The Dusty View of DI from ESO Chile

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Abstract Around the time of the impact of NASA's Deep Impact (DI) mission at comet 9P/Tempel 1, in total 6 telescopes with altogether 7 different instruments, located at the La Silla (LSO) and Paranal (VLT) Observatories of the European Southern Observatory (ESO) in Chile, were used to characterize the dust properties before and after the event. The ejecta cloud expanded at an average speed of about 200 ms^{-1} during the first hours after the event. It reached stagnation distance of 25000 km about 3 days after impact. The pre-impact dust jet and fan activity ('porcupine' pattern) remained undisturbed after impact. In our measurements the jet activity can be traced to a few 100 km nucleus distance. In total 9 comastructures are identified which may originate from at least 4 regions of enhanced dust emission on the nucleus – one of this region may in fact be multiple. No obvious signatures of a new active region created by DI are found. The overall dust production during the impact compares to about 5–10 h of normal activity. The global expansion geometry of the DI cloud is compatible with a majority of dust grains in the micron size range. Indications exist for asymmetric brightness and colour distributions of the dust in the ejecta cloud. The dust temperature rose from about 280–290 K before to 330 K one day after the event and fell to pre-impact level the day thereafter. The dust reflected sunlight was found to be linearly polarized at about 7.5% in the visible and near–IR, at constant level within about 4000 km from the nucleus. No circular polarization of the dust is detected.

1 DI Dust Observations at ESO

The observations of the dust, produced by the DI event at comet 9P/Tempel 1 on 4 July 2005, were performed at ESO's La Silla and Paranal Observatories in Chile. They cover the immediate pre-impact period and extend until several days after the event. However, at the time of the impact (05:53UT) the comet had already set for the ESO sites and could only be re-observed again 14 h (mid-IR) and 16 h(visible and near-IR) thereafter.

All telescopes, operated by ESO at the two sites, together with a number of instruments were 'employed' for the DI dust campaign: at La Silla the 2.2 m ESO/MPG telescope plus the Wide-Field-Imager (WFI), the 3.5 m New Technology Telescope (NTT) plus the EMMI and SOFI instruments and the 3.6 m telescope plus TIMMI2; at Paranal the four 8.2 m unit telescopes (UT1-4) of the Very Large Telescope (VLT) using FORS2 and ISAAC at UT1, FORS1 at UT2, VISIR at UT3 as well as NACO and SINFONI at UT4. The suite of telescope-instrument combinations allowed a comprehensive observing program covering the visible (WFI, EMMI, FORS1, FORS2), near-IR (SOFI, ISAAC, NACO, SINFONI) and mid-IR (TIMMI2, VISIR) wavelength range (0.36 – 20 μm) with different observing techniques (imaging, spectroscopy, polarimetry). Table 1 summarizes the ESO observations obtained for the analysis of the dust component of the Deep Impact event. In parallel, ESO telescopes and instruments were also used for observations of the gas phenomena of the comet and related with DI (for an overview see [3]). The ESO web pages of the La Silla and Paranal observatories provide detailed information on the telescope and instrument equipment used.

2 Results

First results from the ESO DI dust campaign are included in the paper by Meech et al. [7]. Final results from the ESO dust campaign of the DI event – together with more detailed descriptions of the observations, the data processing and analysis methods applied – are found in Boehnhardt et al. [1], Bonev et al. [2], Tozzi et al. [8] and will be released in forthcoming papers (in particular on the polarimetry and adaptive optics observations). Below we summarize our results, focussing on various properties of the ejecta cloud and the 'background' coma produced by normal dust activity of the comet. The instruments that provide the respective observations are indicated as well (usually in parenthesis after the subject title).

Table 1. Overview on the observing schedule of the ESO DI dust campaign in July 2005. The table lists: in the left part – the observing technique (column 'Mode'), the 'field size', the instrument set–up (column 'Setup'); in the central part – indicated by symbol 'X' the usage of the respective configuration for each day during the period 2–11 July 2005; in the right part – the ESO site (column 'Observatory'), the telescopes (column 'Telescopes') and the instruments (column 'Instruments') used for the respective observations. Abbreviations: Small = normal field size of about 5–10 arcmin; Wide = wide field of 32 arcmin; Narrow = very small field size of about 1 arcmin or less; non-AO = seeing limited; AO = adaptive optics; Disp. = dispersion; LSS = longslit spectroscopy; IFU = integral field unit spectroscopy; Spec. = spectroscopy; $BVRIJHKLMNQ$ = broadband astronomical filters; NarrowF = narrowband filters; CometF = narrowband filters for selected cometary molecule and dust continuum bands; Img. linear = linear imaging polarimetry; Spec. linear = linear spectropolarimetry; Spec. circ = circular spectropolarimetry. Column 'Setup' also indicates the wavelength range (in nm or by filter band designations) of the measurements.

Mode	Field Size	Setup	2	3	4	5	6	7	8	9	10	11	Observatory	Telescopes	Instruments
Imaging	Small	NQ	X	X	X	X	X	X	X	X	X		VLT/LSO	UT3/3.6m	VISIR/TIMMI2
	Narrow	LM				X	X	X	X	X			VLT	UT4	NACO
	Narrow	JHK	X	X	(X)	X	X	X	X	X			VLT	UT4	NACO/SINFONI
	Small	JHK	X	X	X		X	X	X	X			LSO/VLT	NTT/UT1	SOFI/ISAAC
	Small	$BVRI$		X	X	X	X	X	X	X	X	X	VLT	UT1/UT2	FORS2/FORS1
	Small	CometF	X	X	X		X	X	X	X			LSO	NTT	EMMI
	Wide	$BVRI$	X	X	X		X	X	X	X			LSO	2.2m	WFI
	Wide	NarrowF	X							X			LSO	2.2m	WFI
Spectroscopy	non-AO LSS	N band	X	X	X	X	X	X	X	X	X		VLT/LSO	UT3/3.6m	VISIR/TIMMI2
	AO/non-AO LSS	L band					X						VLT	UT3/UT1	NACO/ISAAC
	AO LSS/IFU	JHK band	X	X									VLT	UT4	NACO/SINFONI
	non-AO LSS	JHK band	X	X	X		X	X	X	X			LSO	NTT	SOFI
Polarimetry	Img. linear	JHK		X	X		X						LSO	NTT	SOFI
	Img. linear	NarrowF	X							X			VLT	UT2	FORS1
	Spec. linear	400–900nm			X	X							VLT	UT2	FORS1
	Spec. circ.	400–900nm					X						VLT	UT2	FORS1

2.1 Impact Plume

The ejecta cloud (FORS2, EMMI, WFI): The dust cloud produced by the impactor crash into the comet, was detected in broadband and narrowband images from a few hours after the event until at least 8 July 2005. Figure 1 shows in four sub-panels BVR composite images of the ejecta cloud at four epochs after the impact. For clarity the coma background from normal activity is removed which allows a better display of the cloud expansion with time. On 4 July 2005, the ejecta cloud had a semi-spherical shape expanding into the southwestern coma quadrant (central position angle PA ∼235 deg; velocity of dust front ∼220 ms^{-1} and of maximum brightness ∼ 120 ms^{-1}). The surface brightness and dust reddening was slightly higher on the sunward side of the cone (compared to the tailward side). Towards Sun direction the cloud expansion got slowed down by radiation pressure during the subsequent days and reached a maximum projected distance of about 25000 km from the nucleus. No indications for 'mini-comets', neither natural nor impact-induced ones, are found in high-resolution imaging data of the inner coma.

Total dust production (FORS2, SOFI): From the flux enhancement of the ejecta cloud over pre-impact level, we estimate a total dust production by the impact that compares to about 5–10 h of 'normal' undisturbed activity of the nucleus at the time of the encounter (this assumes similar dust properties of the ejecta and the normal activity dust).

2.2 Ejecta Dust Grains

β-factor, terminal velocity and reddening slope (FORS2, EMMI, WFI): The sunward apex distances of the cloud, measured every day, allowed to constrain the radiation-pressure-to-gravity parameter β and the initial ejection velocity v_{eject} of the dust grains: the values found decrease from 1.9 and 370 ms^{-1} about 20 h post-impact to 0.2 and 160 ms^{-1} about 3.5 days after the event. The results suggest that the majority of the dust ejecta seen in the visible wavelength range consisted of grains of a few µm in size. In particular, the high β grains may have consisted of absorptive material. The dust reddening changed from a constant level of 9%/100 nm throughout the coma (within 20000 km from the nucleus) before impact to radially increasing values of 17 to 22%/100 nm at 5000–20000 km towards the end of our observing campaign (9 and 10 July 2005). By 6 July 2005 at the latest, the dust started to be expelled into tail direction (PA = 111 deg).

Grain sizes (SOFI, ISAAC, NACO:) Differences in the radial profiles of the JHK images of the ejecta cloud suggest that heavier dust was concentrated closer to the nucleus than the lighter one (since the flux profile peaks at 2000 km projected nucleus distance in K band compared to a peak distance of 10000 km in J). Following the modeling approach of Kolokolova et al. [4], the dust in- and outside of the ejecta cloud was characterized using radial profiles of various dust continuum filters. The slope of the dust size distribution was found to

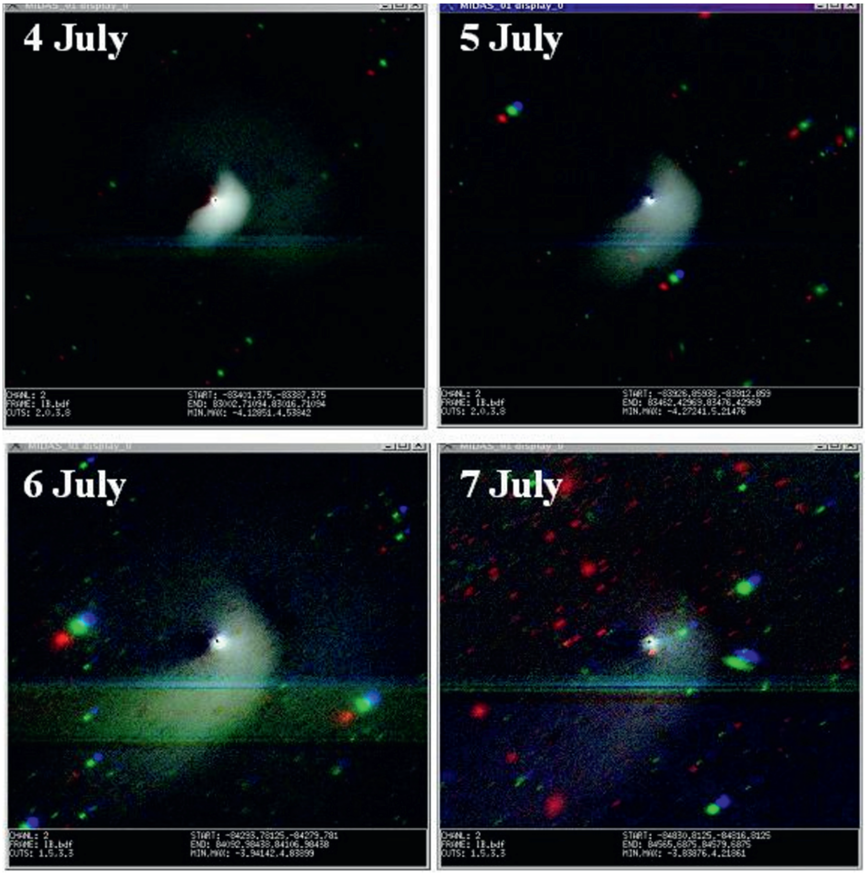

Fig. 1. The expansion of the DI ejecta clouds. The images are composites of BVR exposures taken with FORS2 each night (as noted in the subpanels). The coma background from the normal activity of 9P/Tempel 1 is removed by subtraction of FORS2 pre–impact exposures, obtained in night 3–4 July 2005 through the respective filters. North is up and East is to the left. Field of view is about 150000×150000 km at the distance of the comet. Horizontal stripes result from incomplete removal of the interchip gap of the FORS2 detector array.

be about 2.6 in the overall coma before impact and $\sim$2 in the impact ejecta alone. The minimum grain size is 0.2 µm in the normal coma and 1 µm in the impact plume. Modeling of the ejecta cloud dynamics indicates a total dust production of 6000–13000 tons for grain sizes between 0.2 and 110 µm and size distribution slopes of 2.9–2.5, respectively. We note that the results on the dust size dsitribution determined from the near-IR and visible colours and the dust dynamics as seen in the visible are not in full agreement and suggest revision of the modeling approaches (in particular, they do not consider dust sublimation and hydrodynamic effects).

Dust sublimation (SOFI, ISAAC, NACO:) The presence of sublimating grains which scattered the light very efficiently in the near-IR, has been detected. The mean lifetime of these grains was found to be of the order of 11 h.

2.3 Dust Material

Dust temperature (VISIR, TIMMI2): We used the mid-IR filter photometry of the cometary coma, namely the filters with central wavelength of 8.7 and 13.2 μm, to estimate the temperature of the very inner dust coma (about 3000 km diameter). During the first day after impact a temperature of about 300 K is measured which is significantly higher than the pre- and later post-impact values (280–290 K). With the exception of the first post-impact day, the variability of the mid-IR flux seen in the near-nucleus region around the days of the impact, may be due to normal activity and/or the nucleus itself (cross section variability by rotation). The N band spectra of the dust reveal a silicate emission feature with different profile pre- and post-impact. Modeling of the spectra indicates the presence of a large amount of absorbing material and an enhancement of amorphous and crystalline silicates in the post-impact dust.

Dust polarization (FORS1): The linear polarization of the dust in the visible wavelength range was found to be the same 7.5% before (3 July 2005) and after impact (5+7+9 July 2005). The polarization degree did not change across the coma within ∼5000 km project distance from the nucleus. The anti-correlation between color change and polarization degree throughout the coma is compatiable with a change in the size distribution of the dust grains due to the DI event. Linear spectropolarimetric observations on 5+9 July 2005 support these findings. The cometary dust showed a spatially flat linear polarization that decreased slightly with increasing wavelength (400–800 nm). This may be indicative for a relatively high abundance of organic material in the cometary grains. Measurements of the circular polarization post–impact (on 8 July 2005) showed zero values (within the uncertainties of 0.3%), independant from the nucleus distance ($<$ 5000 km) and wavelength (400–800 nm).

Given the sparse coverage of the DI event by our polarimetry observations and the small coma area (about 5000 km around the nucleus) that provided enough SNR for reasonably accurate polarimetric measurements, we believe that our polarimetry results may be more representative for dust from normal activity of the comet rather than from the impact cloud.

2.4 Localized and Normal Activity of the Nucleus

Localized activity (FORS2, EMMI, WFI, SOFI, ISAAC, NACO): The ejecta plume overlapped in parts with the general dust coma produced by normal activity of the nucleus (see Fig. 2). Image enhancement of the exposures, taken during the nights after impact, reveal the ‘porcupine’ pattern of localized normal dust activity, also shining through the ejecta cloud (i.e. as of 16 h after DI had produced the plume, it was optically thin). No changes from normal appearance

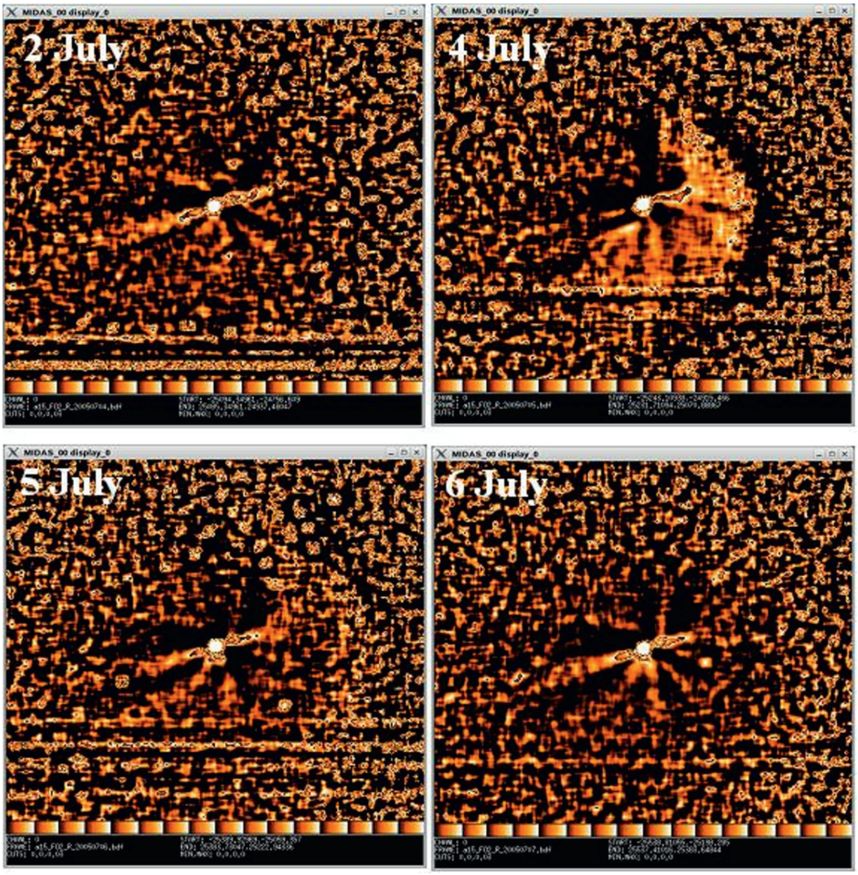

Fig. 2. The ‘orcupine’ pattern of embedded fans from active regions on the rotating nucleus of 9P/Tempel 1. The subpanels show the coma structures after enhancement by Laplace filtering. The original images were taken with FORS2 through broadband *R* filter each night (as indicated in the subpanel). The ‘procupine’ pattern is shining through the DI ejecta cloud on 4 July 2005 (about 16 h after the event). North is up and East is to the left. Field of view is about 85000×85000 km at the distance of the comet. Horizontal stripes result from incomplete removal of the interchip gap of the FORS2 detector array.

in this pattern is found after impact, in particular no jet or fan did evolve that could have been associated with a new, long lasting active area as a DI aftermath. The maximum extension of the ‘porcupine’ structure varied between – at least – 17000 km in sunward and 58000 km tailward direction. The cometary coma as a whole was back to pre–impact state (as for instance reported by [5, 6]) as of 9 July 2005 and no large-scale signatures of the impact are noticed. The pattern produced by localized activity is compatible with the presence of at least 4 active regions and a rotation axis orientation close to the orbital angular momentum vector of the comet. Coma features seen in normal seeing–limited images, can be traced to near–nucleus distances of a few 100 km.

Normal activity (EMMI, FORS2): The normal dust activity of the comet, seen in the general diffuse coma background and the 'porcupine' pattern, remained rather constant and uniform over the 10 days of our observations around the DI event. This can be concluded from the fact that subtraction of pre- from post/pre-impact images removed - almost - all flux from the general coma background and mostly only impact related signatures remained. The only exception is a marginal diffuse near-nucleus feature in the southwestern coma quadrant that is seen in structure enhanced images taken on 7 July 2005. Radial flux profiles of the dust coma, obtained from pre-impact images by integration over 2π position angle around the nucleus, show slope values close to unity which suggests a rather uniform and homogenuous dust production by the nucleus.

We note in passing that the production of CN, C_3, and C_2 gas by the nucleus, measured from EMMI cometary filter imaging, is at similar level on 3 and 9+10 July 2005. Indications are found that some of the dust jets/fans from enhanced localized activity on the nucleus have counterparts in CN filter images of the coma.

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