so-called gaseous comets have low $Af\rho$ values, like comet C/1999 J3.

The derived $Af\rho$ values allow to estimate the color of the cometary dust as the normalized gradient of the $Af\rho$ product, $S(\lambda_1, \lambda_2)$. It is defined by

$$S(\lambda_1,\lambda_2) = \frac{(Af\rho)_{642}/(Af\rho)_{443} - 1}{(Af\rho)_{642}/(Af\rho)_{443} + 1}\frac{2}{\Delta\lambda}. \tag{15}$$

For comet C/1999 J3 we have $S(6420,\ 4430) = 4.0\%$. per $\Delta\lambda = 1000$ Å. As a rule cometary dust is redder with respect to the solar spectrum and its color varies from 0% to more than 30% per 1000 Å (A'Hearn et al. 1995; Jewitt & Meech 1986; Newburn & Spinrad 1985; Remillard & Jewitt 1985). Our result indicates that the dust in comet C/1999 J3 (LINEAR) is gray or slightly red as compared to the solar spectrum.

Finally, we can calculate the ratio $\log((Af\rho)_{443}/Q({\rm CN}))$, as was done previously by A'Hearn et al. (1995). The calculated value, -24.25, exhibits a very low ratio of dust to CN. This is characteristic for gaseous comets. Moreover, only two comets from 85 analyszed ones have a ratio less than our value (A'Hearn et al. 1995).

5. Summary

Table 2 summarizes our results on the coma of comet C/1999 J3 (LINEAR).

Table 2. The coma of C/1999 J3 (LINEAR).

Parameter	Value
Lifetime of CN	1.5×10^5 s
Lifetime of parent of CN	3.2×10^4 s
Lifetime of NH_2	1.0×10^5 s
Lifetime of parent of NH_2	5.0×10^3 s
Production rate of $H_2O^\dagger$	1.6×10^{28} mol/s
Production rate of CN	3.8×10^{25} mol/s
$Q(\mathrm{CN})/Q(\mathrm{H_2O})$	0.24%
Production rate of NH_2	6.9×10^{25} mol/s
$Q(\mathrm{NH_2})/Q(\mathrm{H_2O})$	0.43%
$Af\rho$ at 4430 Å‡	21.6 cm
$\log((Af\rho)_{443}/Q(\mathrm{CN}))$	−24.25
$Af\rho$ at 6420 Å‡	23.4 cm
Color of the dust	4.0%

† Jockers et al. (2000).

‡ Phase angle is 62°.

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