Department: "ASTEROIDS and COMETS"
XI. Report 2008

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1 Introduction (Kührt)

This 11th annual report describes the research results of the "Asteroids and Comets" Department of the Institute of Planetary Research (PF) of the DLR (German Aerospace Center) during 2008. Presently, the Department consists of 9 scientists, 2 PhD student, and 2 guest scientists from the Technical University Braunschweig and from the University Pisa, respectively.

Our scientific goal is to investigate minor bodies in the Solar System by observing them in the visible and infrared wavelength ranges, defining and contributing to relevant space missions and modelling physical processes associated with this class of object.

Our scientific interest in the minor bodies of the Solar System is focussed mainly on their crucial role in the formation of the planets and the development or destruction of life. Asteroids and comets are thought to be remnant material from the process of formation and the initial development of planets. Due to their peculiar dynamical and physical properties, such as small size, lack of a permanent atmosphere, and relatively little thermal processing, these objects have remained largely unaltered since the time of Solar System formation. Their dynamical evolution is a tracer of the mass distribution in the early planetary system.

Highlights of the period covered by this report include:

- 6 refereed papers published in 2008 and 9 papers submitted to refereed journals.
- Our mission proposal AsteroidFinder was successfully reviewed after a Phase A study.
- Contributions to the interpretation of the Rosetta data of Steins flyby.
- A total of nearly 900 hours of observation time with the Herschel and Spitzer space telescopes have been awarded to international teams of researchers, including Alan Harris, to study the nature of trans-Neptunian objects and near-Earth objects.
- The ASTEX study for an in-situ exploration mission to two near-Earth asteroids has been completed successfully.
- A novel model to evaluate cometary activity under the condition of moving boundaries has been developed.
- An international scientific network to the Topic "Impacts and Planetary Evolution" within the HGF-Alliance "Planetary Evolution and Life" has been established.
- A staff member (E. Kührt) was honoured with the "Otto-Lilienthal-Award".

In Chapters 2 to 4 we report on our scientific results. Contributions to space missions and our activities in technology transfer are described in Sections 5 and 6. The appendix summarises publications, project contributions, observation campaigns, public outreach activities, and our funding.

Asteroid science

1.1 Size and density estimates of binary asteroids (Harris)

Observations of binary asteroids can provide valuable insight into the bulk density of the components. Imaging with adaptive optics allows the position of an asteroid moon to be located and its orbit around the primary asteroid to be traced. Application of Kepler's 3rd law then leads to an estimate of the mass of the system. The mass, combined with size estimates from, e.g., thermal-infrared observations, gives an estimate of the density of the primary asteroid (normally the primary mass dominates). Thermal models developed in the Department have been applied to infrared data of a number of binary systems in the main asteroid belt to determine their sizes (e.g. see Fig. 2.2). The results have been combined with adaptive optics and other optical observations of the systems, obtained by collaborators with. e.g. the ESO Very Large Telescope, to provide density estimates. An important aspect of the work is to carefully account for the observed colour temperature, shape and rotation-axis orientation of the asteroid in the size estimates from the infrared data. In a number of cases our more accurate size determinations, compared to previously published results, have led to significant improvements in density estimates.

Fig. 2.1: Artist's impression of a binary asteroid. Credit: Keck Observatory/Lynette Cook.

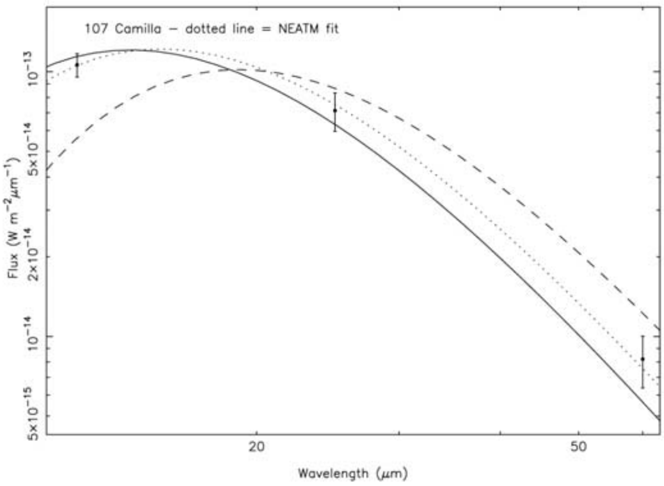

Fig. 2.2: Thermal model fits to flux data from the Infrared Astronomical Satellite for the binary main-belt asteroid 107 Camilla. The best-fitting model has a diameter of 249 km. This value of diameter implies that previous density estimates were overestimated by 30%. The new density of the primary is 1.4 g cm^{-3}.

The results provide further evidence that the bulk densities of asteroids, especially carbonaceous C-type asteroids, are often surprisingly low, in many cases comparable to that of water. It seems that many asteroids are not monolithic slabs of rock but porous objects with internal structures dominated by fractures and cavities.

In the course of the year this program of work has contributed to three refereed papers that have been published in the journal *Icarus.*

1.2 Herschel and Spitzer programs to observe TNOs and NEOs (Harris)

The population of transneptunian objects (TNOs) is believed to consist of frozen planetary embryos remaining from the formation of the outer Solar System. The left-over material beyond the orbit of Neptune is considered to be analogous to the extrasolar debris observed around several 10 - 500 Myr old stars. About 1200 TNOs have been detected so far. A total of 31 collaborators from many institutes around the world submitted a proposal to the Herschel Open Time Key Program for

Fig. 2.3: The Herschel Space Telescope. Credits: ESA/AOES Medialab; Hubble Space Telescope image (NASA/ESA/STScI).

observations to physically characterize the remnant population of "planet embryos" in our own debris disk. The program has been awarded 373 hours of observing time with Herschel, which is scheduled for launch in April 2009.

The remnant embryos, or planetesimal building blocks, of the terrestrial planets have been broken up in collisions, but fragments of them make up the main asteroid belt and the near-Earth object (NEO) populations. A total of 15 US and European collaborators submitted a proposal for observing time on the Spitzer Space Telescope in its forthcoming "warm mission" (after depletion of the cryogen) to physically characterize about 700 fragments of the original planetesimal building blocks of the inner Solar System. The project will focus in particular on dark, carbonaceous objects of the type that probably contributed to the early Earth's inventory of water and organic materials. The results will provide context for the inventory of carbonaceous and other meteorites studied in laboratories. The warm-Spitzer program has been awarded 500 hours of observing time.

For both the Herschel and Spitzer programs observations are expected to commence in the summer, 2009. An application to the DFG has been submitted for support for a research student to work in the Department on data anlaysis and modelling for these projects. Potential candidates should contact Alan Harris.

1.3 ASTEX - An in-situ exploration mission to two near-Earth asteroids (Harris)

An initial study commissioned by the DLR of a mission to two asteroids, ASTEX, has been completed in collaboration with colleagues at the Max Planck Institute for Solar System Research, DLR partners, and industry. ASTEX would land on two NEAs which have different mineralogical compositions, one asteroid being chosen to be of "primitive'' nature, the other to be a fragment of an "evolved" (differentiated) asteroid.

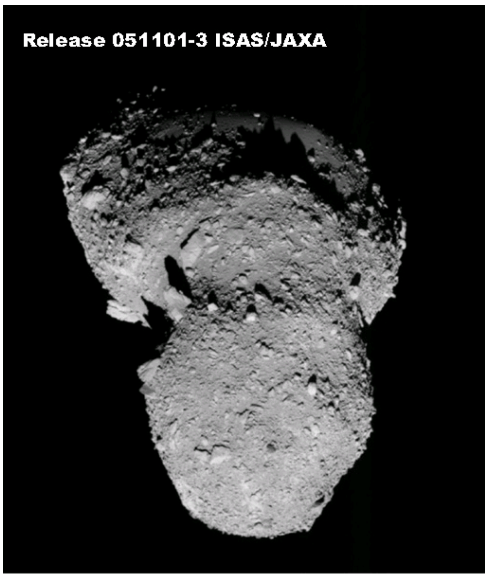

Fig. 2.4: Near-Earth asteroid Itokawa imaged by the Hayabusa spacecraft. Itokawa is about 500 m in length and similar to the potential targets of the ASTEX mission. Credit: ISAS/JAXA.

The ASTEX orbiter design features a radio reflection tomographer to facilitate the exploration, for the first time, of the internal structure of an asteroid. Knowledge of internal structure will shed light on the origin and evolution of asteroids, aid in designing strategies for mitigating hazardous objects, and help to predict the consequences of asteroid impacts on the Earth's biosphere.

The ASTEX mission plan is to set a lander down on the surface of each of the selected NEAs. Each lander will be equipped with identical sophisticated scientific instrumentation, which is designed to investigate the mineralogy and chemistry of the surfaces. The descent phase and landing will be autonomously controlled. ASTEX would perform in-situ measurements on an asteroid surface for the first time.

More detailed studies of the ASTEX concept are currently planned and links to potential international partners are being sought.

1.4 Asteroid search and follow-up programmes and NEO database (Hahn)

Despite the fact that our Asteroid search programmes (ODAS, UDAS, ADAS) have all finished their observing programmes, we still maintain the database of the obtained astrometric positions, and administer the orbits based on the monthly updates from the Minor Planet Center. These updates are incorporated into the web pages of the individual surveys located at:

http://earn.dlr.de/odas/

http://earn.dlr.de/udas/

http://dipastro.pd.astro.it/planets/adas/

respectively.

Physical properties and discovery circumstances of NEOs are available at http://earn.dlr.de/nea/ - a constantly updated database of all known NEOs (as announced and published by the Minor Planet Center - MPC) is maintained, providing a "home-page" for each asteroid. These pages contain the discovery circumstances, and all published data on the physical properties, including references. The database contains an update to the table of physical properties of NEOs published in the Asteroids III book, and is further updated on a regular basis.

More specifically, the database contains a clickable table with entries for more than 700 NEAs, and references to published and pre-published data, comprising some 940 entries.

1.5 Lunar chronology from asteroid impactor modeling (Marchi, Mottola)

We have derived a new method for determining the age of planetary and asteroidal surfaces. This method is based on the modelling of the impactor population that is responsible for cratering in the inner solar system, as derived by Bottke et al (2000). From this model it is possible to compute the impactor size distribution, the impactor velocity distribution, and the intrinsic collision probability with a planet. By applying an appropriate crater-scaling law, we derived the crater relative frequency-size distribution (or production function) for the Moon at the present epoch. We then derived the lunar chronology by calibrating the frequency-size distributions on lunar regions for which radiometric age determinations were available. Our chronology compares reasonably well with the standard lunar chronology derived by Neukum and Ivanov 1994, and has the advantage of being readily applicable to other planetary or asteroidal surfaces. In particular, we have computed the production function for Mercury, in preparation for the analysis of the results from the Messenger mission, and for (2867) Steins in preparation for the first Rosetta asteroid fly-by.

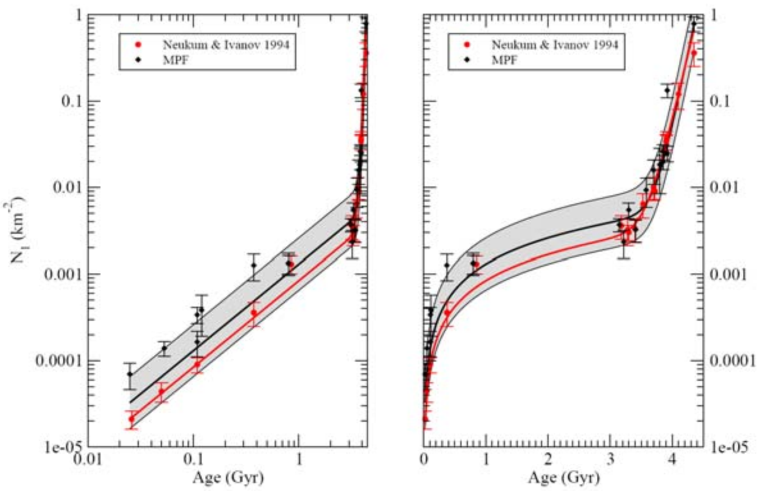

Fig. 2.5: Comparison of the Lunar chronology from our work (MPF) and from the work by Neukum and Ivanov (1994). The ages are reported both in a linear and in a logarithmic scale for clarity.

2 Comet science

2.1 Hybrid plasma simulation of comets (Gortsas, Motschmann, Kührt)

We have continued our investigations of the plasma environment of weak comets during 2008. A sophisticated fully 3D hybrid plasma software package, continuously developed since 2000 at the TU Braunschweig, has been used and adapted to study various aspects of the solar wind-comet interaction phenomena. Our studies on the impact of coma anisotropies to the plasma structures of comets have shown that spatial confinement quantitatively pushes the plasma boundaries towards the sun and increases their spatial extensions (Fig. 3.1). In addition, spatial confinement of cometary activity can increase the mixing region of solar wind protons and cometary ions, thereby creating an additional transport channel of the magnetic field away from the magnetic barrier region. A manuscript on this subject has been accepted for publication by the journal Annales Geophysicae.

Gortsas gave several talks on this subject, namely at the 25th ESA's Rosetta Science Working Team Meeting in ESOC, Darmstadt, Germany, at the Oberseminar für Theoretische Physik at the TU Braunschweig, Germany, and at the meeting of the Comet Modeling Team, ISSI in Bern, Switzerland. In a subsequent project, we combined the water ice sublimation curve of comet 67P/Churyumov-Gerasimenko obtained from our novel thermal model to study in more detail the formation of plasma structures as the comet approaches the sun.

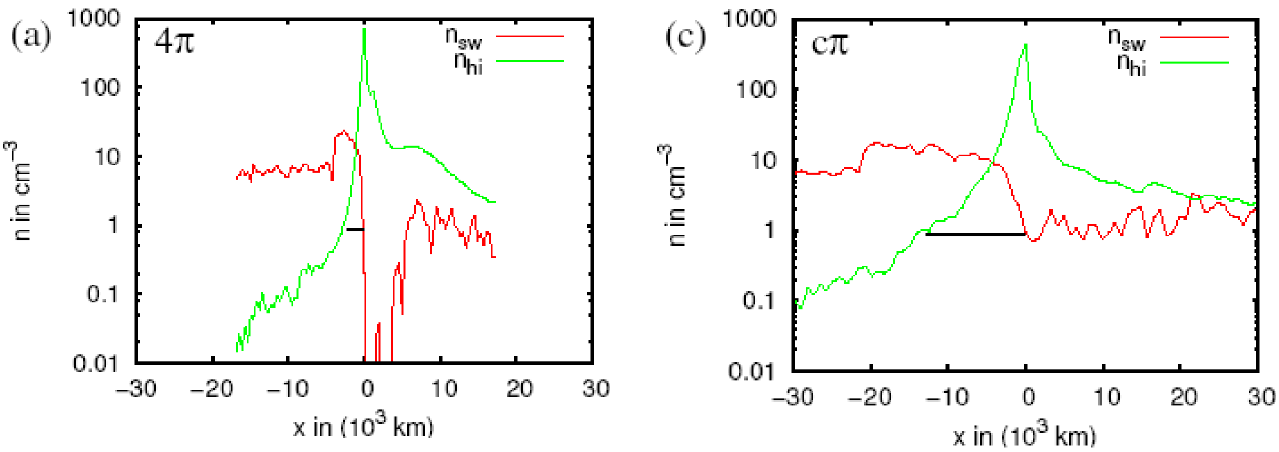

Fig. 3.1: Particle density plots of solar wind protons and cometary ions are shown for a spherically symmetric outgassing pattern (left) and a cone shape model (right). Increasing spatial confinement substantially increases the degree of mixing between the solar wind protons and the cometary ions. As a result, the ion composition boundary is only gradually developed in the cone shape model while it is clearly visible in the spherical symmetric case.

2.2 Moving boundary value problems of comets (Gortsas, Kührt, Motschmann)

In the last decades, observational as well as theoretical efforts have been devoted to addressing the question of the physical state and the sublimation mechanism of ices in comets. As part of the doctoral thesis of Gortsas a novel thermo-physical model has been under development since 2007 to address important, not yet fully understood, aspects of cometary activity. This novel approach enables the resolution of different velocities in surface erosion and thermal diffusion throughout the orbit of a comet.

From a mathematical point of view, these kinds of problem are referred to as moving-boundary value problems and constitute a special class of Stefan problems. After successfully fulfilling a series of numerical and physical tests, the validation period of the novel code has been completed. The model has then been applied to study cometary activity of different comets.

First, we applied the model on the target comet of ESA's Rosetta mission, 67P/Churuymov-Gerasimenko. This comet belongs to the Jupiter family of comets and thus to the class of short-period comets. Treating in a self-consistent and energy-conserving way surface erosion due to surface sublimation, solution of the Stefan problem of comets, leads to a substantially less heated nucleus. The model predicts a strong modification of the production curves of very volatile ices subliming from the interior and a small distance of the CO sublimation front from the surface (Fig. 3.2). A publication of the results is due to be submitted.

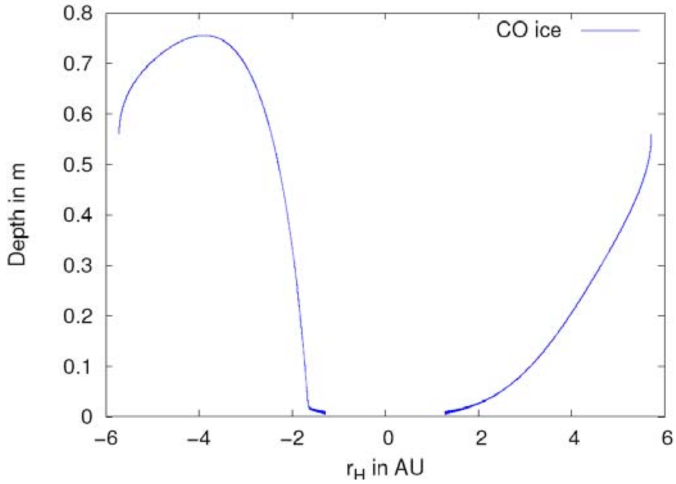

Fig. 3.2: The location of the CO ice front of comet 67P/Churuymov-Gerasimenko is plotted against heliocentric distance. Treating surface erosion due to surface sublimation in a self-consistent and energy conserving way has a strong impact on the thermal state of the nucleus and on the location of the CO front in particular. Close to perihelion CO ice comes very close to the surface leading to high sublimation rates.

As representative of long-period comets we applied the model to C/1995 O1 (Hale-Bopp). This comet has been widely studied both through observations and modeling. It has the best data base on production rates for a variety of ices. Our thermal model is able to reproduce the water ice and CO ice sublimation curve very well. A result not obtained so far by any other group. A publication on this subject is in preparation.

Gortsas and Kührt gave in the course of the last year several talks on this subject, namely at the Asteroids, Comets, and Meteors (ACM) conference in Baltimore, USA, and at a workshop on ices in the solar system in Oxnard, California, USA.

2.3 Interpretation of the Deep Impact experiment (de Niem, Kührt, Motschmann)

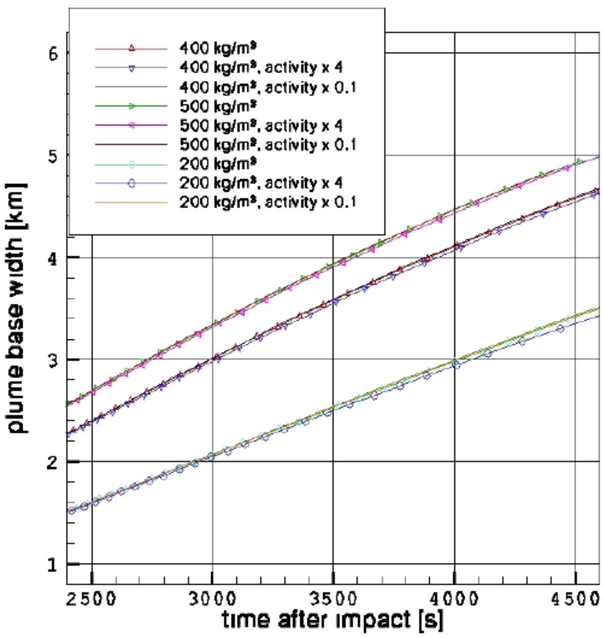

Fig. 3.3: Width of the base of the ejecta curtain vs. time for different gas activity levels and nucleus densities.

The Deep Impact mission in 2005 investigated the consequences of the impact of a ~370 kg spacecraft with the periodic comet 9P Tempel 1, with the goal to understand crater formation on small solar-system bodies and to analyse excavated cometary material. A bright dusty ejecta plume has been observed by cameras and spectrometers aboard the flyby spacecraft, by several other space-based instruments, e.g. OSIRIS NAC aboard Rosetta, as well as many terrestrial telescopes.

Interpretation of the results of the observations is controversial, mainly because the crater has not been observed. Previous models of the ejecta plume dynamics did not take interaction between coma gas and impact ejecta into account. A naive test-particle picture for non-gravitational forces would predict large accelerations on micron-sized dust grains, in contrast to the observation of a dense ejecta plume remaining close to the cometary surface for more than one hour. This motivated us to study the ejecta plume taking into account non-gravitational forces typical for comets. The reaction of ejected dust on the cometary outflow modifies these forces such that the resulting acceleration depends on the local mass density of ejected dust, requiring to obtain the mass density in the ejecta plume within such a model.

Results show only a minor influence of cometary outgassing on the dynamics near the base of the ejecta curtain, at least during the period of observation by the flyby spacecraft, and if cometary activity did not increase by far during the impact (Fig. 3.3). However, the mass density and amount of ejecta lifted to higher altitude above the surface during the first few hours of observation sensitively depends on non-gravitational forces. Our model also helps us to understand the optical depth of ejected mass remaining in orbit for several hours.

3 Impacts and planetary evolution

3.1 Chemical properties and evolution of impactors in the solar nebula (Tornow, Kupper, Kührt, Motschmann)

The collapse of a prestellar cloud core into a thick disk (solar nebula) surrounded by an envelope of the original cloud material and an accreting protostar in the centre triggered the birth of our solar system 4.6 years ago. During the solar nebula (SN) evolution, irregularly shaped nuclei have coagulated from dust grains. These grains have accreted icy mantles earlier in the quasi-stationary phase of the cloud core. In the inner SN the mantles evaporated completely causing a number of chemical reactions, whereas in the outer SN they stayed intact and were incorporated into the nuclei. The coagulated nuclei provided the material of the planetesimals which were the building blocks of our planets and minor bodies (impactors). We have derived parameters to classify the composition of volatiles incorporated into these building blocks by trying to find upper limits of abundances for the related volatile species. These parameters result from their radial distribution profiles and are given by the following characteristic chemical ratios:

- isotopic ratios for water and organic matter (OM): D/H_{H2O} and D/H_{OM},
- element ratios for the complete set of volatiles: C/O and N/C,
- molecule ratios: $CO_2/(H_2O+CO)$, NH_3/HCN, CH_3OH/CO, and CH_3OH/CH_3CN.

Our calculations of the abundance profiles consider deuterium chemistry and an interaction between gas and ice phase.

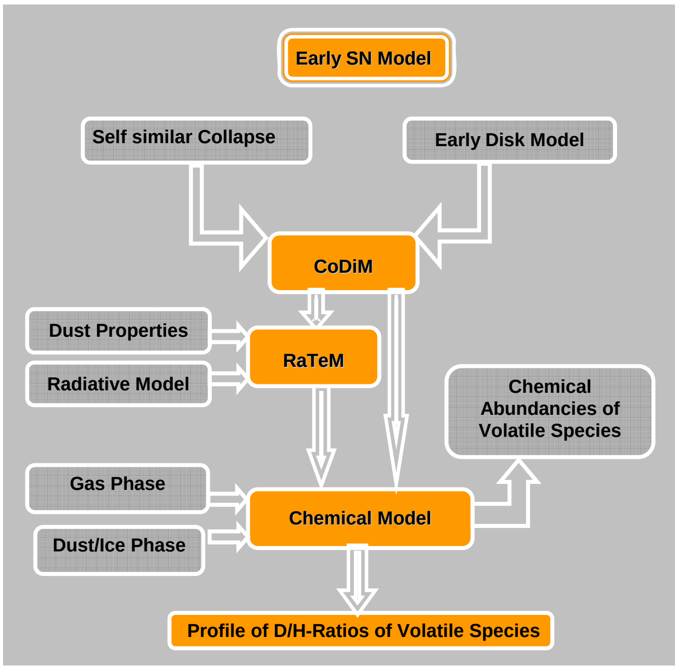

Fig. 4.1: Flowchart of the hydrodynamic-chemical model of the early solar nebula.

Table 4.1 lists main pre-biotic species, their reaction partners and products (Oro, 1995). In the fourth line, the abundances measured for Hale-Bopp are given. Most of these species (CO, CO_2, NH_3, H_2CO) are also contained in the icy mantles of prestellar dust grains. In an early model of the SN (see Fig. 4.1) we combined a selfsimilar collapse of a cloud core with an early disk formation. During the collapse the ratio of specific heat varies, i.e. $\gamma \in [0.95,1.66)$. Disk accretion assumes inviscid material and hydrostatic conditions along the z-axis. The resulting model (CoDiM) calculates the growth of the disk radius and the column densities (Fig. 4.2). The plots show how the formation time of the disk depends on the initial cloud mass.

In the more massive cloud the disk formation starts later but after ~ 1.5×10^5 y the disk radius is larger and its column density is higher than the one of the less massive cloud. The temperature is calculated from our radiation model (RaTeM) assuming a thermal gas-dust coupling TG = TD. The model considers an outer radiation field that is caused by ambient interstellar radiation. In the center, the radiation energy rate results from the accretion process of the protostar. The initial abundances for the two phases are adapted to a young molecular cloud. Since O or O_2 are not observed in these clouds, large amounts of H_2O and CO must be contained in the ice phase. Among the prebiotic molecules listed in Table 4.1. H_2CO is most sensitive to dust chemistry. Its inclusion leads to an increase of the gas phase abundance in the massive cloud (Fig. 4.3).

Table 4.1: Major prebiotic molecules and their abundance relative to water derived for comet Hale-Bopp.

prebiotic molecule	**CO**	**CO_2**	**H_2CO**	**NH_3**	**HCN**	**HC_3N**
reaction partner	H_2^+ catalyst	NH_3	P	H_2O+HCN	H_2O+NH_3	H_2O + Urea
reaction product	Fatty acids	Urea	Ribose	Amino Acids, Urea, Purines	Amino Acids, Purines	Pyrimidines
abundance	23	6	1.1	0.7	0.25	0.021

The production rate of N-bearing molecules is lower than that of O-bearing ones. For the less massive cloud this effect is more pronounced, since the inner core of the massive cloud is nearly 400 K hotter (upper and lower part of Fig. 4.4). We could not find any ice enrichment with H_2O compared to CO. Perhaps, an enrichment might happen in later disk phases and be related to the different CO and H_2O evaporation temperatures. Their amount is mainly determined by evaporation from the dust grains and less by the chemistry.

In order to calculate the ratios given above we need a backward transformation from Lagrange to Euler coordinates and method to compute the composition of the initial abundances during the icy mantle accretion in the quasi-stationary phase of the cloud core. Both procedures are under development.

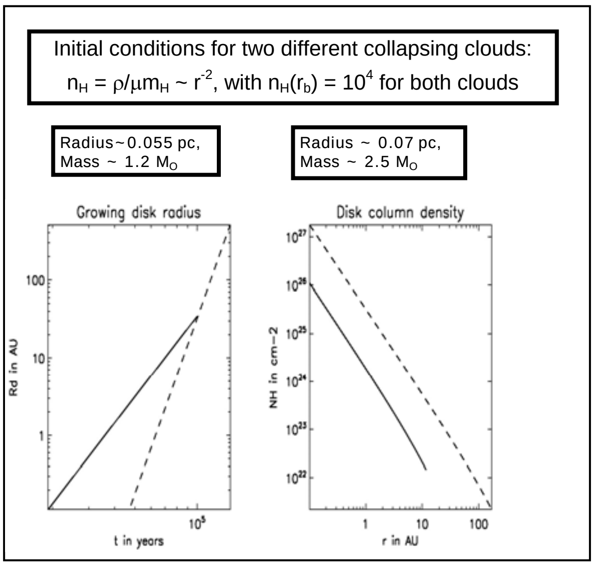

Fig. 4.2: Growth of disk radius for two clouds of different masses. Right: Final radial profile of the column density ascertainable with CoDiM. Solid line refers to a 1.2 MO, dashed line to a 2.5 MO cloud.

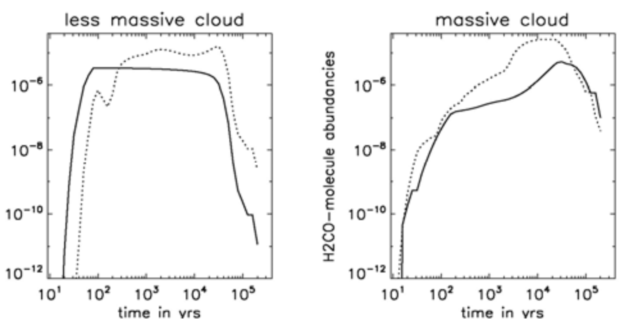

Fig. 4.3: Gas phase abundance of H_2CO in both star forming clouds. The dotted/solid lines illustrate the abundances calculated with/without dust chemistry.

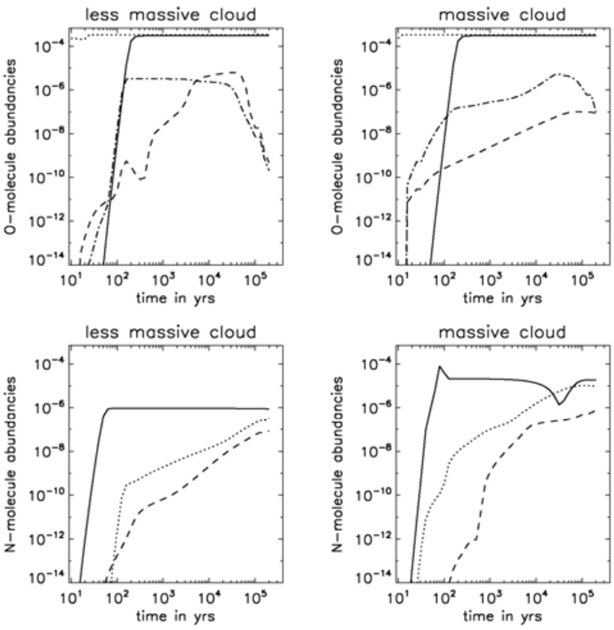

Fig. 4.4: Evolution of abundancies of prebiotic species from Tab. 1. Upper: Solid, dotted, dashed, dashed-dotted lines correspond to H_2O, CO, CO_2, and H_2CO, respectively. Lower: Solid, dotted, and dashed lines are related to NH_3, HCN, and HC_3N, respectively.

3.2 Impacts and chemical processes (de Niem, Motschmann, Kührt)

At the beginning of 2008, time was devoted to continuation of the study of chemical processes in an impact-generated vapor cloud. The main development consisted in the improvement of the equation of state (EOS) containing a fast chemical equilibrium solver for a mixture of molecular gases (de Niem, Kührt and Motschmann, 2008a). A separate program for the chemical equilibrium of gases and liquid solutions based on the SOLGASMIX algorithm, used as a post-processing tool applied after the hydrodynamic simulations with the developed EOS, has been extended to incorporate 3 different phases (de Niem, Kührt and Motschmann, 2008b). The hydrodynamics has been modeled in a simplified geometry, using a version of our multi-material hydrocode (de Niem, Kührt and Motschmann, 2007a, de Niem, Kührt and Motschmann, 2007b) adapted to spherical symmetry. Additional work for the implementation of the volume-of-fluid method in the radial direction in spherical symmetry has been completed. An extension to 2D spherical geometry is possible, but will require reformulation of the hydrodynamic algorithm in the polar direction, and inclusion the Coriolis force terms in the momentum equation.

3.3 Impact ejecta and two-fluid flow (de Niem)

The interaction of impact ejecta with a planetary atmosphere is one of the least understood aspects of planetary impacts. Although such processes are included in a hydrocode simulation in principle, the treatment by multi-material methods does not allow locally differing velocities of various material species (vapor, liquid droplets, solid particles) to be taken into account. Previously, most studies of ejecta transport through an atmosphere were limited to ballistic continuation or extracted statistics from passive Lagrangian tracers or directly from the Eulerian state variables of materials. The spatial scale of ejecta flow phenoma is much larger than the newly-forming crater.

In the context of the interaction of impact-related effects on a larger planetary scale, much more detail is required. A promising direction is to treat ejecta transport processes as two-phase or multi-phase flow, where – in contrast to multi-material hydrodynamics – each material species locally has a different velocity and satisfies a separate momentum balance. This includes the back-reaction of the ejecta flow onto the atmosphere most realistically where relaxation phenomena for the relative velocity between different species become important. The investigation of secondary heating and flow phenomena by the primary ejecta plume is one of the subjects of research devoted to these phenomena. A new algorithm in the area of two-fluid or two-phase flow is that by Pelanti and

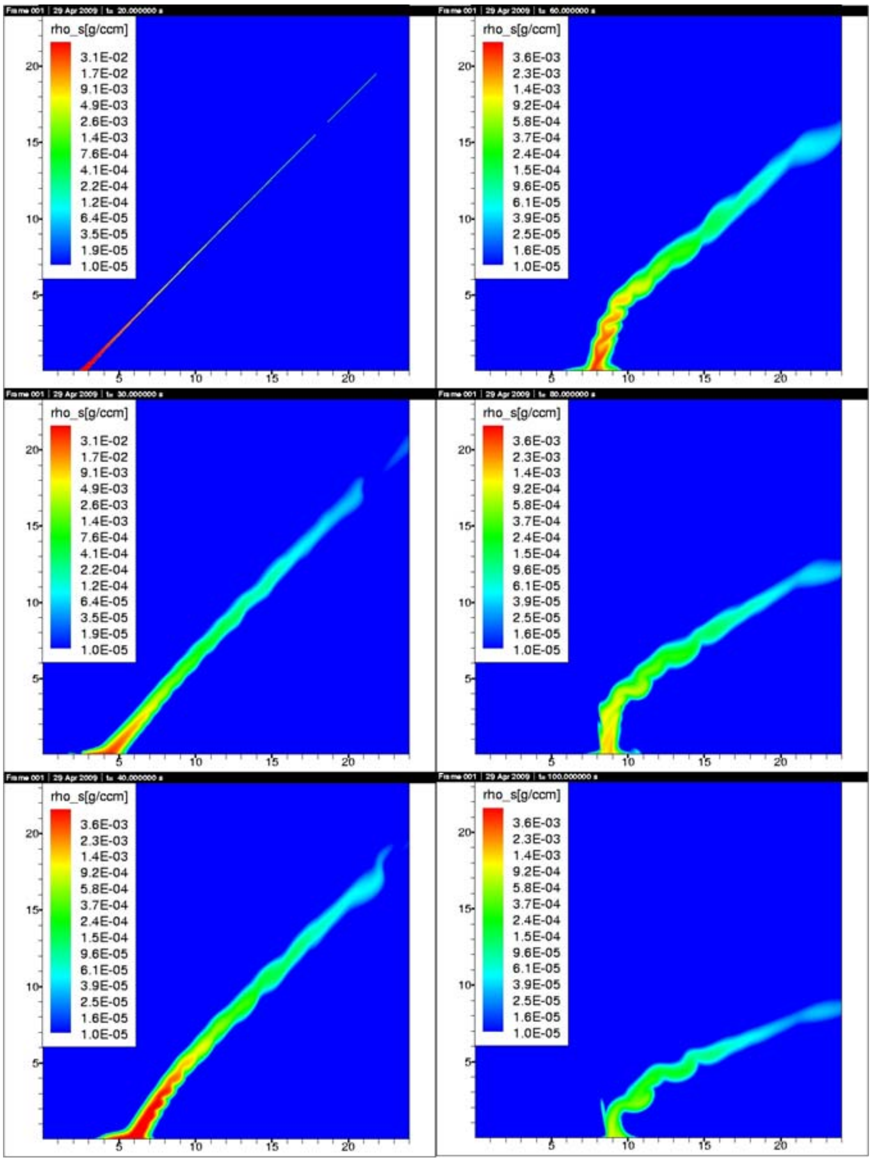

Fig. 4.5: Two-phase flow numerical simulation in cylindrical coordinates: Solid ejecta density for a 2.5 km diameter transient crater. *Left:* results 20 s, 30 s, 40 s. *Right*: 60 s, 80 s, 100 s after impact.

LeVeque (2006), previously used to model volcanic eruptions. We adapted this algorithm to cylindrical coordinates because the original version is restricted to Cartesian coordinates only. A new aspect of the numerical method – besides being a multi-dimensional strictly conservative Godunov-type method – is the Eulerian treatment of dispersed particle phase(s) or 'fluid(s)'. Previously, a dispersed particle phase had been treated by Lagrangian particle methods, necessitating compromises in particular for energy and momentum exchange because particles lived on a different grid to the gas.

As typical for impact processes, hypersonic flow phenomena with strong shocks and rarefactions develop, and rapid momentum exchange between gas and particle fluid(s) requires adequate numerical methods. So it has been necessary in our new implementation to replace the original Roe's Rieman solver for the gas phase used by Pelanti and LeVeque (2006) with the more stable HLLC (Harten-Lax-Vanleer-Contact) solver. Moreover, an alternative treatment of the source terms due to frictional momentum and energy transfer between species, and other terms of a geometrical nature in cylindrical coordinates has been developed. For initial tests, a semi-analytical model for the ejecta curtain supplied the initial data (de Niem, 2008). Fig. 4.5 shows snapshots of the evolution of the solid ejecta density in a two-fluid simulation of an event forming a 2.5 km diameter transient crater. In the future, initial and boundary conditions for our multi-fluid simulations will have to interface with realistic simulations of crater formation, taking into account material strength, parametrised in terms of the velocity and other variables of material reaching the so-called free surface or that present in an initial vapor plume. Some of the changes to the original algorithm were completed in 2008 but further improvement will be required, in particular of the modeling of heat transfer processes between particles and gas. Another important step will be the inclusion of adaptive mesh refinement into our algorithm in order to resolve the flow in and around an ejecta curtain.

4 Space missions

4.1 Rosetta-MUPUS (Knollenberg)

During 2008 MUPUS participated in the PHILAE Payload Checkout #8 and in the Rosetta asteroid Steins fly-by campaign (for calibration purposes only). In PC#8 a patch of the flight software to version V7.2 was uploaded. The main purpose of this update was the improvement of the scientific performance of the Anchor mode by increasing the accelerometer sampling frequency from 33 kHz to 47.8 kHz, which is the maximum speed that could be achieved with the degraded performance of the MUPUS ComDPU. In addition, a few minor bugs in the software were corrected. The software was then tested by executing three different flight control procedures. Nearly all MUPUS modes were tested in different configurations without encountering any problems. The successful execution of these procedures closed the necessary MUPUS "recovery action" activities and all open Non-Conformance Reports. During the fly-by of asteroid Steins MUPUS was continuously operated it its standard temperature measurement mode for 17 hours around closest approach, thereby acquiring 4600 science data packets from all MUPUS temperature sensors located on the PHILAE balcony (PEN, ANC-T and TM). The PEN data shown in Fig. 5.1 were derived using inflight calibration points only, and demonstrate the usefulness and consistency of this approach. The data show the slight increase of the balcony temperatures before the spacecraft flip at t=-0.5 h followed by a steep gradient as the Lander rotated into the Sun between t=-0.5 h to t=0 h.

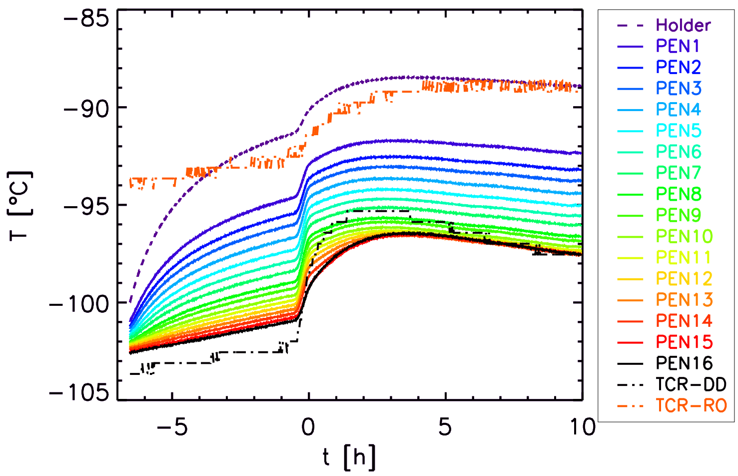

Fig. 5.1 MUPUS PEN temperatures recorded during the Steins fly-by.

In addition, the required input for the PHILAE Science objectives document was compiled and delivered to the Lead Scientists in August 2008.

4.2 Rosetta-SESAME (Seidensticker)

During September 2007 the flight software version FM-2 of the PHILAE experiment SESAME (Surface Electric Sounding and Acoustic Monitoring Experiment) was successfully uploaded. The major activity in 2008 was the use of this software for additional tests and calibration as well as the preparation for the next major software upgrade FM-3 in 2009.

The calibration comprised an interference test with the PHILAE flywheel that will operate in common with SESAME during the descent to the cometary surface in 2014. Whereas no impact could be seen on the DIM (Dust Impact Monitor) instrument, the other two instruments CASSE (Comet Acoustic Surface Sounding Experiment) and PP (Permittivity Probe) experienced considerable disturbances depending on the flywheel rotation rate. Nevertheless, the CASSE time series data still proved suitable for measuring the flywheel rotation rates (Fig. 5.2). The CASSE data allowed the flywheel team first to correct the rotation rate calibration and second, using additionally the rotation data from the orbiter reaction wheels, to determine the moment of inertia of the flywheel.

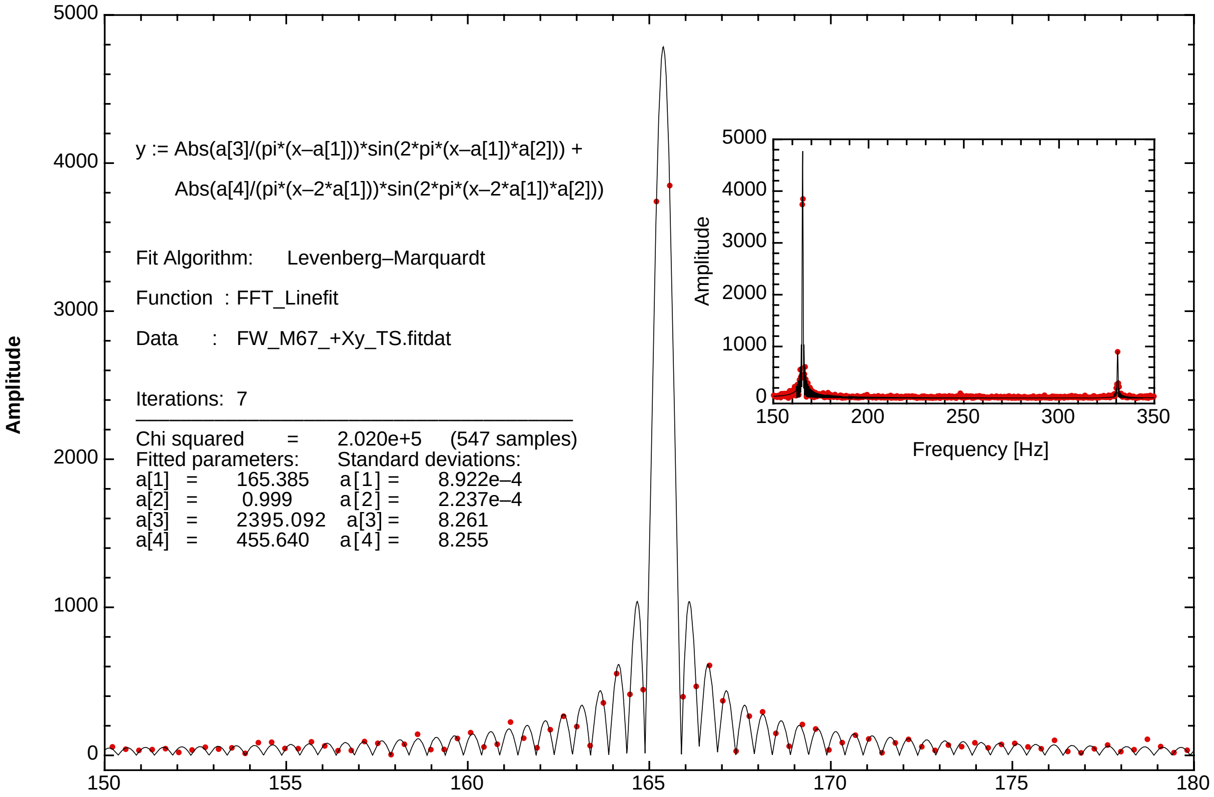

Fig. 5.2: The graph presents the fit to the fundamental vibration (dots) of the PHILAE flywheel. The insert depicts the fitted frequency range (fundamental frequency and second harmonic) of the time series. The equation used for fitting and the fitted parameters are listed in the left part of graph.

The CASSE acoustic sensors in the soles of the PHILAE landing gear are monitored with temperature sensors in order to adjust the sensitivity calibration with temperature. With proper calibration and modeling these temperature sensors can also be used to measure the cometary surface temperature. Due to a manufacturing problem the temperature measuring range has been shifted to higher temperatures starting at about -105 °C. A smart method was developed for flight software FM-2 to measure lower temperatures (in fact voltages). Several PHILAE operation phases during 2008 and the Rosetta Thermal Characterization 2 activity in February 2009 were used to measure temperatures with different settings using the old and the new method in order to test and calibrate the new method for flight software version FM-3.

Fig. 5.3 depicts the voltages measured for four channels in two feet during the second slew of the Rosetta spacecraft within the Rosetta Thermal Characterization 2 activity, when the sun illuminated all soles starting at about 20 min after the SESAME procedure was launched. The temperature related voltage U(t) increase was fitted to the empirical function

$$U(t) = U_0 + \Delta U * [1 - \exp((-t/\tau)] + a * U(TPCB) \quad (5.1)$$

U(TPCB) is the voltage measured on the CASSE PCB.

It should be noted that the raw temperature data (voltages) increased also for the first 20 minutes (soles still in shadow) due to a not sufficiently compensated measuring circuit on the CASSE PCB. This can be accounted for in the calibration process and the new method should now allow temperature measurements down to about -160 °C and with proper modeling also the determination of the cometary surface temperature.

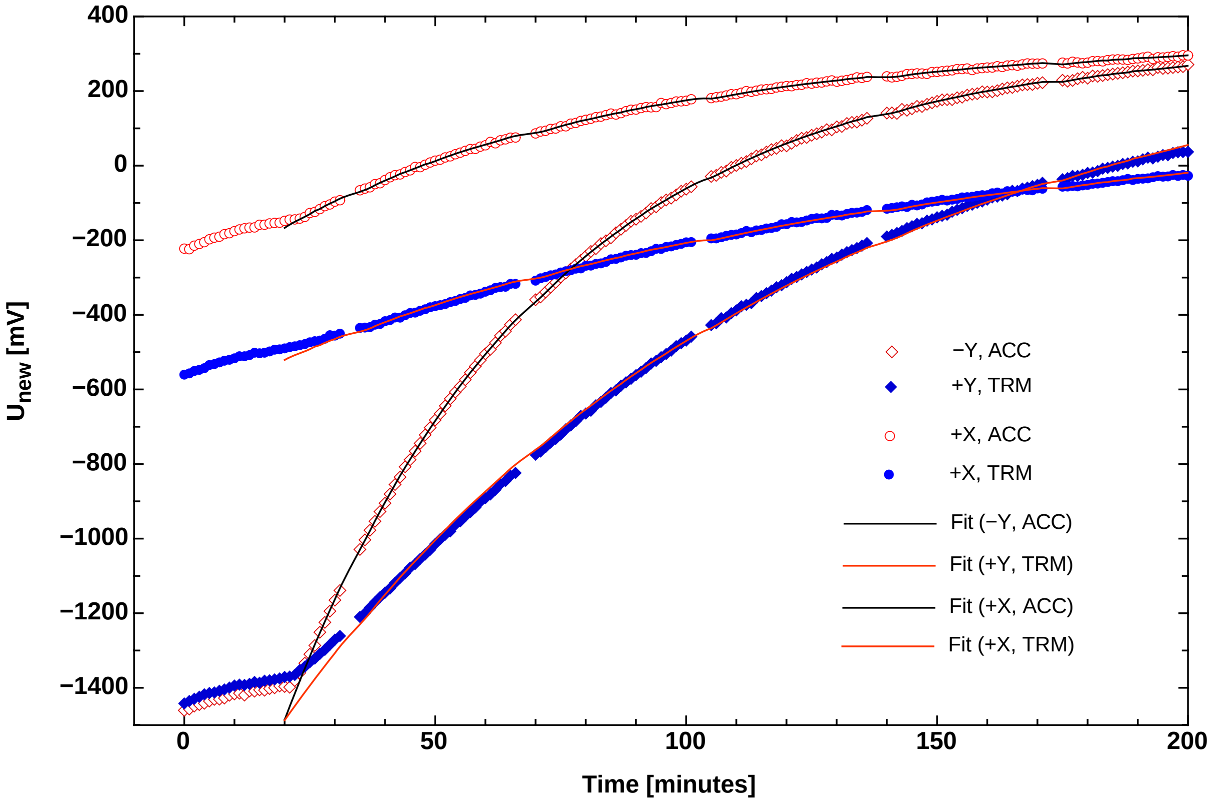

Fig. 5.3: Raw temperature data (voltages of sole temperature channels) versus time after start of the SESAME procedure E3. The curves are the regression results according to equation (5.1).

4.3 Rosetta-ROLIS (Mottola)

ROLIS is a miniature CCD imager developed and built at DLR, Berlin. It is located on the balcony of the Rosetta Philae Lander and oriented in a downward-looking direction. From this position ROLIS can observe a region of about 30x30 cm of the nucleus surface located below the lander with a spatial sampling of 0.3 mm/pixel. In order to illuminate the field to be imaged, ROLIS incorporates four independent arrays of light emitting diodes (LEDs) irradiating through the visible and near IR, in spectral bands centered at about 470, 530, 640 and 870 nm, respectively, and with a FWHM of 10 about 100 nm. ROLIS will also operate during the descent phase, acquiring images of the landing site and its vicinity shortly before touch-down.

During 2008 the ROLIS team participated to a number of scheduled in-flight test campaigns, during which the health of the instrument was thoroughly checked. Furthermore, detailed acquisition sequences for the descent and landing phases were designed and tested.

4.4 BepiColombo-MERTIS radiometer (Knollenberg, Solbrig)

During 2008 the MERTIS (Mercury Infrared Thermal Imaging Spectrometer) radiometer design for the Demonstrator Model was finalised. Five detector units, each comprising of a customized 2x15 elements thermopile double line array with integrated spectrometer slit (see Fig. 5.4) and assembled into a dedicated housing with attached interface flexboard were manufactured by IPHT Jena and delivered to DLR for testing. Measurements of the detector characteristics under vacuum resulted in a detectivity at 25°C of about D*=1.3 10^9 cm $Hz^{1/2}$ W^{-1}, thereby outperforming the design goal by 30%, an expected sensitivity decrease with temperature of -0.4%/K, and a time constant of 330 ms. The detectors were tested under thermal vacuum conditions between -50°C and +50°C and meet the MERTIS requirements. Furthermore, it has been demonstrated that the stringent positioning requirements (< 10 µm) required for the optical alignment could be met.

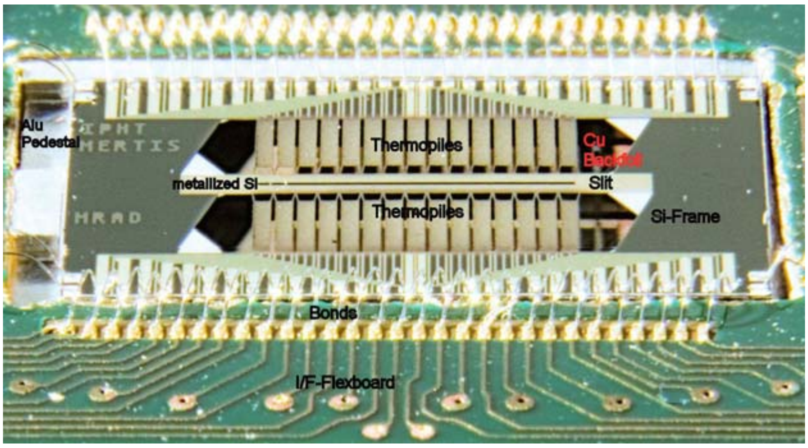

Fig. 5.4: MERTIS radiometer detector chip of size 8x5 mm with integrated spectrometer slit and electrical connections to the interface flexboard.

In addition, a low noise front end electronics together with the necessary EGSE was designed, fabricated and the performance of the FEE was tested standalone and together with the radiometer detector. It could be shown that the integrated system noise of detector and front end electronics is less than 80 nV, again meeting the design goal of 100 nV. An important step to qualify the used commercial high resolution ADC of type LTC2449 for space flight was made in conducting a Single Event Effects test at ESA's Heavy Ion Facility at the accelerator of Louvain-la-Neuve in Brussels. The main outcome of this test was the determined latch-up threshold of 14 MeV cm^2 mg^{-1} with a saturation cross section of $2*10^{-3}$ cm^2/device. These numbers make the part suitable for BepiColombo provided that additional latch-up protection circuitry is implemented.

4.5 DAWN (Mottola)

Dawn is a NASA Discovery mission whose goal is to achieve an understanding of the conditions and processes at the Solar System's earliest epoch. Dawn will investigate the internal structure, density and homogeneity of two complementary protoplanets: 1 Ceres and 4 Vesta, that have remained intact since their formation, by measuring their mass, shape, volume, and spin rate with imagery and gravity. It will record their elemental and mineral compositions and will provide context for the meteorites that have come from these bodies.

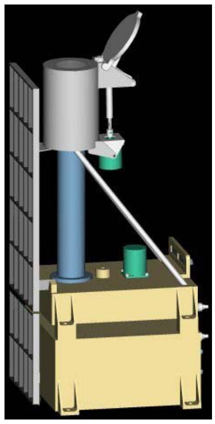

Fig. 5.5: DAWN Framing Camera

Dawn will determine their bombardment and tectonic history, and use gravity and spin-state data to limit the size of any metallic core, and infrared and gamma ray spectrometry to search for water-bearing minerals. The mission uses solar-powered ion engines to deliver the spacecraft first to Vesta, to descend to the high-resolution mapping orbit, and, after a stay of about 7 months, to leave for Ceres, where it stays for 5 months. The spacecraft carries a redundant framing camera, a visible-NIR mapping spectrometer and a gamma ray/neutron spectrometer. DLR contributes to the mission by providing the CCD and front-end electronics of the framing camera. Furthermore, it is represented in the mission Science Team by two co-investigators.

After the successful launch on Sep. 27, 2007, a number of thorough tests have demonstrated the excellent health of the spacecraft and of the payload. During 2008 the activities have concentrated on the planning and implementation of the sequences needed for the next major milestone of the mission: the Mars Gravity Assist Manoeuvre, scheduled for Feb. 2009. This Manoeuvre is fundamental for changing the inclination of the orbital plane of the spacecraft, and put it on a route that intercepts Vesta.

4.6 AsteroidFinder (Kührt, Mottola, Hahn, Harris, Drentschew)

The German Aerospace Center (DLR) is pursuing a program of space-mission development based on a standard satellite bus (SSB), suitable for missions and applications of different types. This project has the strategic objective of establishing within DLR the capabilities and facilities necessary for satellite development and operations.

Our proposed mission, AsteroidFinder, was selected as the first mission to use the SSB.

The primary goal of the mission is to search for Inner-Earth Objects (IEOs), a particular class of Earth-approaching asteroids with orbits lying completely within the Earth's orbit. Due to their proximity on the sky to the Sun, IEOs are extremely difficult to discover from the ground. By the end of September nearly 5700 Near Earth Objects (NEOs) have been discovered, of which only 9 are IEOs. Simulations have shown that AsteroidFinder may detect some dozens of IEOs in an operational period of two years and be able to characterize the population in terms of total number, orbit and size distribution.

A secondary goal of the mission is to demonstrate that the detection of cm-sized space debris is in principle feasible with a satellite-based optical instrument.

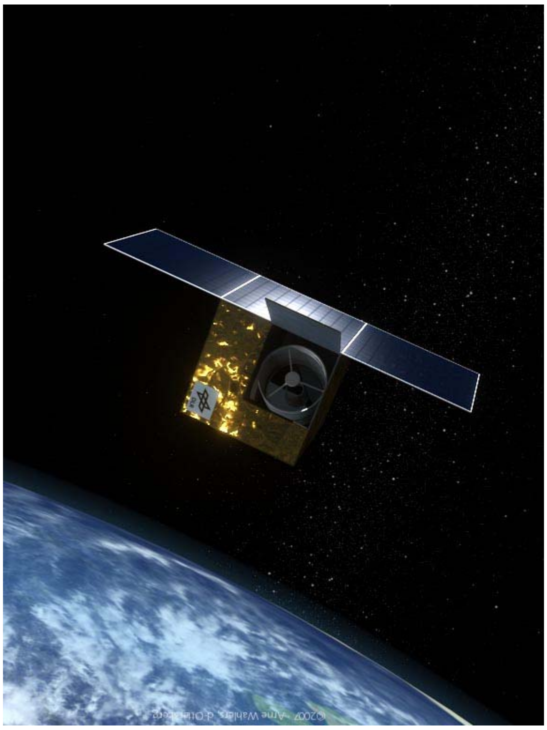

Fig. 5.6: AsteroidFinder

To achieve its goals the mission has to detect small objects of various surface albedos, including extremely dark ones, near the direction of the Sun. This requires a limiting sensitivity of > 18.5 mag. Long exposure times (~ 1 min) and, therefore, a high pointing stability rate (~ 1 arcsec/s) are needed. Since this requirement is beyond the capability of the bus an order- of-magnitude improvement must be achieved at payload level. Stray light from the Sun, Earth and other objects must be effectively suppressed.

The baseline payload of the AsteroidFinder mission consists of two main elements: the telescope and the electronic unit (EU). The EU contains the focal-plane array (detector), the corresponding front-end electronics, the digital-processing unit and power-supply unit. The data produced in the EU are stored in the mass memory of the satellite. The thermal control and telemetry are provided by the spacecraft bus.

In 2008 a Phase-A study, in which several DLR institutes participated, successfully confirmed the feasibility of the project. Scientists in our Department were responsible for payload project management, for the scientific background of the mission, the definition of the scientific requirements, and for the observation strategy.

4.7 HP^3 (Knollenberg)

In 2008 the work on HP^3 (Heat Flow and Physical Properties Probe) was continued in the framework of the Humboldt Lander for the ESA ExoMars mission. The mole payload compartment (MPC) was redesigned, now using an Aluminum hull with integrated copper foil heaters enabling the use of the MPC as a thermal conductivity probe. This concept was successfully tested under simulated Martian conditions during a test campaign conducted in the space simulation chamber of the DLR-Institute for Space Systems in November 2008. During this campaign we also investigated whether the tether with integrated sensors is able to measure the predicted temperature gradient without direct contact to the borehole walls with sufficient accuracy. The result was that the temperature differences between tether and reference sensors under equilibrium conditions were less than 0.2 K. These numbers meet the requirements of HP^3 on ExoMars but repeated calibration measurements have indicated a stability problem of the tether sensors, an issue which needs further investigation. In December 2008 a preliminary design review of HP^3 was conducted by ESA with the result that the "technology readiness level" (TRL) achieved was determined to be TRL=4.8, just short of the development goal of TRL=5, implying that a "Delta PDR" will be necessary.

5 Technology transfer project Firewatch (Kührt, Knollenberg)

Fig. 6.1: Night fire experiment

Our knowledge of camera development and image processing has been applied to a successful long-term technology transfer project to develop a prototype of an Autonomous Forest Fire Detection System FIREWATCH. The aim of the system is to detect smoke clouds arising from forest fires up to a distance of 10 km within 8 minutes from outlook towers. The complex system consists of advanced hardware and sophisticated image processing software based on IDL. The operating camera was originally developed for space applications. The know-how was licensed to IQ wireless GmbH in Berlin which established FIREWATCH on the market. In 2008 the installation of systems in Germany was nearly completed. Meanwhile, about 160 systems are operational and keep the forests under surveillance.

In 2008 improvements were made to meet the operation conditions in other countries. Field experiments were organized to collect night fire data. On this basis a new software package was developed to detect fires independent of the time of day.

6 Appendix

6.1 Scientific publications in refereed journals and books (submitted or published 2008)

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6.4 Publications in the popular literature and public outreach

A. W. Harris

Invited lectures:

- Inst. Raumfahrtsysteme, Univ. Stuttgart, 19.6.2008, 27.11.2008.
- Klaus Tschira Stiftung/University of Heidelberg, Studio der Villa Bosch, "Einschläge von Asteroiden und Kometen – Gefahr für die Erde?", 13.11.2008.
- Technical University of Dresden, 12.6.2008, 11.12.2008.

Outreach to schools:

- Interview with students of the Astronomy Group of the Immanuel Kant Gymnasium, Rüsselsheim.
  http://www.astro.studiocd.de/typo3/

TV appearances (selection):

- 3Sat, *Nano*, 31.03.2008.
- Phoenix, *Armageddon – der Einschlag* (*Super Comet – After the Impact*), ZDF-Produktion, 11.8.2008, 12.08.2008.

http://www.zdf.de/ZDFde/inhalt/7/0,1872,7002599,00.html?dr=1

- SWR/WDR/BR-alpha, *Planet Wissen*, 18.12.2008. http://www.planet-wissen.de/pw/Artikel,,,,,,,5C85F8B652DF0F4FE0440003BA5E08BCTV,,,,,,,,,,,,,,,,.html

Radio:

- Deutschlandradio Kultur, *Forschung und Gesellschaft*, 28.8.2008. http://www.dradio.de/download/90034/
- SWR 2 Impuls, *Deep Impact*, 18.11.2008 http://www.swr.de/swr2/programm/sendungen/impuls/id=1853902/did=4204292/pv=mplayer/vv=big/nid=1853902/uiinp8/index.html

Consultant for articles on asteroids and planetary phenomena (selection):

- Die Vagabunden im Sonnensystem, Bild der Wissenschaft, März, 2008. http://www.bild-der-wissenschaft.de/bdw/bdwlive/heftarchiv/index2.php?object_id=31355052
- Europa verschläft den Weltuntergang, Spiegel Online, 14.11.2008 http://www.spiegel.de/wissenschaft/weltall/0,1518,590379,00.html
- Die Bombe aus dem All, Wunderwelt Wissen, Dec. 2008.

6.5 Space mission responsibilities

G. Hahn

- Member of the study team for the DLR mission "Asteroid Finder", a space telescope to search for inner-Earth asteroids (IEOs).

A. W. Harris

- Chairman, International Astronautical Federation Technical Committee on Near-Earth Objects.
- Member, Spitzer Space Telescope Cycle 5 Time Allocation Committee.
- Member of the study team for the DLR proposal "ASTEX", an in-situ sample analysis mission to two near-Earth asteroids.
- Member of the study team for the DLR mission "Asteroid Finder", a space telescope to search for inner-Earth asteroids (IEOs).

J. Knollenberg

- Project manager and Co-I of the Rosetta lander experiment MUPUS.
- Co-I of OSIRIS on Rosetta.
- Co-I of MERTIS on BepiColombo.
- Member of the science team on HP^3 for ExoMars.

E. Kührt

- Project Manager of the DLR AsteroidFinder mission, Phase A.
- DLR Project Manager of Rosetta Instruments, Phase E.
- CoI of the experiments on the Rosetta mission VIRTIS, OSIRIS and RPC.
- CoI of the ROMA experiment on the Rosetta Lander.
- Team member of the Framing Camera experiment on the Dawn mission.
- Co-Investigator BepiColombo-MERTIS.

S. Mottola

- PI of the ROLIS experiment on the Rosetta Lander.
- PI of the DLR AsteroidFinder mission.
- Co-I of the NASA Dawn Discovery mission to Vesta and Ceres.
- Co-I of the VIRTIS experiment on the Rosetta mission.
- Co-I of the CIVA experiment on the Rosetta Lander.
- Associated Scientist to the OSIRIS experiment on the Rosetta mission.
- Team member of the FC experiment on the Dawn mission.

K. Seidensticker

- PI of the Rosetta lander experiment SESAME.

6.6 Other events and activities

G. Hahn

- Participation as lecturer and jury member at the 2008 Summer School at Alpbach, Austria. (22-31 July).
- Speaker at the "Lange Nacht der Wissenschaft 2008" 14th June.
- Invited Speaker at 250th Birthday Celebration of Wilhelm Olbers in Bremen.

A. W. Harris

- Referee for papers submitted to: Astrophysical Journal Letters; Icarus.
- Invited Key-Speaker at the Eurovision TV Summit (session "Science and Education"),

  Lucerne, Switzerland, May 2008.

  http://www.eurovisiontvsummit.com/en/speakers.php

E. Kührt

- Participation as lecturer at the 2008 Summer School at Alpbach, Austria.
- Talk at 45. Session of the Technical Subcommittee of the Committee on Peaceful Uses of Outer Space of the United Nations, Wien, February 2008.

6.7 Funding

The following funding sources were available for our work:

Programmatic funding from DLR

- Project "Rosetta Instruments, Phase E"
- Project "Asteroids and Comets"
- Project "DAWN"
- Project "Exomars HP^3"
- Project "BepiColombo (MERTIS)"
- TM contract "FIREWATCH, night detection"

Third party funding

- HGF Alliance "Planetary Evolution and Life"
- Study of the DLR proposal "ASTEX", an in-situ sample analysis mission to two near-Earth asteroids ("ASTEX")