Deep Impact at ESO Telescopes

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This article is a first summary of the observations done with ESO telescopes and instrumentation in the context of NASA's Deep Impact (DI) space mission. The ESO observers* were part of an extremely active, communicative and thus successful worldwide network of observers. Through this network all information was freely exchanged and highlights are reported here as well.

Comets and the formation of the Planetary System

The most important scientific rationale for studying comets is to obtain information on their origin, on their relationship with interstellar and interplanetary material, and on implications for the formation of the Solar System. The knowledge about comets had been synthesized in the 1950s by Fred Whipple into the "Dirty Snowball" model for cometary nuclei. Today comets are referred to as "icy dirt balls" of the solar system because this is a better reflection of their constitution of frozen volatiles and dust. Comets are known to arrive in the inner planetary system coming from two main reservoirs: the Oort Cloud at several 1000–10 000 AU distance from the Sun, and the Edgeworth-Kuiper Belt at 30–50 AU from the Sun. The latter is considered to be also the birthplace of most of the short-period comets, while the Oort Cloud contains comets originating in general from the region of birth of the major planets in the Solar System.

Gravitational interaction with the outer planets and the immediate and even more distant neighbourhood of the Sun in the Milky Way (passing stars, molecular clouds, galactic centre) has moved and stored these cometary nuclei into the Oort Cloud, now the repository of non-periodic comets. It is the same process, gravitational interaction with stars and molecular clouds passing our Solar System, which is responsible for injecting comet nuclei from their storage place back into the inner Solar System where they can be observed from Earth. Comets then become sometimes spectacular objects, since close to the Sun, the frozen volatiles sublimate, which creates the dust and gas comae. *Coma* is the Latin word for "hair" and thus, comets have been referred to as "hairy stars" by our ancestors.

Since comets stayed inactive most of their lifetime in the cold environment of the outer Solar System, they are believed to be primordial, i.e. representing in a close to original form an important population of minor bodies that agglomerated in the protoplanetary disc from interstellar dust some 4.6 billion years ago. Comets can thus be considered as fossil records from the formation of our Solar System. Of course, any *fossil* on Earth has been subject of some type of "weathering". Similarly cometary nuclei have not survived 4.5 billion years in the Solar System without any changes. Their upper surface layers of a few metres thickness experience evolutionary modifications due to cometary activity, space weathering and collisions with other minor bodies. Hence it is not surprising that comets have very high priority on the target lists of interplanetary missions of the national and international space agencies: triggered by Halley's comet's encounter of a fleet of five spacecraft in 1986, four more comets were explored by man-made scientific instrumentation in fly-by missions up to the last year. At this point, the exploration of comets with ground-based telescopes and fly-by spacecraft had resulted in a cornucopia of many, sometimes fairly sophisticated detailed observations. The most important parameters

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* The ESO observations were the result of a worldwide scientific cooperation involving the following colleagues: Michael A'Hearn (University of Maryland, USA), Claude Arpigny (Université de Liége, Belgium), Anita Cochran (McDonald Observatory USA), Catherine Delahodde (University of Florida, USA), Yanga Fernandez (University of Central Florida, USA), Damien Hutsemekers (Université de Liège, Belgium), Hideyo Kawakita (Gunma Astronomical Observatory, Japan), Jörg Knollenberg (Deutsches Zentrum für Luft und Raumfahrt, Germany), Ludmilla Kolokolova (University of Maryland, USA), Mike Kretlow (Max-Planck-Institut für Sonnensystemforschung, Germany), Michael Küppers (Max-Planck-Institut für Sonnensystemforschung, Germany), Ekkehard Kührt (Deutsches Zentrumfür Luft und Raumfahrt, Germany), Luisa Lara (Instituto de Astrofísica de Canarias, Spain), Javier Licandro (Instituto de Astrofísica de Andalucía, Spain), Casey Lisse (The John Hopkins University/Applied Physics Laboratory, USA), Karen Meech (Universitiy of Hawaii, USA), Rita Schulz (ESTEC, the Netherlands), Gerhard Schwehm (ESTEC, the Netherlands), Michael Sterzik (ESO), Joachim A. Stüwe (Universiteit Leiden, the Netherlands), Isabelle Surdej (Université de Liège, Belgium), Diane Wooden (NASA Ames Research Center, USA) and Jean-Marc Zucconi (Besançon, France).

of a solar-system body, density and thus mass and the tensile strength of surface and interior, however, were the subjects of theoretical conjectures, but remained basically undetermined. It was thus important to take the next logical step: 2005 has seen a new flavour of cometary exploration, Deep Impact, an active experiment with a cometary nucleus.

The Deep Impact mission

On 4 July 2005, NASA's discovery mission Deep Impact (DI) encountered Comet 9P/Tempel 1, releasing a 370 kg copper probe at the comet (A'Hearn 2005). The probe was hit by the comet nucleus at a speed of 10.2 km/s and penetrated into the upper surface layers of the nucleus while the mother spacecraft flew by the nucleus at a distance of about 500 km observing the event with three on-board remote sensing experiments, a wide- and a narrow-field camera (visible wavelength range) and a near-infrared imaging spectrometer (1–5 micron). The target comet, 9P/Tempel 1, is a medium-bright, slowly rotating (41 h), medium-size (> 7.5 km diameter), low-albedo (8 %) short-period comet, most likely originating in the Edgeworth-Kuiper Belt. During the impact the kinetic energy released by the impactor was 19 GigaJoule or 5 300 kWh (this amount of energy is equivalent to the biannual electricity consumption by the author in his apartment for which the local public utility company charges approximately 900 €. Or it is slightly more than the equivalent of an Airbus A380 airplane flying at cruise speed – pick the unit which is more familiar to you!).

Models describing the subsequent crater formation resulting from this experiment gave a wide range of predictions, from the comet swallowing the impactor with virtually no effects, to complete disruption of the nucleus. The most likely models predicted a crater of football stadium size, an impact flash, an ejecta plume with a high probability that pristine material from the inner "original" layers is released during and after impact, when the Sun will illuminate this newly formed active region on the nucleus. Under lucky circumstances even a new long-lasting active region might have been created by the impact. Due to the fly-by nature of the mission, the spacecraft could perform only a short monitoring campaign of the target peaking in an approximately 800 sec long period around close encounter, when the impact area was in direct view of the instruments on board the fly-by spacecraft. Figure 1 shows an example of images taken by the fly-by spacecraft.

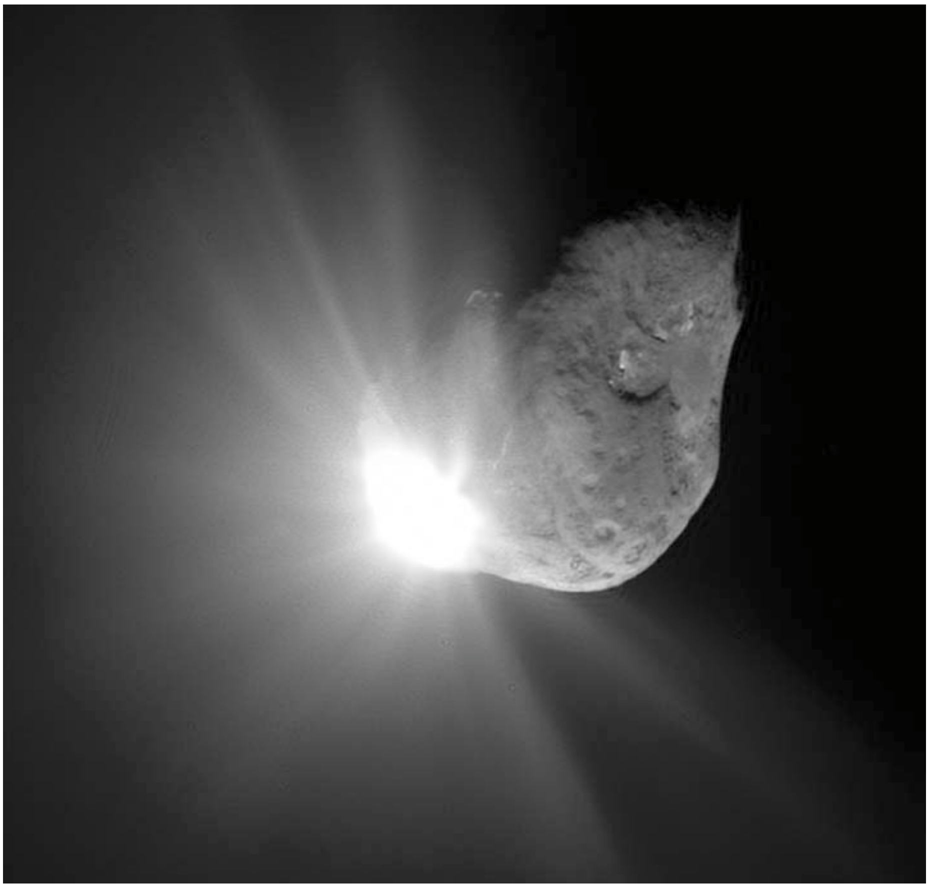

Figure 1: Comet 9P/Tempel 1 imaged 67 seconds after it obliterated Deep Impact's impactor spacecraft. The image was taken by the high-resolution camera on the mission's fly-by spacecraft. The image reveals topographic features, including ridges, scalloped edges and possibly impact craters formed long ago. First light from the impact flash arrived on Earth at 05:52:03.3 UT. For ESO telescopes the comet had just set (see text).
Image credit: NASA/JPL-Caltech/UMD.

Need for earth-based DI science

Given the limited scope of the on-board instrumentation (described in Hampton, 2005) and the short visibility of the impact area from the spacecraft, Earth-based observations were the most important complementary means to guarantee the expected science return and the success of the mission. Hence, they formed an integral part of the DI mission concept and have been coordinated world-wide by a dedicated mission scientist (Karen Meech, University of Hawaii, see Meech 2005). Due to the limitations of man-made interplanetary spacecraft a short-period comet had to be picked for this experiment. The comet should have a perihelion not too far from our Earth's orbit. The encounter could only take place close to a crossing point of the cometary orbit with the orbital plane of the Earth, the Ecliptic. For Comet 9P/Tempel 1, one of the few comets fitting the set of constraints, perihelion passage (July 5, 2005)

Figure 2: The participants of the ESO-Deep-Impact preparatory workshop in February 2004.

was very close to the descending node crossing (July 7, 2005). To have optimum conditions for ground based follow-up, the event should take place during “dark time” (new moon July 6, 2005). These constraints set the date for the experiment. The visibility of the immediate impact event on Earth covered most of the Pacific Ocean region except for the west coast of South America. ESO’s role in the scientific follow-up was to study and document the activity of Comet 9P/Tempel 1 until shortly before impact. The comet set for Chile approximately two hours before impact. From the study of spontaneously broken-up comets it was known, that the break-up related phenomena peak in brightness 12–24 hours after the event. For an example we refer to Comet 73P/Schwassmann-Wachmann 3 (c.f. *http://www.eso.org/outreach/press-rel/pr-1996/pr-01-96.html*). In that sense it was considered advantageous, that the comet became visible in Chile 16 hours after impact. Given the light-collecting power and instrumental multiplexing capabilities, the ESO observatories in Chile were considered critical sites for the ground-based observational coverage of the impact event. Moreover, ESO is in the special position of having its telescopes located on two different mountain tops separated far enough geographically that they have different weather. Both sites by themselves are already excellent astronomical sites, but in combination it is highly unlikely that both observatories would be clouded out. For a time critical event such as Deep Impact, this was, of course, an invaluable asset, especially in Chilean winter!

The coordinated ESO DI campaign

For an optimum preparation of the campaign, an impromptu weekend workshop was sponsored and organised at ESO in February 2004, to get the ESO community involved. Many of the participants had been involved in the July 1994 observing campaign for the collision between the fragments of Comet Shoemaker-Levy 9 with Jupiter (SL9, c.f. The Messenger 77, 1994 or *http://www.eso.org/outreach/info-events/sl9/*). In total five proposals received time at ESO telescopes, of which

Table 1: Usage of different observing modes during impact period.

ESO Campaign	Obs. mode	Setup	July 2005										Observatory	Telescope	Instrument
			2	3	4	5	6	7	8	9	10	11			
Imaging	Small field	NQ-Filters	x	x	x		x	x	x	x	x		VLT/LSO	UT3/3.6-m	VISIR/TIMMI2
	AO	LM-Filters				x	x	x	x	x			VLT	UT4	NACO
	AO	*JHK*-Filters	x	x	(x)	x	x	x	x	x			VLT	UT4	NACO/SINFONI
	Small field	*JHK*-Filters	x	x	x		x	x	x	x			VLT/LSO	NTT/UT1	SOFI/ISAAC
	Small field	BVR-Filters		x	x	x	x	x	x	x	x	x	VLT	UT1/UT2	FORS1/FORS2
	Small field	Comet. Filters	x	x	x		x	x	x	x			LSO	NTT	EMMI
	Wide field	BVRI-Filters	x	x	x		x	x	x	x			LSO	2.2-m	WFI
	Wide field	NB-Filters	x							x			LSO	2.2-m	WFI
Spectroscopy	Low Disp. LSS	*N*-Band	x	x	x	x	x	x	x	x	x		VLT/LSO	UT3/3.6-m	VISIR/TIMMI2
	AO long slit	*L*-Band					x						VLT	UT1/UT4	ISAAC/NACO
	AO IFU/LSS	*JHK*-Band	x	x									VLT	UT4	NACO/SINFONI
	Low Disp. LSS	*JHK*-Band	x	x	x	x	x	x	x	x			LSO	NTT	SOFI
	Low Disp. LSS	370–920 nm	x	x	x	x	x	x	x	x	x	x	VLT/LSO	UT1/UT2/NTT	FORS1/FORS2/EMMI
	High Disp. SSS	304–1040 nm	x	x	x	x	x	x	x	x	x	x	VLT	UT2	UVES
Polarimetry	Imaging linear	*JHK*-Band		x	x	x							LSO	NTT	SOFI
	Imaging linear	NB visible	x						x				VLT	UT2	FORS1
	Spectro. linear	400–900 nm			x	x							VLT	UT2	FORS1
	Spectro. circular	400–900 nm					x						VLT	UT2	FORS1

four were closely coordinated and performed by an international team of cometary experts, experienced observers, data analysts and modelers. Two of the proposals (PIs: Hainaut, Käufl) characterised the pre-impact status of the comet, the other two (PIs: Böhnhardt, Rauer) focused on the observation of the impact event and its aftermath. During the impact period the team used all seven telescopes currently operated by ESO at Paranal and La Silla, i.e. the four 8.2-m unit telescopes of the ESO Very Large Telescope (VLT) and the 3.6-m, the NTT and 2.2-m telescopes at La Silla (LSO). Altogether 11 instruments at these telescopes delivered scientific measurements covering the widest possible wavelength range from 300 nm to 20 micron and exploring almost all possible observing techniques such as seeing and diffraction limited direct imaging through broadband, narrowband, and special cometary filters, spectroscopy using long-slits/low-dispersion, short-slit/high-dispersion and integral field optics as well as imaging and spectro-polarimetry with linear and circular polarisation optics. Table 1 provides an overview of the usage of the different observing modes applied during the impact period at the various ESO telescopes and instruments. In this context it is interesting to note that one of the reference science cases for the VLT was to repeat an observational campaign such as SL9 and indeed, the VLT proved to be perfectly suited for such a unique and unpredictable event.

Paranal and La Silla, part of a world observatory

Even if the Deep Impact spacecraft had missed the comet, the data set would be absolutely unique, as the worldwide campaign to observe Comet 9P/Tempel 1 involved all major observatories and various spacecraft. Hubble Space Telescope, Spitzer Infrared Space Observatory, and Chandra and XMM/Newton in X-rays, to name just the most important observatory type missions observed in parallel and even ESA's Rosetta space-

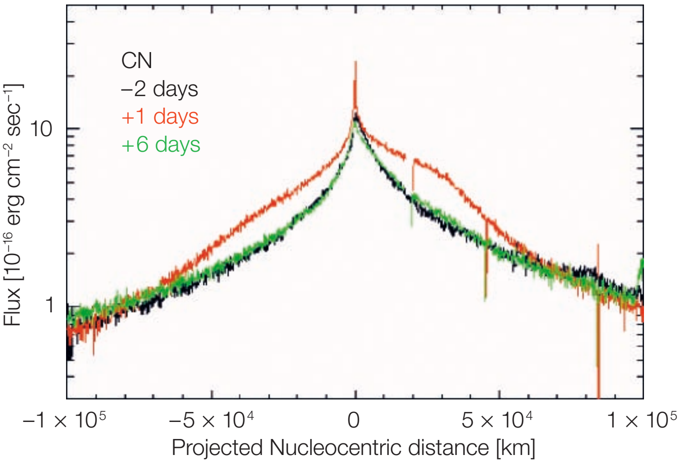

Figure 3 (above): Comparison of the spatial profiles along the slit for the integrated CN emission (at ~ 390 nm) on the nights July 2/3 (black), July 4/5 (red) and July 9/10 (green). The impact plume can be seen in CN and dust, being more extended in the CN than in the dust continuum (not shown here). The distances are positive towards the sun direction (Rauer et al., in preparation).

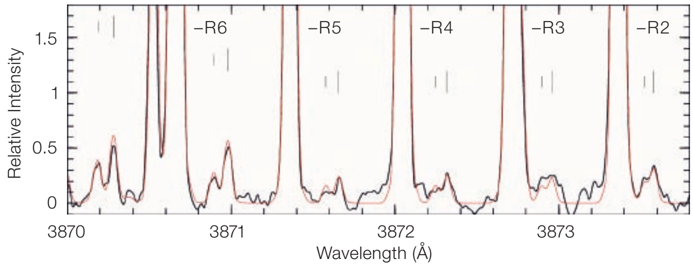

Figure 4 (above): Section of the UVES spectrum of the CN (0,0) band in Comet 9P/Tempel 1. The black *thick line* is the observed spectrum (50 hours); the *thin (red) line* is the best fitting synthetic spectrum of $^{12}C^{14}N$, $^{12}C^{15}N$ and $^{13}C^{14}N$ obtained for an isotopic mixture $^{12}C/^{13}C = (95 \pm 15)$ and $^{14}N/^{15}N = (145 \pm 20)$. The lines of $^{12}C^{15}N$ are identified by the short ticks and those of $^{13}C^{14}N$ by the longer ticks. The quantum numbers of the R lines of $^{12}C^{14}N$ are also indicated. This is only the second time that the C and N ratios have been measured in a Jupiter-family comet. The ratios are the same as in Oort Cloud comets. This will put important and interesting constraints on the formation history of Jupiter-family comets. (Jehin et al., in preparation).

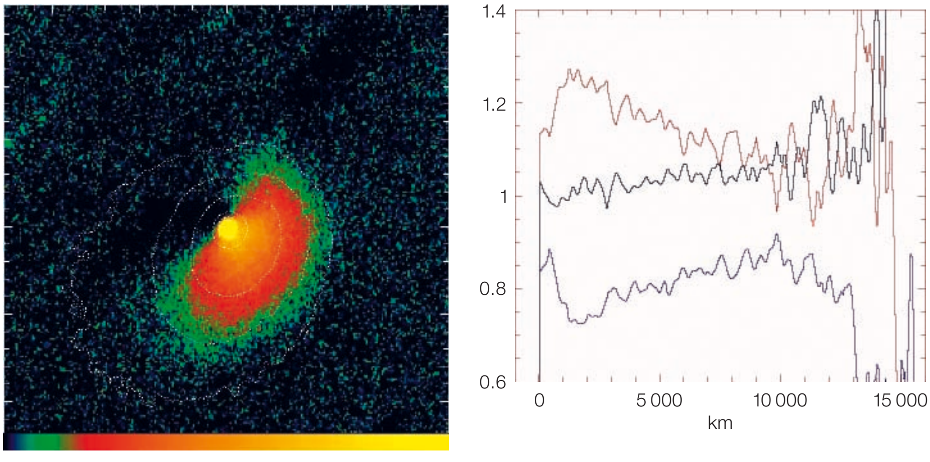

Figure 5 (left): Dust ejecta with SOFI: The left image shows the extra signal after impact ("normal" comet coma subtracted, July 4 – July 2) of the dust ejecta in *J*-band. The differences in the radial profiles of JHK images (right) of the ejecta cloud suggest that heavier dust is concentrated closer to the nucleus than the lighter one, since the *K*-band profile peaks at 2000 km projected nucleus distance while the *J*-band reaches maximum around 10 000 km distance. From the flux enhancement of the ejecta cloud over pre-impact level, we deduce 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 grain properties and a mean expansion velocity of about 100–200 m/s) (Tozzi et al., in preparation).

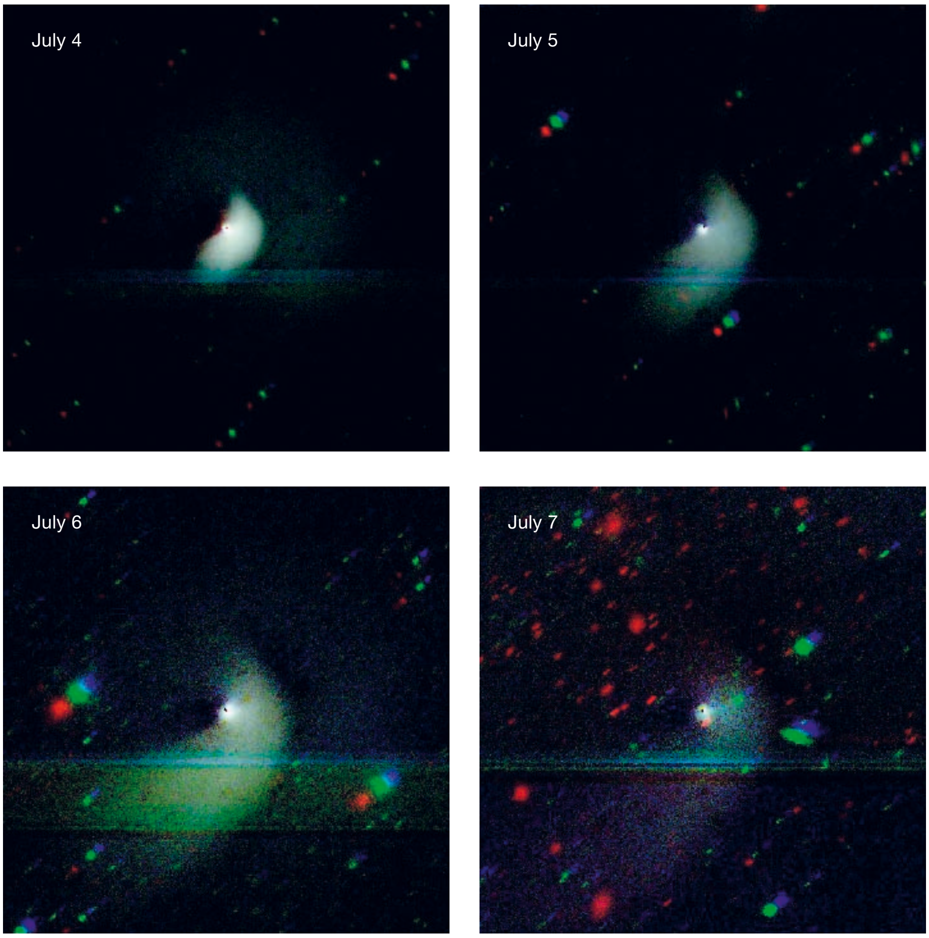

Figure 6: A set of four quasi-true-colour composite images with FORS2. The dust cloud from the impact was detected in broadband and narrowband images until July 8, 2005. On July 4 it had a semi-spherical shape expanding at the front edge with an average speed of about 200 m/s into the south-western coma quadrant (velocity of brightness maximum moved at about 120 m/s). The main axis of the cloud was at position angle (PA) of about 225 deg, which indicates that the impact happened below the orbital plane of the comet. The cloud expansion was slowed by radiation pressure during the subsequent days and reached a maximum expansion in the Sun direction of about 30 000 km. This distance compares to dust grains with a ratio of radiation pressure to gravity $\beta \sim 0.3$ (assuming an initial expansion speed of 200 m/s). Latest as of July 6, 2005, the dust started to be expelled into the tail direction (PA = 111 deg). The sudden drop in surface brightness between July 6 and 7 is yet to be understood.

craft – en route for a rendezvous with Comet 67P/Churyumov-Gerasimenko in January 2014 took part in the scientific observations of the impact event. Thanks to the coordination through Karen Meech at the University of Hawaii and colleagues at the University of Maryland a dedicated web-server was available and a permanent multi-site videoconference moderated from the control room of the NASA-3-m Infrared Telescope Facility (IRTF) on Mauna Kea provided the tools to communicate preliminary results and to have mutual consultation on the observations. Thus very effective observing was possible and duplication of observations minimised.

Observational results

All scientists involved in the ESO campaign met after the observations in Santiago at the ESO-Vitacura premises for a 10-day “conclave”. ESO had made available two conference rooms, and two data servers were set up, so that data reduction could start immediately. At this point nearly all data are reduced in the sense that the instrumental signatures have been removed and the data have been calibrated and converted into physical units. Now the real work has to begin, that is to compare the data to theoretical models and to put them into context with data from the spacecraft and from other observatories. The ESO data set was already partially presented at the IAU Symposium 229, August 7–12, 2005 *Asteroids, Comets, Meteors* (one oral presentation and four posters).

The following results from the spacecraft were reported at the recent IAU Symposium 229:

- the impact did release 1–2 * 10^7 kg of dust with a particle size < 10 µm; particles were pre-existing, i.e. not the result of impact shattering of larger structures
- the nucleus albedo is 4 %
- the crater formation was most likely “gravity controlled”; this implies that the tensile strength of comet material is of order of ~ 100 Pa, very similar to the limits set by the tidal disruption of comet Shoemaker/Levy 9 by Jupiter
- the impact angle was 50–70 deg (measured in the optical convention, from the surface normal)
- the nuclear shape model is not finished, but the size is 3.5 × 5 km (A’Hearn, IAUS 229)
- the infrared spectrum during the first seconds after impact showed: H_2O, HCN, (CH)x, CO_2 $(CO_2/H_2O) \sim 0.08$, CH_3CN (Sunshine, IAUS 229)

As a selection of ESO results a few spectra and images are presented here. In general one can note that 4–5 days after impact all impact related signatures had disappeared in the “noise” of normal cometary activity.

Dust grain characterisation

The characterisation of the physical and chemical properties of the dust grains was attempted – among others (dynamics, near-IR) – through mid-IR and polarimetric observations of the cometary coma before and after impact.
Mid-IR: By black-body fitting to mid-IR filter photometry of the cometary coma obtained with VISIR (VLT) and TIMMI 2 (LSO), a significant temperature increase of the dust was seen post-impact (330 K). The dust temperature dropped to the pre-impact level (280–290 K) as of July 6, 2005. However, the overall mid-IR flux,

measured in the very inner coma (3–5″), was higher from July 4–7, 2005 and returned to the pre-impact state only thereafter. The *N*-band spectra of the inner coma reveal a silicate emission with different profile shape pre- and post-impact. Preliminary modelling indicates the presence of a large amount of absorbing (carbon-like) material and an enhancement of amorphous and crystalline silicates in the post-impact dust. Furthermore, the post-impact dust seems to be enriched in crystalline silicates and displays a shallower size distribution (indicating larger grains present).

Polarimetry: The linear polarisation of the dust was found to be 7.5 and 0 % (Stokes Q and U, respectively) in the visible wavelength range. The polarisation did not change across the coma within ~ 7 000 km projected distance from the nucleus and was found the same on July 3, 2005 (before impact) and July 5, 7, 9, 2005 (after impact). Using spectro-polarimetric observations (July 5 + 9, 2005) we could not detect any wavelength dependence of the linear polarisation over the wavelength range ~ 400–850 nm. Moreover, the post-impact dust was found not to be circularly polarised over the wavelength and distance range mentioned above (July 8, 2005).

TIMMI 2 observations

Thanks to daytime observing, the comet could be observed from La Silla 3–4 hours before Paranal. Indeed the TIMMI 2 data are most likely the first data taken after impact with a professional telescope west of Greenwich! While the comet coma appears clearly brighter in the “after-impact” frames it is not entirely clear if this is due to the impact or normal activity. Ground-based mid-IR observations cannot detect a signal for distances exceeding typically ~ 4 arcsec or 2 600 km due to sensitivity limitations. Assuming a “canonical” outflow velocity of 200 m/s this in turn implies that ground-based thermal IR observations are sensitive only to material (dust) produced by the comet in an interval of 10–15 000 s before observation. This has to be kept in mind when comparing any mid-IR data set obtained from the ground with optical, near-IR or data obtained by the Spitzer space-based observatory. TIMMI 2 data shown here (as well as the VISIR data) thus refer to material which either has been released hours after the impact (fresh material under the impact site?), or is very slowly moving or even gravitational bound to the nucleus. (Käufl et al., in preparation).

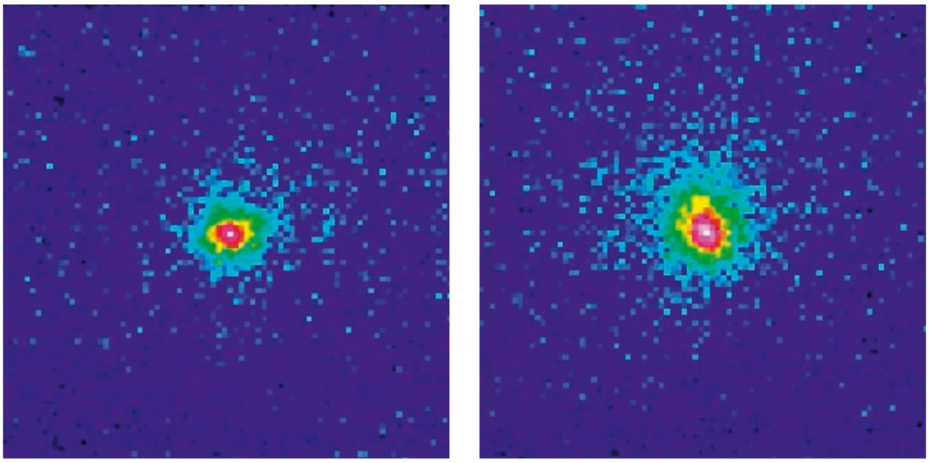

Figure 7: Sample images from TIMMI 2 before and after impact: the left image was taken on July 3 00h38 UT while the right image was recorded on July 4 19h38 UT. The filter was the OCLI 11.9 μm filter, showing the strongest variations after the impact. The pixel scale in both cases is 0.2″/pix (130 km at the comet), N up E right. The right image was taken in daytime.

Outlook and future work

At this point a series of special publications in Science is under way. Once results of the spacecraft are published in refereed journals we can start to assemble the global picture from all observations. Back during the Jupiter-SL 9 event, the analysis of all observational data was severely handicapped as the impact areas were just behind the visible limb of Jupiter. Astronomers thus did not know the physical details of the impact and the viewing geometry was awkward. The DI spacecraft data, however will provide us with the “ground truth” of the impact and the associated physics. This will make the analysis much clearer. However, a synthesis of this unprecedented worldwide multi-wavelength data set is required to uncover synergies.

To that end a dedicated workshop “Deep Impact as a World Observatory Event – Synergies in Space, Time, and Wavelength” will take place August 7–10, 2006 at the Palace of The Royal Academies for Science and the Arts in Brussels (for more information consult *http://www.eso.org/~hukaufl/deepimpact.html*). The workshop will be organized by the Vrije Universiteit Brussels and ESO.

Acknowledgements

On behalf of all scientists involved in the campaign we wish to thank the observatory staff for “a job well done”. In spite of all the “extras” asked for by this unusual and demanding campaign we felt a very positive attitude towards this project, including a genuine interest in the results of the observations. We appreciate the outstanding professionalism and dedication of everybody involved: everything worked perfectly for this campaign. After the observations, in Vitacura we found excellent working conditions and a warm hospitality.

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Note: For in-depth reading on the subject, *http://deepimpact.eso.org/* is a good starting point.