GAS AND DUST IN COMET 2P/ENCKE OBSERVED IN THE VISUAL AND SUBMILLIMETER WAVELENGTH RANGES

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In November 2003 Comet 2P/Encke was observed simultaneously with the 10-m Heinrich–Hertz Submillimeter Telescope on Mount Graham, Arizona, USA, and the 2-m optical telescope on Mount Rozhen, Bulgaria. Simultaneous radio observations of the 4–3 and 3–2 rotational transitions of HCN and the 0–0 transition of the CN violet band system provide a three-dimensional view on the comet. The observations are consistent with outgassing from the source region I with location and pole position of Comet Encke taken from [14]. The outflow speed is 1.2 km. There is some evidence for another possible parent for CN besides HCN. The visual dust coma of Comet Encke is nearly spherical with a diameter of about 1000 km and a slight extension into Comet Encke's fan. The polarization of the observed NH_2 transition at 662 nm is 7% at a phase angle of 94.5°, close to the value for two-atomic molecules. At this phase angle and a wavelength of 642 nm the polarization of Comet Encke's dust is greater than 30%, *i.e.*, exceeds the value for so-called dusty comets.

INTRODUCTION

Comet 2P/Encke is the second comet (after Comet 1P/Halley) of which a periodic orbit was determined. In contrast to the orbit of Comet Halley the orbit of Comet Encke turned out to have a period of 3.4 years (the smallest one known up to now) and a perihelion distance of 0.33 AU. Because Comet Encke is always orbiting in the inner solar system it has lost a large amount of its volatile substances and is perhaps the most evolved short-period comet. In its visual appearance Comet Encke does not display a tail, *i.e.*, lacks the most well-known attribute of a comet. Instead, a so-called "fan" is observed, a broad feature visible at an angle to the Sun-comet line. It is generally assumed that most of the surface of aged short-period comets is an inactive crust left behind after sublimation of the volatile material. The activity of such comets is restricted to small localized active vents (holes in the inactive crust) deep enough to reach down to depths which are less depleted from volatile substances. Z. Sekanina studied optical images of the inner coma region of comets (which do not show the nucleus itself but only jets or fans emanating from it) in order to infer the existence and location of active areas on the surfaces of cometary nuclei and to derive the position of their rotation axis and the rotation rate. Three papers refer to Comet Encke [14–16]. According to this work the north rotation pole of Comet Encke is located at right ascension 205° and declination 2°. The obliquity of the orbit plane relative to the nucleus equator is 70° and the solar longitude at perihelion is 230°. The Sun transits the equator of the cometary nucleus from north to south 8 days before perihelion (at the heliocentric distance $r_H = 0.40$ AU) and from south to north 65 days after perihelion at $r_H = 1.35$ AU. Two vents on the nucleus surface were identified, one at latitude +55° (source I) and another one at latitude –75° (source II). While source I is in sunlight 94% of the time of revolution of the comet, source II is illuminated only 6% of the time, but this time includes the perihelion.

Z. Sekanina attributes the fan to being caused mostly by scattered light from dust grains. The dust coma of Comet Encke has been imaged by the ISOCAM device on the ISO satellite of ESA [13] at a wavelength of 11 μm. No dust tail in the usual sense was observed and there is agreement with other authors that the size of the dust grains emitted by Comet Encke is about 15 μm. The dust fan was not observed, but the reason may be the visibility restrictions. In the visual wavelength range Encke's dust has not been convincingly observed, as it is difficult to separate it from molecular emissions. In particular there is disagreement about the polarization of cometary dust from optical measurements.

In this paper we report about observations in the visual and millimeter wavelength range conducted in November 2003. The simultaneous microwave and visual observations provide a three-dimensional view on the source region I. In addition, photometric and polarimetric observations of Comet Encke's dust and NH_2 emission at 0.642 and 0.662 μm will be presented.

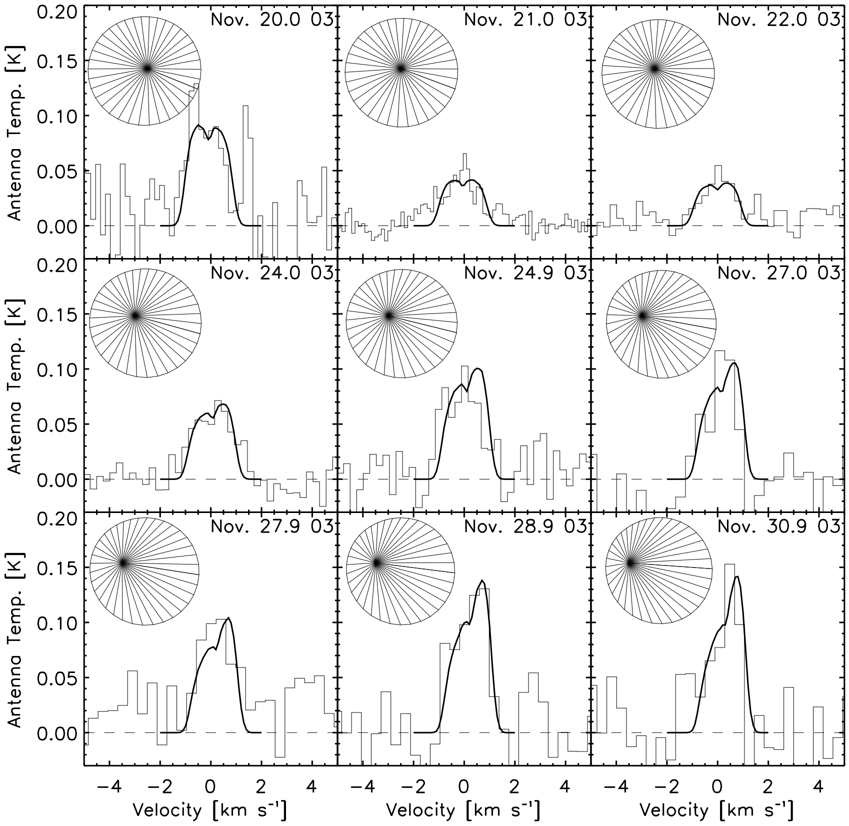

Figure 1. The sub-millimeter spectra observed with the Heinrich–Hertz telescope (histograms). Superimposed as heavy lines are the line profiles calculated from our active region emission model. The vectors (resembling the spokes of a wheel) are the projected emission directions during a full nucleus rotation (north is up, the sight direction is from left to right). The absolute values of the (unprojected) vectors vary with $\cos^{1/4}$ of solar elevation angle

OBSERVATIONS

Comet 2P/Encke had a favourable apparition in fall 2003 when it approached the Earth to a minimum distance of 0.260 AU. We observed the comet on November 18–30, 2003. During this period the comet was at the distances $r_h = 0.97$–0.77 AU from the Sun and $\Delta = 0.26$–0.32 AU from the Earth. The phase angle was large and increased from 87° to 124°. As the comet went through perihelion on December 29, it was still observed during activity of source I.

The radio observations took place at the 10-m Heinrich–Hertz telescope of the Steward Observatory on Mount Graham, Arizona, on November 18–30, 2003. The heterodyne spectrometer of MPS [17] was used to observe the 4–3 (354.505 GHz, beam diameter 21 arcsec) and 3–2 (265.886 GHz, beam diameter 28 arcsec) rotational transitions of HCN. The integration times per day were usually about 4 hours. The observations were performed with beam switching and position switching ($t/2 = \mathrm{ON}$, $t/2 = \mathrm{OFF}$). The aim of the observations was to derive the HCN production rate and the velocity profile of the HCN lines in order to draw conclusions about the nucleus source from the velocity distribution along the line of sight. The spectral scans averaged over one observing day are shown in Fig. 1.

The visual observations were conducted with the Two-Channel Focal Reducer of MPS [4] at the 2-m telescope of the Bulgarian Institute of Astronomy (Rozhen, Bulgaria) on November 18–25, 2003. Comet Encke was imaged at 388 nm (CN 0–0 band of the Violet System) to get information on the spatial distribution of CN, the daughter molecule of HCN. Imaging polarimetry and photometry were performed at 642 nm (continuum) and 662 nm (NH_2 0–7–0 α ammonia band), in order to derive a dust image from comparison of images in the "continuum" (central wavelength 642 nm, *FWHM* 2.6 nm) filter (which also transmits faint lines of NH_2) with images in the "NH_2" (central wavelength 662 nm, *FWHM* 5.9 nm) filter (which also transmits the dust continuum, but to a much smaller extent), and to measure the polarization of the dust. One pixel of the detector corresponds to 0.89 arcsec and the imaged area was at least 7.5 arcmin (1.5 arcmin for polarimetry). Each clear night observations were conducted for about 3 hours with exposure times of 5 to 10 minutes. The inner area of the CN images, corresponding in a linear extent to about two times the beamwidth of the radio telescope, is shown in isocontours in Fig. 2. Adjacent contours differ by a factor of 0.9.

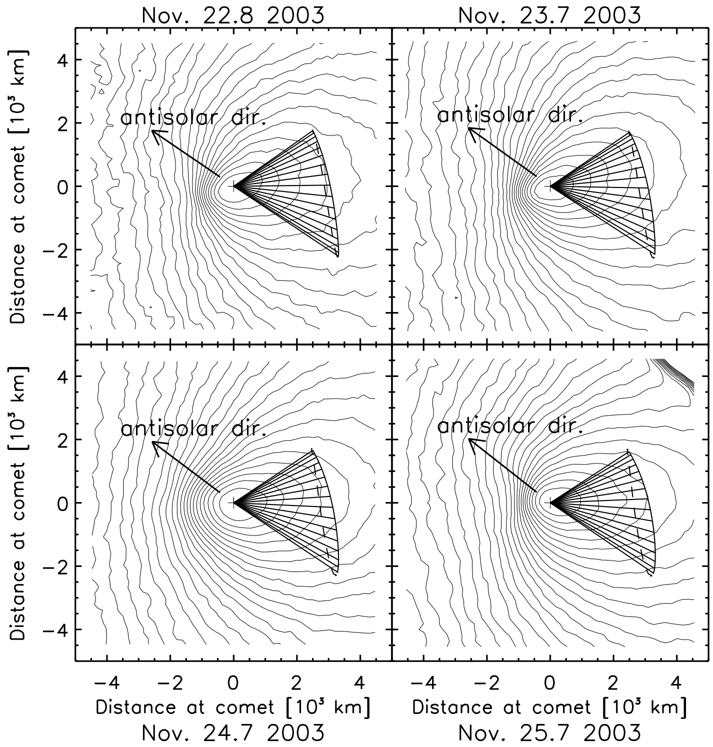

Figure 2. Isophotes of Comet 2P/Encke observed at 388 nm (CN 0–0 band of Violet System). The vectors indicate the changing emission direction of source I proposed by Z. Sekanina during one nucleus rotation. The absolute values of the (unprojected) vectors vary with $\cos^{1/4}$ of solar elevation angle. North is up, east to the left

ROTATION OF THE NUCLEUS AND POSSIBLE STRUCTURE OF THE SOURCE REGION

The gas coma of the CN radical is observed to be asymmetric. This contradicts the usual understanding that a gas coma is isotropic and spherical. It also contradicts the idea expressed in [14–16] that the fan consists of dust grains. An asymmetric gas coma of Comet Encke has already been inferred in [6]. Evidently, the gas is mostly released from a single active vent on Comet Encke's nucleus. This fact opens the possibility to investigate the properties of this active region and of the nucleus itself. The rotation period of Comet 2P/Encke is 15.2 ± 0.3 hr [5] or 15.08 ± 0.08 hr [12]. Such a rotation rate should be immediately apparent in the radio as well as in the optical data. Figure 2 shows optical data from four consecutive days. At least two of the four images should show the rotating source at upper or lower elongation. Some tendency of the innermost ellipsoidal contour to have its long axis inclined with respect to the horizontal can be noticed but this by far does not go up to the full opening angle of the cone. In [14] the rotation axis was determined from the projected center axis of the fan (some visibility criteria were checked *a posteriori* and data rejected if they were not satisfied) and the latitude of the active region was determined from the width of the fan. From this work no conclusion can be drawn if the source region is localized at a certain nuclear longitude or if it forms a ring at its latitude. Even more, the source region could extend all the way from the pole to the determined latitude, *i.e.*, the source region could comprise the polar cap down to the derived latitude. These possibilities will be studied in more detail in the future. In the following we will assume a ring-shaped source region extending at latitude 55° all the way around the nucleus. This model describes an active polar cap almost as well.

MODELLING THE HCN LINE PROFILES

A Monte Carlo model of the outflow from a ring-type source region was constructed. The rotation axis was assumed at right ascension 205° and declination 2° as proposed in [14]. Precession of the pole was not taken into account. The source region was assumed at a cometocentric latitude of 55° extending through all longitudes. HCN particles are released with a thermal speed of 0.176 km s^{-1} (temperature of 100 K) superimposed on a prescribed outflow speed v_{out} into a (three-dimensional) cone with opening half angle of 30°. The number of particles released was modulated $\sim \cos^{1/4}(\epsilon)$ (ϵ solar zenith angle) corresponding to radiative energy balance. After a stationary state has been reached in the Monte Carlo model, the particles in the telescope beam are counted and the velocity profile is determined. An HCN lifetime $\tau_{HCN} = 1.5 \cdot 10^4$ s was determined from the CN observations (see next section). The telescope beam halfwidth at the comet is $\approx$ 2300 km at the frequency of the HCN (4–3) line and $\approx$ 3100 km at the frequency of the HCN (3–2) line. As both sizes are small as compared to the scale length of HCN = $\tau_{HCN} \times v_{out}$ the line profile is not affected by the selection of the HCN life time. The crucial input parameter is the outflow speed. A good fit to the observed profiles is obtained with $v_{out} = 1.2$ km s^{-1} (see Fig. 1). As in course of the observations the rotation axis of the nucleus gradually tilts away from the observer the line becomes gradually more redshifted. Figures 1 and 2 do not support any evidence for a rotation of the active area. The source could be a ring of constant latitude or, more probable, could be centered at the pole and extend down to 55 degree latitude. A more quantitative check still needs to be done.

PRODUCTION RATES: HCN SOLE PARENT OF CN?

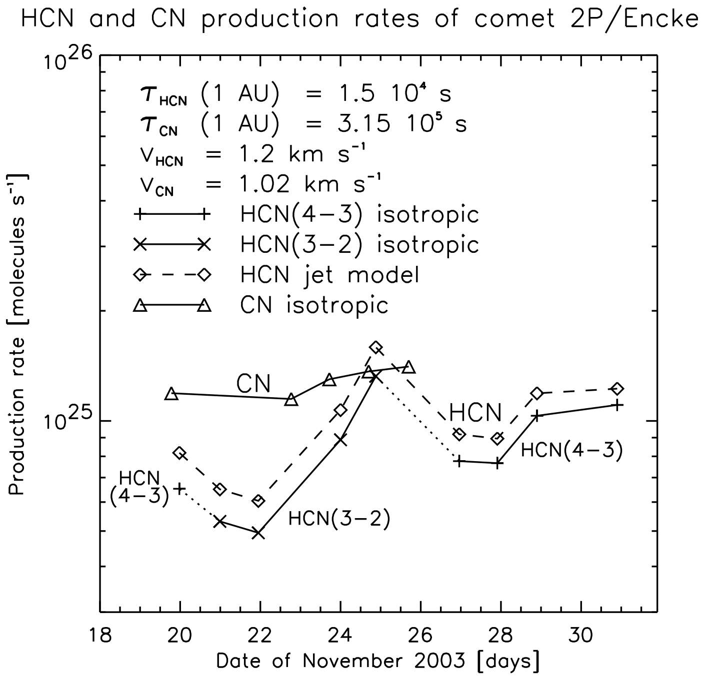

Figure 3. Production rates of parent molecule HCN and its daughter CN. Full lines: HCN isotropic model [1]. Crosses: (4–3) transition. Diagonal crosses: (3–2) transition. Dashed line and diamonds: HCN jet model. Full line and triangles: CN isotropic model. Lifetimes and velocities are indicated

It is interesting to compare HCN and CN production rates in Comet Encke to find out, if HCN can be the sole source of CN. In order to derive CN production rates, the CN images of each night were combined into single images with the star trails removed. These combined images were azimuthally averaged and fitted with Monte

Carlo calculations [2] which assume isotropic HCN and CN distributions. The daughter speed was 1.02 km s^{-1} based on molecular data [3]. The field of view of the ground-based CN images is large enough to allow the determination of the parent life time. The outflow speed v_{out} is already known from the radio observations. The fitted parent life time τ_{HCN} is consistent with a heliocentric variation in proportion to the inverse square of heliocentric distance r_H. Its derived value at 1 AU of $1.5 \cdot 10^4$ s is, however, small as compared to the theoretical values of the HCN life time of 79 400 s for low solar activity and 31 900 s for high solar activity [8]. It is also small as compared to the value adopted by [3]. The reason for this must be investigated. In any case, if the same values of parent lifetime are assumed for the production rate determination of parent and daughter, the production rate ratio is rather insensitive to the actual values [7].

The HCN production rate was determined using the standard method for isotropic outflow [1]. The integrated line areas $\int T_B dv$ varied from 0.067 ± 0.009 K km s^{-1} (HCN(3–2), November 21) to 0.194 ± 0.036 K km s^{-1} (HCN(4–3); November 28). They were converted to column densities. For this purpose, thermal equilibrium was assumed. A rotational temperature of 43 K scaled with heliocentric distance $\sim r_H^{-1.5}$ gave the best agreement between the observations of the 4–3 and 3–2 transitions. The evolution of the rotational population with increasing distance from the nucleus from LTE to fluorescence equilibrium was not taken into account. From the column densities we calculated production rates as described in [1]. The isotropic model underestimates the real HCN production rate. The telescope beam of the Heinrich–Hertz telescope is small as compared to the extent of the HCN coma (see above). In case of an isotropic coma a significant amount of flux detected by the telescope comes from particles moving close to the line of sight either toward or away from the observer (this is why line profiles of comets observed in the millimeter wavelength range frequently show a dip at zero velocity shift). In our case such particles are underabundant. Therefore, the outflow model with a ring-type source as described in the preceding section has also been used to calculate the HCN production rate. As expected, the values of this model are higher but remain smaller than the CN production rates by about a factor of two. In view of the low signal/noise ratio of the HCN observations we cannot decide if the difference necessitates an additional parent of CN. An additional parent seems, however, to be required to explain the large difference between the life time of the parent of CN derived from the CN profiles and the theoretical HCN life time. For a more detailed discussion see [18].

COMET ENCKE'S DUST AND ITS POLARIZATION

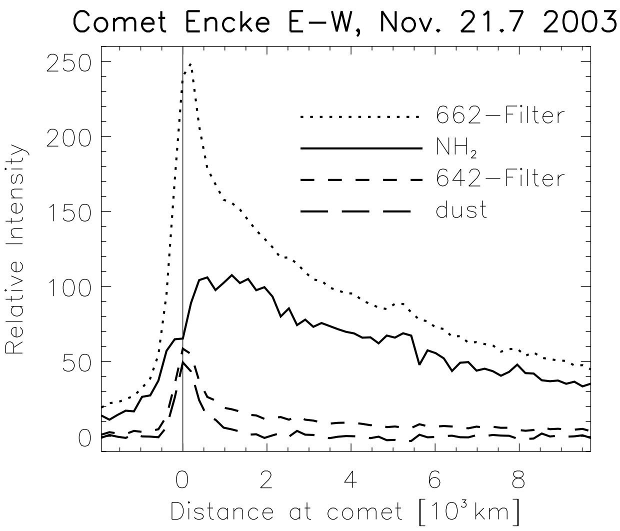

Figure 4. East-west cuts (along fan) through images of Comet Encke. Dotted: filter 662 nm. Dashed: filter 642 nm. Full: pure NH_2. Long-dash: pure dust. Images of a series of 300 s exposure frames were median filtered to obtain the displayed profiles. Three rows of the image passing closest to the nucleus have been averaged (see text)

As mentioned above, polarimetric images of Comet Encke in the filters "642" and "662" (the names stand for the central wavelength in nanometers) were acquired during the observations. Both filters transmit continuum and NH_2 lines, but the NH_2 contribution is much weaker in the "642" filter. The continuum contribution in both filters is proportional to their transmission integral multiplied with the solar intensity in both wavelengths. As the two wavelengths are not far from each other a reddening of the cometary dust can possibly be neglected.

Subtraction of the normalized images cancels out the dust contribution and produces a clean NH_2 image. To derive a dust image we have subtracted from the "642" filter image the true NH_2 image multiplied with the largest possible factor not producing negative counts in the resulting dust image. As can be seen in Fig. 4 the true dust image is nearly symmetric with respect to the nucleus with a slight extension into the fan. As small particles should form a dust tail we confirm the large size of Comet Encke's dust grains [13]. The resulting NH_2 image is shifted with respect to the dust image in the direction of the fan.

The photometric profiles have been derived by adding the four polarimetric subimages of the imaging polarimeter [4]. Applying the above discussion to the polarimetric subimages themselves we have determined the polarization of NH_2 and of the dust corrected for the influence of the NH_2 coma. The results are shown in Fig. 5. The left panel shows the polarization in the uncorrected "662" filter. The polarization rises toward the nucleus because of the increased contribution of the Comet Encke's dust. Farther from the nucleus the polarization becomes constant and equals $\approx 7\%$. The dust polarization is expected to be higher than that. Therefore, if there would be a significant but decreasing amount of dust at larger distances from the nucleus in the fan the polarization would be higher and continue to decrease. Therefore, we interpret the polarization of 7% as polarization of the NH_2 molecule in the observed 0–7–0 α ammonia band (we do not know of a determination of this value in the laboratory) and conclude that there is no dust at larger distances from the nucleus in the fan. In this way our scaled subtraction procedure to derive the true dust image is *a posteriori* justified. The right panel of Fig. 5 shows the polarization of the Comet Encke's dust. In contrast to [11] the polarization is comparable to or even larger than the polarization of so-called dust-rich comets. This result was predicted in [10] and agrees with observations in [9].

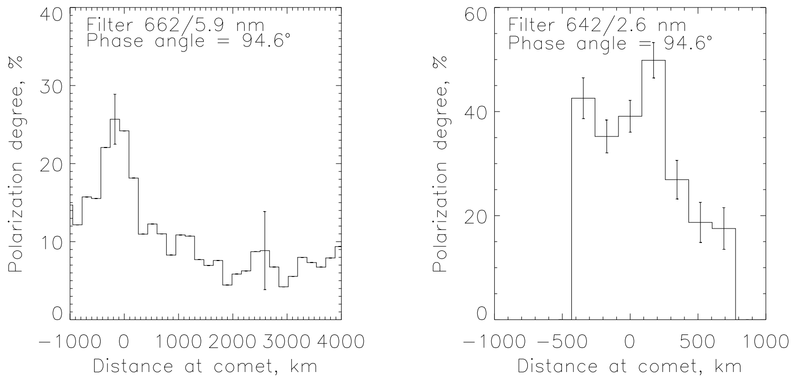

Figure 5. E–W cuts (along fan) of polarization of Comet Encke (November 21, 2003). Left panel: uncorrected image through "662" filter. Right panel: corrected dust image

CONCLUSIONS

HCN and CN was observed in November 2003 with the submillimeter Heinrich–Hertz telescope on Mount Graham, Arizona, USA, and the 2-m telescope on Mount Rozhen, Bulgaria. The work on data reduction and interpretation is continuing but the following results are already apparent:

1. The outgassing from the nucleus of Comet 2P/Encke is not isotropic but occurs from a limited active area.

2. The observed HCN line profiles can be explained by our Monte Carlo model of a ring-shaped active source, with the position of Comet Encke's north pole at right ascension 205° and declination 2° [14], and the ring-shaped activity at a latitude of 55° (source I of [14]). Instead of a ring-shaped active region an active polar cap extending from the north pole to 55° latitude could possibly also explain the observations.

3. The observed radio lines of HCN reveal a gas expansion velocity of the coma equal to 1.2 km s^{-1}.

4. The location of the optical CN jet is also consistent with the pole and source position of [14].

5. The CN production rate is about twice as high as the HCN production rate, even if the outgassing from the local source (our Monte Carlo model) is taken into account. Within the systematic errors present in the production rate determinations HCN can possibly still be the sole parent of CN. But the life time of

the CN parent derived from our data is 15 000 s at 1 AU, that is significantly less than theoretical values of 31 900 s for high solar activity and 79 400 s for low solar activity [8]. This provides a strong argument in favour of another CN parent.

6. The visual dust coma is only a few 1000 km wide and almost spherically symmetric with only a very slight extension in the fan direction. This contradicts the idea of the fan consisting mostly of dust particles [14].
7. The polarization of NH_2 at 662 nm (0–7–0 vibrational transition of α ammonia band) at a phase angle of 94.6° is $\approx 7\%$, close to the value for two-atomic molecules.
8. The polarization of the dust of Comet Encke at a phase angle of 94.6° exceeds 30%, *i.e.*, the dust of Comet Encke has a polarization even higher than so-called dusty comets. This contradicts the idea that all gas-rich comets have lower polarization than the dust-rich ones [11].

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