Behaviour of Comet 21P/Giacobini-Zinner during the 1998 perihelion

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Abstract. Comet 21P/Giacobini–Zinner was observed from Nov. 8 to Dec. 10, 1998. Pre- and post-perihelion CCD images of the gas (CN, C2) and dust (green and red continua) coma were obtained with the 82 cm IAC-80 telescope at Teide Observatory (Canary Islands, Spain). For tp = 0.85vH and vij = 1.19 km s\(^{-1}\) (i.e. characteristic of HCN being the CN parent species), the CN column density profiles are best reproduced with parent and daughter lifetimes of the order of 19,000 and 256,000 s. An equally good reproduction of the observed profiles is achieved by considering that a mixture of nitrogen compounds expanding at vij = 1 km s\(^{-1}\) and with a lifetime of 19,000 s produces CN with an ejection velocity of vij = 2.5 km s\(^{-1}\) and a lifetime of 174,000 s. Fitting the observed CN profiles with variable velocities and lifetimes, the results indicate that the nature of the CN precursor in comet 21P/Giacobini–Zinner is still unclear, ruling out HCN as the only precursor and favouring a mixture of nitrogen compounds. Regarding C2, the derived lifetimes are 35,000 and 62,000 s, if the parent and daughter velocities are fixed at ∼1 km s\(^{-1}\). Gas production rates derived by means of the Vectorial modeling with the mentioned above lifetimes and velocities indicate that (i) the comet activity decreases with decreasing vij (i.e. peak activity is not reached at the perihelion), and (ii) as already known, the comet is typically depleted in C2 with a log ρ C2/C3 < ∼0.4. The azimuthally averaged surface brightness profiles of the continuum images are well fitted with m ≥ 1 in a log B = log ρ representation at projected radial distances (ρ) larger than 1000 km. The continuum light scattered from the dust in the coma of comet Giacobini–Zinner is redder than the Sun light on every date from Nov. 8 to 24, regardless the cometocentric distance. On Nov. 25, there is a sudden change in the dust color, being considerably bluer than the Sun, whereas on Dec. 7 and 8, the dust became much redder than it was before. These color variations do not seem to be related to sudden variations (relative minimum or maximum) in the cometary activity. The gas-to-dust mass ratio is ∼1, but affected by a large uncertainty (about a factor of 2) since the comet was not simultaneously imaged in the OH band, and the H2O production rate has been considered from other measurements taken some weeks before ours.

Key words. comets: individual: 21P/Giacobini–Zinner – comets: general

1. Introduction

Comet 21P/Giacobini-Zinner (hereafter referred to as G–Z) is a short period comet (6.6 yr), with perihelion at a distance of 1.03 AU, belonging to the Jupiter-family and with a relatively stable orbit since it was discovered in 1900. However, it has been known for long that G–Z is an unusual comet in several aspects. Its molecular abundances had been noted as anomalous during previous apparitions, when C2/CN, C3/CN and NH/CN abundances were much lower than those measured in other comets (Bobrovnikoff 1927; Herbig 1976; Cochran & Barker 1987; Schleicher et al. 1987; Konno & Wickoff 1989; Beaver et al. 1990) and only slightly lower the CN/OH abundance. This fact seems to indicate that C2, C3 and NH are underabundant in the coma of G–Z. In their survey of 85 comets, A’Hearn et al. (1995) describe G–Z as the “prototypical carbon-depleted comet”, with C2 and C3 abundances relative to H2O ∼ 10 times lower than the values measured in most comets that define the “normal” cometary composition. A’Hearn et al. (1995) hypothesized that this depletion is associated with the formation...
region in the solar nebula, more concisely in a flat trans-Neptuni-
region called the Edgeworth-Kuiper belt (EKb). On the other
hand, the quasi-normality in the CN/OH abundance leaves
open the possibility that other (excluding the C₂ and C₃ pro-
genitors) carbon-bearing molecules in the nucleus may not be
depLETED.

This comet, during its 1985 apparition, also showed the pe-
culiarity of peaking in gas production a full month before peri-
helion (McFadden et al. 1987), yet the visual light curve did not decline until after perihelion. Photometry in the 1–20 µm
range by Hanner et al. (1992) confirmed that the visual light
curve did not follow either the water production rate (which peaked ~30 days pre-perihelion) or the scattering and emit-
ting cross section of dust in the inner coma. The shape of the
light curve had varied from the 1979 to the 1985 apparition,
implying that the location of active areas on the nucleus may
have changed. Hanner et al. (1992) also concluded that the low
abundance of C₂, C₃, NH and NH₂ is not associated with an
unusually low dust/gas ratio.

At the time of the 1998 apparition, to our knowledge, G–Z
was only observed by Weaver et al. (1999) during October 25–
29, and by Mumma et al. (2000) during October 2–10 in the IR,
and by Biver et al. (1999) in radio-wavelengths from Oct. 26
to 31. The IR observations by both groups were made using
the same instrument CSHELL at the NASA Infrared Telescope
Facility, Mauna Kea, Hawaii. Weaver et al. (1999) derived H₂O
and CH₃OH production rates of (2–3) × 10²⁸ s⁻¹ and ~2.7 ×
10²⁶ s⁻¹, respectively. Emissions from C₂H₆, CO, HCN, C₂H₂
and H₂CO were also examined by Weaver et al. (1999) but were
not clearly detected, it being possible only to set upper limits
for their abundances relative to H₂O. From observations taken
a few days before October 25–29, Mumma et al. (2000) were
able to detect ethane and carbon monoxide for the first time
in a Jupiter-family comet (probably originating in the EKB).
The ethane production rate was (7.0 ± 1.5) × 10²⁵ s⁻¹, whereas
carbon monoxide was produced at a rate of (3.28 ± 0.64) × 10²⁷.
When compared with other comets originating in the
O1 – Hale-Bopp), the production rates and abundance ratios
from G–Z may imply that ethane was depleted in precometary
ices from the region of the solar nebula in which it formed in
the EKB.

Charged Coupled Device (CCD) imaging and aperture pho-
tometry of G–Z were also conducted by Kiselev et al. (2000a,b)
on November 20, 1998 and January 25, 1999. For both dates,
there is an uncommon behaviour of polarization, i.e. the wave-
length gradient of the polarization of its dust is negative. This
effect is not caused by the presence of molecular emission in
the pass band of the filter, but it may be due to either a large
content of organic matter in its dust (Lebedinets 1991), or to an
overabundance of large particles as compared to other comets
(Hanner et al. 1992).

In this paper, we present pre- and post-perihelion CCD
images of the gas (CN, C₂) and dust (green and red con-
tinua) coma of Comet 21P/Giacobini-Zinner, obtained with
the 82 cm IAC–80 Telescope at Teide Observatory (Canary
Islands, Spain) from November 8 to December 8, 1998.
Assuming certain parent species, this data provide us with
parent and daughter lifetimes (τ_p and τ_d), and the production
rates Q for CN and C₂ from the best fit of the observed pro-
files with the Festou modeling (Festou 1981). The continuum
images are used (i) to derive radial brightness profiles as a func-
tion of the projected distance to the nucleus, ρ, and to fit them
with the law ρ³m, and (ii) to obtain the dust production rate
from the Afρ parameter. The gas and dust production rates en-
able us to compute C₂/CN and Afρ/CN (and thus the gas-to-
dust mass ratio) abundances to better understand the nature of
this comet in the framework of our and other previous and/or
simultaneous observations.

2. Data acquisition and reduction

Comet G–Z was observed on nine photometric nights from
November 8 to December 8, 1998, using the 82 cm IAC–80
Telescope at Teide Observatory (Canary Islands, Spain). CCD
images were obtained using the Thomson 1024 × 1024 CCD
(pixel size 0'′.4325, FOV ~ 7'′ × 7'′) and the CN, C₂, GC and RC
narrow-band interference filters specifically designed to isolate
continuum regions and some of the stronger emission bands in
cometary spectra (see Farnham et al. 2000 for a detailed de-
scription of the filters). Several images of the comet, with the
telescope tracking on the comet proper motion, were obtained
each night using each filter. Details of the observations are pre-
sent in Table 1.

Several spectrophotometric standard stars and solar analogs
from the list of Farnham et al. (2000) were observed each night at different airmasses to render the absolute cali-
bration of the images. The air-mass coefficient, kₐ, was also
determined for each filter, each night, using these data (see Table 2). The kₐ obtained for the narrow-
band filters are coherent with the ones obtained for the broad-band filters usually installed at the IAC-80 telescope
(see http://www.iac.es/telescopes/ten.html). Also, the day–to–day variations of the extinction coefficients so de-
termined are similar to that observed with the broad-band filters
and are mostly due to the variation of the amount of dust from
the Sahara desert in the atmosphere of the observatory. As an
example, on Nov. 8 there was a lot of dust over the observatory
and the k₋₁ were larger than usual.

Images were reduced by making the overscan correction, and
then using very high S/N ratio sky flat-fields obtained
each night in order to correct pixel-to-pixel variations to
below 1%. After that, all comet images were divided by their
exposure times (in seconds) to normalize the image intensities
to counts per second. The contribution of the sky was determined
by computing the median of the pixels close to the border of
the images, since the comet did not fill the field of view, and
it was subtracted from each image. Then, the images were flux
calibrated in the HB system, and the underlying continuum and
gas contamination were removed following the procedure pre-
sented in Farnham et al. (2000).

To obtain the final images of the comet, the position of the
comet optocenter in the calibrated images was determined by
fitting a two-dimensional Gaussian to the inernost 20 pixels
of the coma, all images were centered and those taken with
the same filter on each night were median combined. Examples
of the final images taken on Nov. 10 are shown in Fig. 1 in a logarithmic look-up table. We should note that, as we did not observe the comet in the \( C_3 \) band, it was impossible to remove any possible \( C_3 \) contamination in the \( CN \) band. In any case, this contamination should be very small (<10%) in the particular case of G–Z as it is a carbon-depleted comet.

### 3. Results

#### 3.1. Spatial gas profiles

All the images were used to investigate the \( CN \) and \( C_2 \) profiles derived from an azimuthal average, leading to energy flux as a function of the projected radial distance, \( \rho \). The conversion of the emission band fluxes into column densities was done with a constant \( g \)-factor for \( C_2 \) equal to \( 4.476 \times 10^{-13} \) ergs s\(^{-1}\) mol\(^{-1}\) (A’Hearn et al. 1985) and \( g \)-factors for \( CN \) that were calculated for the heliocentric distances and heliocentric velocities of Comet 21P/Giacobini-Zinner from Nov. 8 to Dec. 8, 1998.
from the set of values given by Schleicher (1983), and are listed in Table 3.

The azimuthally averaged CN and C₂ spatial profiles are presented in Figs. 2 and 3, respectively, together with the theoretical profiles best resembling the observed ones. These theoretical profiles were obtained by means of the Festou modeling (Festou 1981), where parent and daughter and lifetimes \((\tau_p, \tau_d)\) at \(r_H = 1\) AU, as well as production rates, \(Q\), were derived as follows.

Assuming that HCN might be the CN precursor, we fix \(v_p = 0.85 \times v_H^{-0.5}\) (Biver et al. 1999b, 2000) and \(v_d = 1.19\) km s\(^{-1}\) (Bockelée–Morvan & Crovisier 1985). To derive the \((\tau_p, \tau_d)\) that best resemble the shape of the observed profiles, we constructed theoretical radial profiles with an arbitrary (however approximated) gas production rate with lifetimes spanning the reported values, i.e. \(\tau_p\) ranging from \(1.6 \times 10^4\) s to \(6.6 \times 10^4\) s, whereas \(\tau_d\) covered the \((1.5–4.0) \times 10^5\) s. Once the theoretical profile was computed, we compared it with the observed profile by dividing both profiles. We selected the profiles computed with \((\tau_p, \tau_d)\) giving rise to those theoretical profiles whose standard deviation of the quotient calculated at distances \(3 < \log \rho < 4.64\) (i.e. between \(1 \times 10^3\) and \(3.2 \times 10^3\) km not to hit the sky) was lower than \(3 \times 10^{-3}\). All of the \((\tau_p, \tau_d)\) better fitting the observed profiles for every date (i.e. parameters producing quotient images with the lowest standard deviation, in some cases as low as \(3.6 \times 10^{-4}\)) were then averaged to produce the values listed in Table 3. These daily averages have standard deviations \(\leq 17\%\) for \(\tau_p\) and \(\leq 24\%\) for \(\tau_d\). The gas production rates were obtained once the lifetimes were derived and the values are also presented in Table 3. As the CN precursor is not clearly known, according to Krasnopolsky (1991) a mixture of \(\text{C}_2\text{N}_2\) and \(\text{HC}_3\text{N}\) expanding at \(1\) km s\(^{-1}\), might give rise to CN with an ejection velocity of \(2.5\) km s\(^{-1}\). By considering these velocities, the procedure to derive lifetimes was the same as outlined above and the best theoretical profiles were obtained with the lifetimes listed in parenthesis in Table 3 where the uncertainties in both lifetimes are of the same order as in the previous case. Differences among individual \(\tau_p\) and \(\tau_d\) are not outstandingly large. As a final test, we additionally allowed \((v_p, v_d)\) to vary from \(0.6\) to \(1.2\) km s\(^{-1}\) and \(1.0\) to \(3.0\) km s\(^{-1}\), respectively. Theoretical profiles were obtained for every combination of \((v_p, v_d, \tau_p, \tau_d)\) and then compared to the observed ones following the same criteria as previously mentioned. In this case, the values of \((v_p, v_d, \tau_p, \tau_d)\) providing the best daily fits are affected by an uncertainty of \(\leq 25\%\). Averaging these pre- and post-perihelion values, we obtain \(v_p = (0.84 \pm 0.06)\) km s\(^{-1}\), \(v_d = (1.38 \pm 0.37)\) km s\(^{-1}\), \(\tau_p = (19.5 \pm 2.2) \times 10^3\) s and \(\tau_d = (2.68 \pm 0.18) \times 10^5\) s, where the errors represent the standard deviation of the sample. It should be noted that the parent and daughter velocities so derived are merely indicative. The profiles are very sensitive to the parent and daughter scale lengths, and therefore to the two products \(v_p \tau_p\) and \(v_d \tau_d\) of the Haser-equivalent parameters (Combi & Delsemme 1980a,b) or to more complex combinations of the physical parameters.
Table 3. CN g–factors, τp, τd and Q derived from the best fits to the observed profile by using the Festou modeling assuming that νp = 0.85 × r−0.5
and νd = 1.19 km s−1 or that νp = 1 km s−1 and νd = 2.5 km s−1 (values in parenthesis). CN production rate from Haser modeling assuming standard λp and λd. Measurement of the dust-to-gas ratio by means of log A(CN).

<table>
<thead>
<tr>
<th>Date</th>
<th>g-factora</th>
<th>τp (10^3 s)</th>
<th>τd (10^4 s)</th>
<th>QHCN (10^25 s⁻¹)</th>
<th>QHCN (10^25 cm⁻³)</th>
<th>Δlog A(CN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov. 8</td>
<td>3.16</td>
<td>1.91 (1.97)</td>
<td>2.69 (1.98)</td>
<td>4.72 (0.27)</td>
<td>4.44</td>
<td>−22.82</td>
</tr>
<tr>
<td>Nov. 10</td>
<td>3.04</td>
<td>2.45 (2.21)</td>
<td>2.23 (2.08)</td>
<td>5.20 (0.59)</td>
<td>4.34</td>
<td>−22.82</td>
</tr>
<tr>
<td>Nov. 21</td>
<td>2.36</td>
<td>1.74 (1.71)</td>
<td>2.65 (1.34)</td>
<td>2.95 (0.95)</td>
<td>2.87</td>
<td>−22.83</td>
</tr>
<tr>
<td>Nov. 22</td>
<td>2.42</td>
<td>1.87 (1.94)</td>
<td>2.73 (1.86)</td>
<td>3.30 (6.51)</td>
<td>3.10</td>
<td>−22.84</td>
</tr>
<tr>
<td>Nov. 23</td>
<td>2.50</td>
<td>1.87 (1.99)</td>
<td>2.74 (1.70)</td>
<td>3.09 (6.20)</td>
<td>2.93</td>
<td>−22.93</td>
</tr>
<tr>
<td>Nov. 24</td>
<td>2.56</td>
<td>1.69 (1.80)</td>
<td>2.58 (1.68)</td>
<td>2.86 (5.70)</td>
<td>2.82</td>
<td>−22.87</td>
</tr>
<tr>
<td>Nov. 25</td>
<td>2.70</td>
<td>1.71 (1.63)</td>
<td>2.63 (1.33)</td>
<td>2.66 (5.34)</td>
<td>2.67</td>
<td>−22.94</td>
</tr>
<tr>
<td>Dec. 7</td>
<td>4.31</td>
<td>2.31 (2.08)</td>
<td>2.16 (2.04)</td>
<td>2.92 (5.40)</td>
<td>2.45</td>
<td>−23.06</td>
</tr>
<tr>
<td>Dec. 8</td>
<td>4.35</td>
<td>1.83 (1.81)</td>
<td>2.66 (1.65)</td>
<td>2.23 (4.43)</td>
<td>2.14</td>
<td>−23.03</td>
</tr>
</tbody>
</table>

Averagec: 1.93 ± 0.27 2.56 ± 0.21 (2.86 ± 0.34)c  (2.71 ± 0.32)c −22.91 ± 0.09

Averagef: 1.90 ± 0.18 1.74 ± 0.28 (5.64 ± 0.68)f −22.91 ± 0.09

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 × 10^5 s and 1.34 × 10^3 s at high solar activity. Bockelée–Morvan & Crovisier (1985) reported the HCN photodissociation rate of the order of 1.5 × 10^−5 s⁻¹, i.e. lifetime ~6.7 × 10^4 s. A more precise HCN lifetime, corresponding to the solar activity of Nov.–Dec. 1998, may be estimated as 4.8 × 10^4 s (Crovisier 2002, private communication). From our analysis of the CN profiles, the parent lifetime we obtain, (1.93 ± 0.27) × 10^4 s, is lower than that expected for HCN as the sole precursor of CN. On the other hand, the deduced CN lifetime, (2.56 ± 0.21) × 10^5 s, agrees well with theoretical determinations for a moderate-to-high solar activity. For a mixture of nitrogen compounds (for example C2N2 and HC3N) as the CN parent species, the obtained τp = (1.90 ± 0.18) × 10^4 s approaches the theoretical values of cyanoacetylene (1.4 − 2.6) × 10^4 s and, to a lesser extent, of dicyanogen, (0.74 − 2) × 10^5 s. A mixture of nitrogen compounds, richer in HC3N than in C2N2, not ruling out HCN, could be considered as the CN precursor in G–Z.

The results of the problem of four parameter (velocities and lifetimes) fits do not provide a firm constraint to the “determination” of the CN parent species. Although νp favours HCN (an expansion velocity 10% lower than that deduced for Comet Hyakutake and Comet Lee can be expected, Biver et al. 1999b, 2000, 2002, private communication), the deduced parent lifetime is too short compared to 4.8 × 10^4 s as deduced for the solar activity of Nov.–Dec. 1998 (Crovisier 2002, private communication). Similarly, a CN ejection velocity of (1.38 ± 0.37) km s⁻¹ might rule out HCN as its only precursor (note that the uncertainty is large and 1.19 km s⁻¹ is within the νd derived values), pointing to a mixture of nitrogen compounds (hydrogen cyanide, cyanoacetylene, dicyanogen) as cyanogen parent species.

Theoretical predictions of the photodissociation time scales for many cometary species under solar irradiance have been provided by Huebner & Link (1999) and Huebner et al. (1992). 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...
Given that CN production rates can considerably vary as a function of parent and daughter velocities and lifetimes (see Table 3), we have also used the Haser modeling (Haser 1957) to fit the observed column density profiles in order to consistently compare our results with those published in the 85 comet survey by A Hearn et al. (1995), or with G–Z specific observations (Schleicher et al. 1987; Beaver et al. 1990; Churyumov et al. 1991; Landaberry et al. 1991; Singh et al. 1997; and Ellis & Neff 2000). Although the Haser formalism is physically unrealistic, it is an empirical description that can serve as a basis of comparison of gas production and distribution in different comets observed under quite different circumstances of heliocentric and geocentric distances and aperture sizes. The Haser model scale lengths are not meant to be true molecular scale lengths, but rather values that best fit the observed spatial distribution when using this formalism. The resulting production rates can be compared with those derived from the more physically relevant production as obtained from the Vectorial modeling (Festou 1981). Thus, we use the Haser scalelength equal to 1.3 × 10⁴ and 2.1 × 10³ km, for CN parent and CN itself, respectively, with a r² dependence (A'Hearn et al. 1995; Randall et al. 1992). Velocities are held constant at 1 km s⁻¹. The best CN production rates fitting the observed profiles are also included in Table 3. Differences in Q from both models can be as high as a factor of 2. Fits to observed profiles by means of this formalism are as good as those presented in Fig. 2 with the Vectorial modeling (Festou 1981).

Regarding C₂, we followed the same approach as for CN. Parent and daughter lifetimes for the Vectorial modeling ranged from 30 000 to 45 000 s, and from 40 000 to 100 000 s, respectively. Velocities were held constant and equal to 1 km s⁻¹ (values proven to be a reasonable approximation from the analysis of the coma distortions caused by radiation pressure acceleration, Schulz et al. 1993). It is well known that C₂ does not seem to be produced by a single photolytic step, the observed profiles being flatter than the ones produced by the vectorial or Haser model in the inner coma. By taking v_p of the same order as CN (i.e. v_p ≈ 0.83 km s⁻¹), the C₂ parent lifetime has to be larger than 10⁴ s to obtain a reasonable fit of the C₂ column density at distances shorter than 5000 km. After computing theoretical profiles for every combination of τ_p and τ_d and comparing them with the observed ones, we averaged those pairs (τ_p, τ_d) satisfying the criterium previously stated. The resulting lifetimes are presented in Table 4 together with the gas production rates computed by means of the Vectorial modeling. Bearing in mind that the C₂ parent remains unknown (halo of large icy particles, three-step grandparent–parent–daughter, and CHON grain halo scenarios have been claimed), the deduced lifetimes are of the same order as determinations for other comets such as Comet Wilson (1987 VII) (Schulz et al. 1993). The Haser formalism has also provided us with C₂ production rates by considering gas production rate and long-lived grains expanding radially outwards, where the spatial number density should decrease as r⁻², r being the heliocentric radial distance. Consequently, the projected surface brightness would decrease as ρ⁻¹.

Estimates of the dust production in comets are usually made by means of the parameter A(θ)f_p (A'Hearn et al. 1984). A(θ) is the Bond albedo for the particular scattering angle, θ.

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![Fig. 4. Brightness profiles of Comet 21P/Giacobini-Zinner in the green continuum. The profiles were obtained from azimuthal averaging of the images. The surface brightness, B, is plotted against the projected radius, ρ, in double logarithmic representation. Dots represent the observed profiles and the solid lines are the best fits verifying dlog B dlog ρ = −m starting at log ρ ≥ 3, with slopes listed in Table 5.](image-url)
Table 4. \( \tau_p \), \( \tau_d \) and \( Q \) for C2 derived from the best fits to the observed profile by using the Vectorial modeling. C2 production rate from Haser modeling assuming standard \( l_p \) and \( l_d \). Measurement of the C3 to CN ratio.

<table>
<thead>
<tr>
<th>Date</th>
<th>( \tau_p )</th>
<th>( \tau_d )</th>
<th>( Q_{C2} )</th>
<th>( Q_{CN} )</th>
<th>( \Delta \log \frac{Q_{CN}}{Q_{C2}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov. 8</td>
<td>33.5</td>
<td>56.6</td>
<td>2.08</td>
<td>1.45</td>
<td>-0.48</td>
</tr>
<tr>
<td>Nov. 10</td>
<td>33.6</td>
<td>61.5</td>
<td>2.02</td>
<td>1.44</td>
<td>-0.48</td>
</tr>
<tr>
<td>Nov. 21</td>
<td>32.5</td>
<td>57.9</td>
<td>1.56</td>
<td>1.13</td>
<td>-0.40</td>
</tr>
<tr>
<td>Nov. 22</td>
<td>34.0</td>
<td>58.8</td>
<td>1.47</td>
<td>1.04</td>
<td>-0.47</td>
</tr>
<tr>
<td>Nov. 23</td>
<td>36.0</td>
<td>67.0</td>
<td>1.54</td>
<td>1.11</td>
<td>-0.42</td>
</tr>
<tr>
<td>Nov. 24</td>
<td>34.4</td>
<td>60.1</td>
<td>1.41</td>
<td>1.00</td>
<td>-0.45</td>
</tr>
<tr>
<td>Nov. 25</td>
<td>33.6</td>
<td>57.1</td>
<td>1.40</td>
<td>1.00</td>
<td>-0.43</td>
</tr>
<tr>
<td>Dec. 7</td>
<td>37.6</td>
<td>70.4</td>
<td>1.23</td>
<td>0.88</td>
<td>-0.44</td>
</tr>
<tr>
<td>Dec. 8</td>
<td>37.6</td>
<td>70.4</td>
<td>1.18</td>
<td>0.84</td>
<td>-0.41</td>
</tr>
</tbody>
</table>

Average \( 34.7 \pm 1.9 \) \( 62.2 \pm 5.6 \) \( 1.44 \pm 0.12 \) \( 1.00 \pm 0.11 \) \( -0.44 \pm 0.03 \)

\( ^a \) CN and C2 Production rates derived from the Haser model. \( ^\circ \) Post-perihelion \( Q_{CN} \) average.

Table 5. Linear fits to the brightness continuum profiles. Dust production rate by means of the parameter \( Af_\rho \) and color of the cometary grains measured as the reddening of the dust.

<table>
<thead>
<tr>
<th>Date</th>
<th>( m )</th>
<th>( Af_\rho ) (cm)</th>
<th>( m )</th>
<th>( Af_\rho ) (cm)</th>
<th>( % ) / 1000 ( \lambda )</th>
<th>( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov. 8</td>
<td>1.26</td>
<td>670</td>
<td>1.25</td>
<td>830</td>
<td>12.8</td>
<td>12.2</td>
</tr>
<tr>
<td>Nov. 10</td>
<td>1.26</td>
<td>656</td>
<td>1.24</td>
<td>644</td>
<td>806</td>
<td>-0.9</td>
</tr>
<tr>
<td>Nov. 21</td>
<td>1.29</td>
<td>420</td>
<td>1.18</td>
<td>567</td>
<td>649</td>
<td>18.7</td>
</tr>
<tr>
<td>Nov. 22</td>
<td>1.27</td>
<td>444</td>
<td>1.22</td>
<td>564</td>
<td>669</td>
<td>14.5</td>
</tr>
<tr>
<td>Nov. 23</td>
<td>1.12</td>
<td>305</td>
<td>1.00</td>
<td>388</td>
<td>401</td>
<td>14.6</td>
</tr>
<tr>
<td>Nov. 24</td>
<td>1.23</td>
<td>380</td>
<td>1.21</td>
<td>440</td>
<td>522</td>
<td>8.4</td>
</tr>
<tr>
<td>Nov. 25</td>
<td>1.12</td>
<td>309</td>
<td>0.82</td>
<td>223</td>
<td>206</td>
<td>-14.9</td>
</tr>
<tr>
<td>Dec. 7</td>
<td>1.26</td>
<td>209</td>
<td>1.19</td>
<td>300</td>
<td>363</td>
<td>23.3</td>
</tr>
<tr>
<td>Dec. 8</td>
<td>1.33</td>
<td>197</td>
<td>1.21</td>
<td>302</td>
<td>367</td>
<td>28.5</td>
</tr>
</tbody>
</table>

Average \( 34.7 \pm 1.9 \) \( 62.2 \pm 5.6 \) \( 1.44 \pm 0.12 \) \( 1.00 \pm 0.11 \) \( -0.44 \pm 0.03 \)

of the observations, \( f \) is the filling factor of the grains in the field of view (number of grains per unit area times their mean cross-section divided by the area of the field of view), and \( \rho \) is the radius of the assumed circular field of view. This parameter assumes that physical characteristics of the dust grains remain unchanged as they move outward and that the column of grains is optically thin. Table 5 also contains the values for \( A(\theta)\rho \) computed in circular apertures of \( 1 \times 10^4 \) km and \( 1.5 \times 10^4 \) km radius.

A relative determination of the gas-to-dust ratio for G–Z can be made by computing the ratio of the OH production rate to \( Af_\rho \). If CN is produced in constant proportion to OH (Schleicher et al. 1987), the \( Q(CN)/Af_\rho \) quantity is proportional to \( Q(OH)/Af_\rho \) and, therefore, the gas-to-dust mass ratio can be determined. Since G–Z was not imaged with the OH narrowband interference filter, we have used the CN observations and the mean ratio of OH to CN, \( \log \left( \frac{Q(OH)}{Q(CN)} \right) = 2.5 \) (A’Hearn et al. 1995), to derive the OH production rate. Typical values for \( \log \left( \frac{Q(OH)}{Q(CN)} \right) \) range from 2.83 to 2.17, which implies that the OH derived from this expression can reasonably be as much as 2 times smaller or larger than the actual value. In line with A’Hearn et al. (1995), the gas-to-dust mass ratio can be evaluated by

\[
\log \left( \frac{M_{gas}}{M_{dust}} \right) = \log [Q(OH)/Af_\rho] - 25.4.
\] (1)

According to this expression and using the \( Q_{CN} \) obtained with the Haser model (see Table 3), we computed a mean gas-to-dust mass ratio of \( \sim 1.02 \) during our observations (with an error of a factor of \( \sim 2 \), introduced by the approximate \( Q_{OH} \)). The \( \log \left( \frac{Af_\rho}{Q_{CN}} \right) \) on every date is also listed in Table 3. Note that these ratios can be directly related to the log of the gas-to-dust mass ratio by simply adding 22.9.

Since the comet was imaged in two continuum filters, we used the calibrated images to determine the average dust color and to search for spatial variations. We first computed the color two-dimensionally according to

\[
\text{color} = -2.5 \log \left( \frac{F(\lambda)}{I(\lambda')} \right).
\] (2)

being \( F_c \) the cometary flux in erg cm\(^{-2} \) s\(^{-1} \) at two different wavelengths, \( \lambda \) and \( \lambda' \), with \( \lambda' > \lambda \). In our case, \( \lambda \) and \( \lambda' \) correspond to the central wavelengths of the GC and RC continuum filters, i.e. \( \lambda_c = 525.9 \) and \( \lambda'_c = 713.3 \) nm, respectively. The resulting two dimensional images show no clear features. The color or reddening of the dust can also be computed in terms of \( Af_\rho \):

\[
\text{reddening} = \frac{1}{Af_\rho} \cdot \frac{(Af_\rho \lambda') - (Af_\rho \lambda)}{\lambda' - \lambda}.
\] (3)
During the 1985 apparition, observations by Schleicher et al. (1987) gave rise to log $Q_{\text{CN}} / Q_{\text{H}_2 \text{O}} = -0.94$ as the average value from pre- and post-perihelion observations ($r_H = 1.507 \text{ AU}$ on June 15 to $r_H = 1.457 \text{ AU}$, Nov. 20, 1985, perihelion date for the 1985 approach was on Sept 9). Beaver et al. (1990), from observations on June and on Sept 1985, reported a $C_2$ to CN mean relative abundance of 0.11, that is, log $Q_{\text{CN}} / Q_{\text{H}_2 \text{O}} \sim -0.96$. On the other hand, Landaberry et al. (1991) derived a slightly higher value of $-0.52$ (assuming a gas expansion velocity of 1 km s$^{-1}$ for both species) from post–perihelion observations on Oct. 10, 1985 when the comet was at $r_H = 1.17 \text{ AU}$. Our results are closer to those of Landaberry et al. (1991) ($-0.44 \pm 0.03$ vs. $-0.52$) which could be expectable since our and Landaberry et al.’s observations were made when the comet was closer to perihelion. From the survey of 85 comets by A’Hearn et al. (1995), G–Z was classified as a $C_2$ depleted comet with log $Q_{\text{CN}} / Q_{\text{H}_2 \text{O}} = -0.67$. The $C_2$ depletion in the coma of G–Z has not yet been explained as the detailed chemistry giving rise to $C_2$ is still not clear (note that the inner log $N$ vs. log $\rho$ profiles have been repeatedly reported to be too flat to be produced by a single parent species and in single photodissociation step). Comparing the available $C_2$H$_6$ detections in Oort-cloud comets (i.e. in comets C/1996 B2, C/1995 O1 and C/1999 H1) and Jupiter family comets (21P/Giacobini–Zinner), G–Z appears to be also depleted in $C_2$H$_6$ compared to comets Hyakutake, Hale–Bopp and Lee which are “typical” comets in terms of $C_2$ abundance.

The detection of ethane in G–Z (first detection in a Jupiter-family comet) by Mumma et al. (2000) allowed them to establish an ethane production rate of $(7.0 \pm 1.5) \times 10^{23} \text{ s}^{-1}$ at $r_H = 1.25 \text{ AU}$. If ethane is the only precursor of $C_2$, and $Q_{\text{C}_2 \text{H}_6}$ scales as $r_H^{-2}$, the quantum yield of the process $\text{C}_2 \text{H}_6 \rightarrow C_2 + \text{ products is } \geq 0.09$, i.e. $\sim 10$ molecules of ethane are required to form one $C_2$ molecule. From the same observations, a line of $\text{H}_2 \text{O}(111 - 110$ in the $v_3 - v_2$ hot band, Dello Russo et al. 2000) should have appeared near the clearly detected $R1$ line of CO. No strong line was seen and the excess of flux at the proper frequency (2151.26 cm$^{-1}$) allowed Mumma et al. to establish an upper limit for the water production rate of $(3.2 \pm 1.7) \times 10^{26} \text{ s}^{-1}$ at $r_H = 1.25 \text{ AU}$ (October 2-10, 1998). Scaling this production rate by $r_H^2$ with $k = -2.7$ (A’Hearn et al. 1995) to $\sim 0.04 \text{ AU}$ at the time of our observations, the water production rate could have been $\sim 5.3 \times 10^{28} \text{ s}^{-1}$. Therefore, the production rate of $\text{C}_2 \text{H}_6$ relative to that of $\text{H}_2 \text{O}$ is much higher than the $C_2$ one $(2.2 \times 10^{-2}$ vs. $2.0 \times 10^{-4}$) assuming that the variations of the gas production rates as a function of heliocentric distance are the same for both species. At this point, we note that Weaver et al. (1999) could not detect any ethane emission in the coma of G–Z from infrared spectra taken two weeks after Mumma et al.’s observations, only an upper limit of $1.6 \times 10^{25} \text{ s}^{-1}$ could be set. This upper limit to the ethane production rate together with a water production rate in the order of $(2-3) \times 10^{28}$ (Weaver et al. 1999) adequately scaled to $r_H \sim 1.04 \text{ AU}$ (i.e. $2.95 \times 10^{28} \text{ s}^{-1}$) provides $\text{C}_2 \text{H}_6/\text{H}_2 \text{O} \leq 0.05 - 0.08\%$, in the same order as the $\text{C}_2/\text{H}_2 \text{O}$ derived in this work (0.04\%) when using $Q_{\text{C}_2} = 1.1 \times 10^{25} \text{ s}^{-1}$ from Table 4.

where $(Af\rho)$ is computed at wavelengths $\lambda = 525.9 \text{ nm}$ and $\lambda' = 713.3 \text{ nm}$.

Values for $(Af\rho)$ have been considered for two different circular apertures (i.e. $1 \times 10^4$ and $1.5 \times 10^4 \text{ km}$) and the average color of the dust in regions $\rho \leq 1 \times 10^4 \text{ km}$ and $\rho \leq 1.5 \times 10^4 \text{ km}$ is shown in Table 5.

4. Discussion

To our knowledge, no other optical observations of G–Z during the 1998 passage were made, or have been published so far. Therefore, our results can be only compared to those obtained during previous approaches of the comet to the Sun, or to global results of the gas and dust behaviour in a Jupiter-family comet at similar heliocentric distances.

As already noted by several authors (Schleicher et al. 1987; Beaver et al. 1990; Churyumov et al. 1991; Landaberry et al. 1991; Singh et al. 1997; and Ellis & Neff 2000), it is clear that the gas production rate seems not to peak to the perihelion (Nov. 21) but some time before (see Tables 3 and 4). Although our observations all take place in the vicinity of the perihelion date, this trend is clear and the comet activity (gas and dust) steadily decreases from Nov. 8 to Dec. 8 with day-to-day variations of $\leq 20\%$. As known from previous passages of the comet and as mentioned in the introduction, the $C_2$ abundance, relative to CN (and to OH), is unusually low as compared with that normally seen in comets.
Contrary to the C_2 depletion in G–Z, CN seems to have a “quasi–normal” abundance relative to H_2O. The CN production rate from Nov. 8 to Dec. 8, 1998 slightly decreases with decreasing r_1, that is, when the comet approaches perihelion) with negligible day-to-day variations (~15%). The ratio of CN to OH production rates is ~7×10^{-4} assuming that the water production rate at r_1 = 1.1 AU is (5.6±0.4)×10^{28} s^{-1} (Biver et al. 1999a) conveniently scaled by r_1^{−2.7} to ~1.04 AU. On the other hand, if we consider the H_2O production rate given by Weaver et al. (1999) from IR observations, this ratio increases to 0.15%. These two values bracket a value of log ρ_{CN} between ~3.15 and ~2.82, which is more characteristic of “depleted” comets (see Table VI in A’Hearn et al. 1995) as G–Z indeed is, than of a normal comet. Comparing this ratio to that obtained from previous passages of the comet, Schleicher et al. (1987), from observations at similar r_1 as ours (from 1.053 to 1.043 AU), derived a CN production rate of 7.2×10^{25} ≤ Q_{CN} ≤ 3.63×10^{25} s^{-1} by means of the Haser model. The values presented here are similar to these ones, whereas the relative abundance of CN to OH during the 1985 passage (0.2%) can be considered similar to the one derived in this work during the 1998 approach (0.15–0.07%). These differences, if any, given the uncertainties in the determination of OH production, can be attributed to different behaviour of the comet and/or to different scale lengths in the Haser modeling, and/or to different production rates of H_2O directly measured in the IR or indirectly (OH in radio wavelengths or in the UV).

During their IR investigation of volatiles in the coma of G–Z, Weaver et al. (1999) were not able to detect HCN. This non-detection allowed them to set an upper limit for the HCN production rate of 5.4×10^{25} s^{-1}, later confirmed by Biver et al. (1999a) (Q_{HCN} ~ 3 × 10^{25} s^{-1}), and a quotient of the HCN to H_2O abundance of 0.05 to 0.07% at r_1 ~ 1.1 AU below the normal abundances of 0.08–0.25% (Biver et al. 2002). It is interesting to note that this HCN/H_2O is very similar to the CN/H_2O (=0.11% to 0.22%) that we report from our CN measurements and available water measurement, either from IR (Weaver et al. 1999) or OH radio observations (Biver et al. 1999a). At first sight, this result seems to indicate that CN can be solely produced by HCN, however the required τ_p (~2×10^5 s) to fit the CN column density profiles by means of the Vectorial model is low when compared with determinations by Bockelée-Morvan & Crovisier (1985) or by Huebner & Link (1999). The nowadays available information is not enough to rule out other CN parent, species such as C_2H_2 (Festou et al. 1998; Komitov & Bonev 1999), C_2N_2+HCl_3N (Krasnopolsky 1991) and/or evaporation from the dust grains.

Our dust analysis of the surface brightness profiles has shown that most profiles can be fit by the law log B = −m log ρ with 1 < m ≤ 1.33 (except the red continuum profile on Nov. 25 which shows a slightly flatter profile) in contradiction with previous analysis of the G–Z brightness profiles by Jewitt & Meech (1987). Those authors indicated that the log B profile vs. log ρ for G–Z did not strictly follow the law log B = −m log ρ with 1 ≤ m ≤ 3/2 at distances larger than 10'' from the nucleus (~7500 km or log ρ = 2.87 in our case), and the negative curvature dm/d(log ρ < 0 could be indicative of variations in the strength of the nucleus source on time scales comparable to the grain flight time. In fact, the activity of G–Z did vary during our observations, but the derived continuum profiles do not exhibit slopes higher than 3/2 at distances from the nucleus larger than 10'' (log ρ ~ 2.9). The dust production rate, either derived from the green or the red continuum filter, decreases from Nov. 8 to Dec. 8, regardless of the approach of the comet to the Sun.

The polarization of the scattered light of the dust particles in G–Z has an unusual behaviour. Contrary to all other comets, the wavelength gradient of the polarization of the continuum is negative. Kiselev et al. (2000a,b) have attributed this effect to a high abundance of organic matter in its dust and/or to an over- abundance of large particles, also supported by the weak 10 µm silicate feature detected by Hanner et al. (1992). However, comets with low abundance of submicron silicate grains have a low degree of polarization (10–15%) for both the blue and the red domain of the spectrum at large phase angles, this not being the case for G–Z. Due to this, Kiselev et al. (2000a,b) favour the idea that the dust particles in G–Z have an overabundance of organic matter. Furthermore, an abundance of large particles in the coma may also produce a redder colour as is computed from our continuum images at ρ = 10 000 km. The reddening of the dust ranges from a common 13%/1000 Å (in agreement with the ~15% reported by Schleicher et al. 1987) to a high value of 29%/1000 Å which could be indicative of an over-abundance of large grains in the dust coma of G–Z after the perihelion (Dec. 7 and 8, 1998).

Although the general behaviour of the dust color is to be redder than the Sun, there are two dates when this trend was not followed. On Nov. 10, the dust was neutral (Sun color) and on Nov. 25 it was much bluer than the Sun. On the latter date, the dust production rate decreased by a 20% (if measured in the green continuum) and by a 50% (if measured in the red continuum) with respect to the previous day, and this variation had no clear counterpart in the gas activity since it was steadily decreasing from Nov. 8 to Dec. 8. Previous observations by Singh et al. (1997) also noticed a change of color (from red to blue relative to the Sun) of grains during a 24 h period in G–Z together with a Q_{CN} decrease of 25%. However, as these authors only observed the comet on Oct. 15 and 16, 1985, we cannot conclude that this sudden blueing of the dust was due to a noticeable variation in the cometary activity.

Regarding the gas-to-dust mass ratio, it can vary largely depending on the water production rate we use (from 1.02 to 3.6, lower than and similar to previous passages, respectively). Schleicher et al. (1987) determined a relative gas-to-dust ratio by simply dividing the OH production rate (s^{-1}) and Af_f (cm) which resulted in a value of 1×10^{26} s^{-1} cm^{-3}. By applying Eq. (1), the gas-to-mass ratio is ~4. Singh et al. (1997) concluded that the dust-to-gas ratio was always less than unity (that is, gas-to-dust ratio > 1) during Oct. 15–16, 1985. In Table III in A’Hearn et al. (1995), log Af_f = ~25.94, which means a gas-to-dust mass ratio of ~3.5. Mumma et al.’s (2000) determination for the water production rate at r_1 = 1.25 AU adequately scaled to ~1.04 AU, at the time of our observations, allows us to derive a mean gas-to-dust mass ratio of 3.6 from Nov. 8 to Dec. 8, 1998. Let us note that this value might be affected by some errors since the gas production can substantially
vary from one comet to another and the expression $Q \sim r^{-2.7}$ may be inaccurate for G–Z. In fact, if we assume this water production rate as valid, this would mean that OH is produced at a rate of $3.51 \times 10^{28}$ s$^{-1}$ (relatively higher than the maximum reported measurement of $3.23 \times 10^{28}$ s$^{-1}$ in A'Hearn et al. 1995), meaning log $(Q(\text{OH})/Q(\text{CN})) = 3.1$, larger than the typical 2.83–2.17 given by A'Hearn et al. (1995) or than the 2.74 (specific for G–Z) listed in their Table III. All these values are not associated with an unusually low abundance of C$_2$, C$_3$, NH, and NH$_2$, that is, regarding the gas-to-dust ratio, G–Z is a typical comet.

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