# ESO Spectrophotometry of Comet 9P/Tempel 1

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**Abstract** The Deep Impact target comet 9P/Tempel 1 was observed by means of long-slit spectroscopy from two nights before impact up to eight nights after impact, using the ESO VLT UT1, UT2, and ESO NTT telescopes. Spectra covering the complete optical wavelength range were obtained, and information at different position angles in the coma was collected. The data were used to study the gas and dust activity of comet 9P/Tempel 1. Gas production rates before and after impact and the amount of material in the impact cloud were determined. The pre-impact $Af\rho$ parameter, the dust production rate and the dust-to-gas mass ratio were derived. A variation of the cometary gas activity with rotation of the nucleus was detected. A difference in the variation of the brightness of the CN gas emission band compared to the variation of the emissions by $C_2$, $C_3$, and $NH_2$ in the inner coma suggests compositional differences between different parts of the surface of comet 9P/Tempel 1's nucleus.

## 1 Introduction

As part of the ESO Deep Impact observing campaign, optical long-slit spectra of comet 9P/Tempel 1 were obtained from July 2 to July 12, 2005. For this purpose, the ESO VLT UT1 telescope was used from July 2 to July 8, and the VLT UT 2 from July 10 to July 12. Additional spectra were taken with the ESO NTT telescope on July 4. Observations were possible for about four hours in the beginning of each night. At the time of impact, the target comet had already set at the ESO observatories.

The instruments FORS2, FORS1, and EMMI were used, respectively. Two grisms were used to cover the whole optical wavelength range. The focus was on the use of a grism covering the wavelength range from 3700 to 6200Å, since the most prominent gas emission features in the cometary coma, originating from the radicals CN, $C_2$, $C_3$, and $NH_2$, fall into this region. With this grism, spectra at four different slit orientations were obtained. The center of the long-slit was placed on the optocenter of the coma, assuming this to be the position of the cometary nucleus. Therefore, information at the position angles with respect to the projected solar direction of 0°–180°, 90°–270°, 45°–225°, and 135°–315° were obtained in the coma. Furthermore, one spectrum per night was obtained with a second grism at one orientation of the long-slit (position angles 0°–180°). These spectra cover the wavelength range from 6100 to 9200Å.

The spectra obtained with the different grisms and instruments have a wavelength resolution between 570 and 780. A detailed observing log and a description of the reduction of the FORS data is provided by Rauer et al. [9].

The long-slit spectroscopic observations were performed to study the gas activity around the time of impact. Furthermore, the dust activity can be constrained from the continuum of scattered sunlight in the spectra.

## 2 Study of the Gas Activity

The results presented in this chapter represent a summary of Rauer et al. [9] and Weiler et al. [13].

The gas emissions of CN, $C_3$, $C_2$, and $NH_2$ could be detected in the spectra before and after the impact. In the four nights following the impact, an expanding gas cloud was observed. This cloud expanded all around the nucleus of the comet within about 18 hours after impact, when the first post-impact spectra were obtained. A projected velocity of about 1.2 km $s^{-1}$ for the outermost dectectable parts of the CN and $C_2$ clouds was determined, while the center of the clouds moved with about 0.6–0.8 km $s^{-1}$.

No new gas emission bands could be observed after the impact. The Haser model [5] was used to determine the scale lengths and gas production rates in the two nights before impact and again from the fifth night after impact on. The scale lengths for the four detected radicals in the coma of 9P/Tempel 1 are typical compared to other comets. Gas production rates were about $11.3 \times 10^{24}$ $s^{-1}$ for CN, $15.9 \times 10^{24}$ $s^{-1}$ for $C_2$, $1.5 \times 10^{24}$ $s^{-1}$ for $C_3$, and $8.3 \times 10^{24}$ $s^{-1}$ for $NH_2$, averaged over for different position angles (0°, 90°, 180°, and 270°) and over two nights before impact and the fifth and sixth night after impact.

The amount of parent species in the impact cloud was determined by computing the total number of radicals in the impact cloud as a function of time and using a Haser-like two-step chemical model. The parent and daughter life times were computed using the determined maximum gas expansion velocities and the Haser scale lengths determined from observations of the undisturbed coma. This approach makes the assumption that all parent molecules are released at the same time, i.e. the time of impact, and that the formation chemistry is the same in the impact cloud and in the undisturbed coma. The averaged numbers of parent molecules released by the impact are $3.7 \times 10^{29}$ for the CN parent, $4.7 \times 10^{29}$ for the $C_2$ parent, and $0.8 \times 10^{29}$ for the $C_3$ parent, respectively. Due to the low signal-to-noise ratio of the $NH_2$ emission, the number of parent molecules could not be determined for this species.

Since the used chemical model is the same for the undisturbed coma and the impact cloud, the ratios of the parent species of $C_2$/CN and $C_3$/CN before the impact, in the impact cloud, and after the impact could be determined. No significant differences in these ratios were observed, indicating no compositional differences of the impact cloud compared to the undisturbed coma as far as CN, $C_2$, and $C_3$ are concerned.

When plotting the flux of the emissions from CN, $C_3$, $C_2$, and $NH_2$ in the innermost coma versus the rotational phase of the nucleus, a variation of the gas activity with the nucleus rotation became obvious. The rotational light curve in the innermost coma shows two maxima, indicating the presence of at least two active regions on the nucleus surface. The light curves for the four different radicals show the same variation with rotation, except for CN. For the CN emission, one maximum is less pronounced compared to the lightcurves from the other species. This indicates a compositional difference of one active region compared to the rest of the nucleus surface.

## 3 Study of the Dust Activity

An expanding cloud was also observed in the continuum of sunlight scattered by dust particles in the cometary coma. The dust cloud is directed towards the west and south of the nucleus 18 hours after impact, and it moves with a projected velocity of about 200 m $s^{-1}$, showing a deceleration with time as a consequence of solar radiation pressure.

When assuming spherical symmetry of the dust coma, the dust activity parameter $Af\rho$ [1] can be determined from the spectra. This was done for the long-slit spectra of the night of July 3/4, 2005, resulting in a pre-impact $Af\rho$ value of $134.5 \pm 54.6$ cm. This value was obtained by averaging the values obtained from radial emission profiles at four different position angles in the coma (0°, 90°, 180°, 270°), and the large uncertainty results from coma asymmetries. The $Af\rho$ value was determined with $\rho = 5 \times 10^4$ km at a wavelength of 4422Å. This wavelength was chosen for comparison with other results, since it is the central wavelength of the ESO "blue" comet continuum filter. The $Af\rho$ value derived in this work is in agreement with results by previous publications (e.g. [10], and references therein).

From $Af\rho$, the dust mass production rate can be computed. This requires the knowledge of the size-dependent dust expansion velocity in the cometary coma and the maximum dust grain size in the coma [6]. In order to compute these quantities, first the gas flow from free sublimating water ice at a mean solar zenith angle of 60° was computed. In a second step, the equation of motion for test dust particles in this gas flow and under the influence of the nucleus gravity was solved. A summary of this approach is given by Weiler et al. [11]. A nucleus bulk density value of 800 kg $m^{-3}$ and a value of the nuclear radius of 3 km [1] were used for the computation. For the assumed spherical dust grains a density according to Newburn & Spinrad [8] was assumed. After 100 nuclear radii, the dust has decoupled from the diluted gas flow and the nucleocentric dust velocities remain about constant. The resulting size-dependent final dust

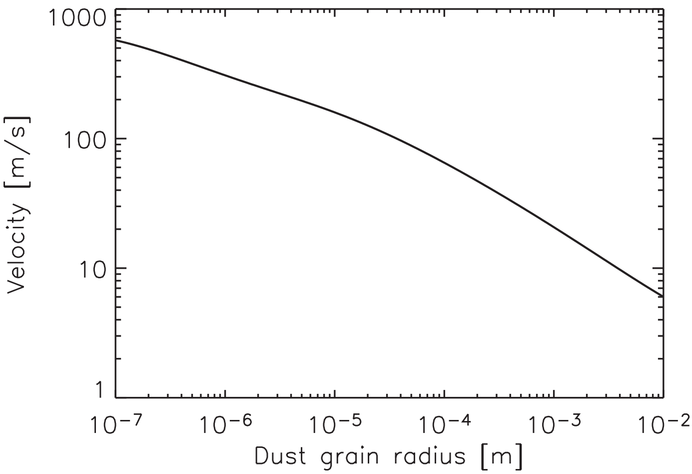


**Fig. 1.** Nucleocentric dust velocities as a function of dust grain radius in the coma of comet 9P/Tempel 1 before impact.

velocities are displayed in Fig. 1. This results in a maximum radius of 10.9 cm for dust particles that can be lifted off the surface by the gas flow.

For the computation of the dust production rate, a dust phase function according to Divine [3] is assumed. With a dust size frequency distribution according to Newburn & Spinrad [8] with a typical exponent of the size distribution of −3.5 and a maximum at a size of 0.54 µm, a dust mass production rate of 141.8 kg $s^{-1}$ results, with the minimum and maximum values of 83.0 kg $s^{-1}$ and 199.4 kg $s^{-1}$ obtained with the lower and upper value of $Af\rho$. Assuming a water production rate of $3.4 \times 10^{27}$ $s^{-1}$ [7], this corresponds to a dust-to-water mass ratio of about 1.4. However, the uncertainty of this value remains large not only due to uncertainties in the model assumptions, but also due to the large uncertainty in $Af\rho$ and the water production rate. The water production rate might be as high as $10.4 \times 10^{27}$ $s^{-1}$ [4], meaning the dust-to-water mass ratio would be less than one.

## 4 Conclusions

No influence of the impact event upon the gas production rates of comet 9P/Tempel 1 on a timescale of several days was observed. No new active region of significant size on the nucleus surface was therefore created by the impact. Since no new gas emission features were detected in the spectra obtained after impact, no significant amount of species unusual for cometary comae were produced due to the impact. The ratio of $C_2$/CN and $C_3$/CN in the impact cloud is identical to the the corresponding values in the undisturbed coma, thus no indication for compsitional inhomogeneities of the cometary nucleus with depth was found. The large numbers of parent molecules in the impact cloud cannot be produced by sublimation due to the impact energy alone. The presence of sublimating grains in the coma after impact is therefore likely. Differences in the rotational lightcurve of the CN emission in the inner coma compared to the lightcurves of the $C_2$, $C_3$, and $NH_2$ emissions indicate compositional differences between different regions on the nucleus of comet 9P/Tempel 1.

The dust-to-gas mass ratio derived from the dust mass production rate is close to one, thus comet 9P/Tempel 1 is not a dusty comet (e.g. for comet 67P/Churyumov-Gerasimenko, the dust-to-water mass ratio was determined to about 4.8, see [12]).

A more detailed discussion of the results presented here is provided by Rauer et al. [9] and Weiler et al. [13].

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