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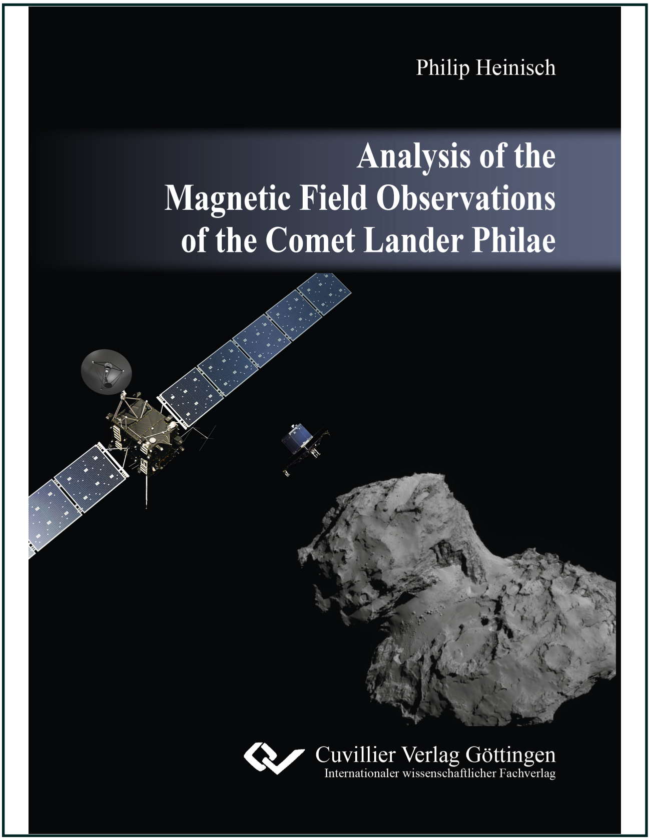
Analysis of the Magnetic Field Observations of the Comet Lander Philae



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Kurzfassung

Am 12. November 2014 wurde die Landeeinheit Philae von der Rosetta Sonde abgesetzt und landete auf dem Kometen 67P/Churyumov-Gerasimenko. Beide Raumfahrzeuge erreichten den Kometen im August 2014 als Teil der ESA Rosetta Mission. Nach dem ersten Aufsetzen versagte das Ankersystem, der Lander prallte ab und kam nach drei weiteren Oberflächenkontakten unter einem Kliff zum Liegen. Durch die schlechten Beleuchtungsverhältnisse war nicht ausreichend Solarenergie verfügbar um die Akkus wie geplant aufzuladen. Daher brach der Funkkontakt mit dem Lander am 15. November um 00:36 UTC ab. Rosetta blieb für weitere zwei Jahre im Orbit um die Entwicklung des Kometen und der Plasmaumgebung während und nach dem Perihel-Durchgang zu untersuchen. Nach drei Verlängerungen endete die Rosetta Mission offiziell im September 2016 mit dem Aufsetzen des Orbiters auf dem Kometen.

Diese Arbeit behandelt den Philae Lander, speziell die Messungen mit dem ROMAP Magnetometer. Während des Abstiegs und nach der Landung waren sowohl das Orbiter Magnetometer RPC-MAG als auch das ROMAP Magnetometer gleichzeitig aktiv und ermöglichten simultane Zweipunkt - Messungen. Diese erlaubten es, die Frequenz, Ausbreitungsrichtung und Geschwindigkeit der oberflächennahen niederfrequenten "singing comet" Plasmawellen zu analysieren. Die Ergebnisse zeigten, dass sich diese Wellen primär aus der Richtung des Nucleus zur Sonne mit einer mittleren Phasengeschwindigkeit von ~ 5.3 km/s und einer Wellenlänge von ~ 660 km ausbreiten. Der typische Frequenzbereich ist 5 mHz bis 50 mHz.

Die gleichzeitigen Messungen wurden darüber hinaus verwendet, um die Dynamik und Orientierung des Philae Landers während des Abstiegs und des weiteren Flugs nach dem Abprallen zu bestimmen. Mit diesen Ergebnissen war es möglich, einen neuen Grenzwert von 0.9 nT für den Beitrag einer möglichen Oberflächenmagnetisierung zum gemessenen Magnetfeld abzuleiten. Daher wurde im Rahmen dieser Arbeit die bisherige Abschätzung der Magnetisierung aktualisiert. Basierend auf dem rekonstruierten Flug nach dem Abprallen war es auch möglich, die bisherige räumliche Auflösung der bestimmten Magnetisierung bis auf die Größenordnung einzelner Aggregate im Bereich von ~ 5 cm zu verbessern. Für solche Partikel bedeutet die Grenze von 0.9 nT ein maximales spezifisches magnetisches Moment von $\sim 5 \cdot 10^{-5}$ Am^2/kg. Basierend auf verfügbaren Modellen zur Magnetisierung und abhängig von der Entstehungsgeschichte ermöglicht die feinere räumliche Auflösung, die Stärke des Hintergrundmagnetfelds im solaren Nebel während der Entstehung des Kometen auf unter 4 μT einzugrenzen.

Durch eine Kombination der Flugrekonstruktion mit Bildern des Kamerasystems an Bord des Orbiters konnten mögliche Flugbahnen nach dem Abprallen bestimmt werden. Dies ermöglichte es, die Energiebilanz des Flugs zu bestimmen. Diese Analyse zeigte, dass bereits ein Druck von ~ 100 Pa ausreichend ist, um das Oberflächenmaterial des Kometen bis zu einer Tiefe von ~ 20 cm zu komprimieren. Unter Berücksichtigung der Fehler zeigte die Druckfestigkeit nur eine geringe Abhängigkeit vom Ort und es ergab sich eine maximale obere Schranke von ~ 800 Pa.

1 Introduction

Comets have always fascinated mankind and sparked scientific interest. Because their relatively fast movement across the sky is apparent even with basic instruments, they were one of the first objects used to experimentally study the motion of celestial bodies. Most notably comet C/1680 V1 Kirch passing the earth at 0.42 AU in 1680 spurred interest in finding a mathematical base for Kepler's laws of planetary motion (Lancaster-Brown 1985). Isaac Newton succeeded in calculating the orbit of comet Kirch and later published an extended version of his mathematical framework in 1687 (Newton 1687), revolutionizing modern physics. Edmond Halley, who arranged for the publication of Newtons work, later used the results himself to calculate the orbit of comet 1P/Halley (Halley 1705). This comet became the target of five different satellites (the so called Halley Armada) during its apparition 281 years later in 1986. These space probes were launched in a coordinated effort by the Soviets, ESA and Japan to perform flybys and study 1P/Halley in situ (e.g. Grewing et al. 1988). Additionally NASA intended to support observations with two space shuttle missions. Being the first time close-up images of a small solar system object were taken by space probes, it marked a great technological and scientific achievement. The success of the Halley Armada demonstrated the capabilities of unmanned space probes and the scientific importance of in situ observations. Shortly after ESA and NASA started planning possible follow-up missions. After several delays and unsuccessful attempts to secure the necessary funding, ESA finally approved the Rosetta mission in 1993 (Glassmeier et al. 2007a). Consisting of the Rosetta orbiter and the Philae lander and being supported by NASA, the space probes were launched in March 2004 aboard an Ariane 5 rocket. After arriving at the target comet 67P/Churyumov–Gerasimenko (in the following shortened to 67P) in 2014 and delivering the lander to the surface, the mission was successfully concluded in 2016 after several extensions. The Rosetta mission achieved several scientific and technological firsts. Most notably the in situ study of a comet around perihelion and the controlled landing of a space probe on a small solar system object.

In this thesis, the measurements returned by Philae after separation from the Rosetta orbiter on November 12, 2014 until radio contact was lost on November 15 are analyzed and put in context. The focus lies on the magnetic field observations provided by the ROMAP magnetometer (Auster et al. 2007) onboard Philae and the concurrent measurements of the orbiter magnetometer RPC-MAG (Glassmeier et al. 2007b). Based on these observations, the magnetic field in the plasma environment around the nucleus is characterized, and upper limits for the surface magnetization and compressive strength are derived. Additionally the magnetic measurements are used to reconstruct the lander dynamics and attitude and provide status information about the internal lander systems.

The second chapter provides an overview about the Rosetta mission, the Philae lander and comet 67P. Because of the importance for this study, the lander instrument ROMAP is described in detail. Chapter three gives an introduction to the cometary plasma environment and the typical accompanying magnetic field structures. One of the most striking magnetic features during the joint Rosetta and Philae mission in fall 2014 were low frequency magnetic waves (Richter et al. 2015, 2016). These newly detected waves were analyzed using concurrent two-point observations from Philae on the surface and Rosetta in orbit above the comet. At the end of the chapter it is explained, how magnetic field measurements can also be used to determine the attitude of Philae and derive the lander dynamics.

In the following, the magnetic field observations already analyzed in the previous chapter are combined with images and status information from the solar arrays and radio communication equipment to determine in detail what happened to Philae during its flight above the surface of 67P. In addition to a description of the descent dynamics and the attitude during rebound, the approximate coordinates for the surface contacts are estimated. It will be shown, that Philae did not change attitude between the end of the initial measurements in 2014 and the discovery of the lander on Rosetta images in 2016.

The flight reconstruction in conjunction with the magnetic field analysis performed in chapter three is used in chapter five to derive an upper limit for the surface magnetization of the comet. While the magnetization has been investigated before, this work makes use of the comprehensive understanding of the circumstances of Philae's descent and landing, gained after the end of the mission, to revisit the magnetic properties.

In chapter six the previous results were combined to approximate the descent and rebound trajectory of the Philae lander and use this information to derive the compressive strength of the surface material from the different surface contacts and scratches created during the final touchdown. One of the primary objectives of the lander mission was to measure the surface properties (such as the compressive strength) of 67P in situ to determine what comets are made of and where they formed. While the growth of kilometer-sized planetesimals to larger planet-sized objects in the early Solar System is well understood, it is still under debate how smaller objects formed out of sub-decimeter-sized dust aggregates (see Blum (2018) for a recent review). Because of their primitive nature, comets are the best candidates for planetesimals and possibly the sole small survivors of the planet-formation era (Davidsson et al. 2016). The mechanical strength of the cometary material strongly depends on the formation history and evolution of the nucleus (Blum et al. 2014). Thus, measurements of mechanical properties combined with already available laboratory results can be used to study the origin and evolution of comets and can thereby provide the missing link between protoplanetary dust and planets.

2 The Rosetta Mission

Rosetta was an ESA cornerstone mission to study the periodic comet 67P. It was launched on March 2, 2004 as part of ESA's Horizon 2000 program with support from NASA. The initial target for the Rosetta mission was comet 46P/Wirtanen, but due to uncertainties concerning the reliability of the Ariane 5 system, the launch was postponed and 67P selected as the new target (Ulamec et al. 2006). One of the major objectives of the mission was to deploy the Philae lander to allow scientific measurements on the surface. While the Rosetta spacecraft was managed by ESA, Philae was developed and build by a consortium headed by the German space agency DLR and the french CNES. In contrast to previous missions, Rosetta should not only collect data during short flybys, but be the first space probe to rendezvous with a comet and closely follow it for more than a year. After being the first man made craft to land on a comet, Philae was intended to take different measurements on the surface for several days.

2.1 Rosetta Overview

Figure 2.1 gives an overview of the trajectories of comet 67P and Rosetta during its mission. The spacecraft reached 67P shortly after it passed aphelion in August 2014 at a heliocentric distance of more than 3.6 AU, after a 31 month deep space hibernation phase. To match the speed of the comet Rosetta performed several gravity assist manoeuvres. Flying this trajectory required additional time, stretching the journey to about ten years. Using chemical boosters to accelerate instead, would have required prohibitively large fuel supplies. Electrical propulsion systems, while being capable of providing long term thrust with little fuel, are unsuitable for missions like Rosetta due to the limited electrical power budget.

In the outer solar systems at distances of more than 5.3 AU the generated solar power was only sufficient to supply basic survival heaters to keep the spacecraft from freezing. Hence, it was necessary to put Rosetta into a special hibernation mode during the cruise phase from 2011 until 2014 to conserve power. Before entering hibernation, Rosetta performed flybys of asteroids 2867 Steins and 21 Lutetia (Barucci et al. 2007). These flybys returned initial scientific results even during the cruise phase (Auster et al. 2010, Keller et al. 2010, Schulz 2010, Schulz et al. 2012, Richter et al. 2012) an allowed in-flight testing and calibration of both lander and orbiter instruments.

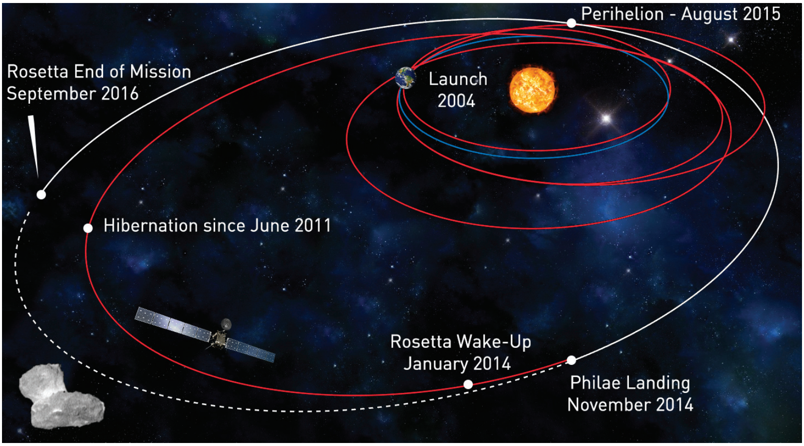

Figure 2.1: Illustration of the orbits of comet 67P (white), Rosetta (red) and the earth (blue) during the progression of the Rosetta mission (parts of this illustration were released by ESA under the Creative Commons Attribution Share Alike 3.0 license).

In November 2014, Rosetta deployed the Philae lander and the orbiter operations were primarily aimed at supporting the lander mission for several weeks (Ashman et al. 2016). Before deployment, concurrent observations from different Rosetta instruments were used to map the comet in preparation of the landing site selection process (Jurado et al. 2016). Afterwards, the antennas onboard Rosetta had to be pointed at the landing site of Philae to communicate with the lander, leading to significant pointing constraints. As the exact position of Philae after landing was unknown, the area around the suspected position was photographed from orbit in an attempt to locate the lander. During this time Rosetta remained in a terminator orbit close to the nucleus, at a mean distance of 38 km. A terminator orbit is defined as a trajectory above the division between the illuminated and dark hemispheres. In early 2015, Rosetta started to perform close flybys at distances going down to 6 km. Closer to perihelion in the spring of 2015, stronger insolation increased the activity of 67P causing more dust to be ejected from the surface. These particles interfered with the star tracker cameras (Buemi et al. 2000) used by Rosetta to automatically determine its position and attitude. The effect of the dust on the tracking cameras was worse than expected and the cometocentric distance had to be increased significantly to ensure safe operations.

To study different regions of the plasma environment (Volwerk et al. 2018), Rosetta performed excursions with significantly increased cometocentric distance (> 1500 km). After several extensions, the Rosetta mission ended on September 30, 2016 with the controlled impact of the Rosetta probe on the comet. During its two years around 67P, Rosetta collected enough scientific measurements that a comprehensive analysis will take years (Barthelemy et al. 2018).

2.2 Overview of the Philae Landing

On November 12, 2014 at 08:35 UTC Philae was detached from Rosetta and touched down at 15:35 UTC, after a controlled descent. After separation, Philae descended on a ballistic trajectory towards the surface, landing 7 h later. This first part of the Philae operations, known as separation, descent and landing (SDL), was executed as planned and Philae operated flawlessly. During the descent in addition to a farewell and several descent images (Mottola et al. 2015), only ranging and magnetic field measurements were performed to conserve telemetry bandwidth and power. Accelerometers in the feet were automatically triggered during the initial surface contact, to measure the shock of the touchdown. After touchdown, Philae was intended to automatically anchor itself to the surface using harpoons and ice screws, while a cold gas thruster should have provided hold-down thrust (see section 2.5.1 for a description of the lander subsystems). All these systems failed, causing Philae to rebound (Ulamec et al. 2016). Nevertheless the touchdown signal automatically started the initial sequences of preprogrammed measurements called the first science sequence (FSS). These observations were intended to be performed after Philae was stationary and secured to the surface. As the lander was instead in-flight, the scientific return of these initial FSS measurements was limited.

After three bounces the still operational lander came to a final stop approximately 1.3 km away from the intended landing site (for a detailed description of the trajectory see section 4). The regular sequence of measurements was remotely terminated and instead replaced by several so called “mechanical safe blocks”. During these sequences only instruments without mechanical components (i.e. no drilling or hammering) were operated. In addition to camera images and thermal mapping, ranging and magnetic field measurements were performed. While radio contact was still possible, Philae was below a cliff-like structure, shadowing the solar arrays in an already sparsely lit area. Therefore the solar panels could not provide enough power to simultaneously heat and recharge the batteries (Ulamec and Taylor 2016). Because of the chemical characteristics of the lithium based batteries, the internal temperature had to be > 10° C to allow for safe recharging. This should have allowed for several days or even month of lander operations (Bibring et al. 2007b), before the rising internal temperature would have caused the lander to fail, as it got closer to the sun.

Initially it was unknown how stable Philae was without any anchoring, hence the intention of the safe blocks was to prevent mechanical systems from accidentally moving, tilting or even tipping the lander. These unfortunate circumstances only allowed for minimal scientific surface operations and prevented the use of some of the main instruments completely. It was deemed too dangerous to use the drill stack to sample the surface. Therefore the onboard mass spectrometers were not able to analyze the composition of the cometary material and were only operated in a passive sniffing mode (Goesmann et al. 2015). After both the primary and redundant radio transceivers onboard Philae started to malfunction, it became clear, that the planned long term science operation (LTS) was most likely not feasible. To measure at least some mechanical properties of the surface (mainly compressive strength and thermal conduction), the MUPUS hammer system (see section 2.5.1) was deployed shortly before the battery was depleted (Spohn et al. 2015).

Because of power and up-link data rate limitations, it was not possible to use the camera system to track the deployment of the hammer. Afterwards, the lander body was rotated around the landing gear to improve the illumination of the solar panels. Contact was lost on November 15, at 00:36 UTC when the battery drop-out voltage was reached.

Afterwards the Rosetta orbiter remained close the nucleus for several days, trying to reestablish radio contact and identify Philae on orbiter camera images to confirm the position. These initial attempts failed and due to increased activity of the comet, Rosetta was moved to a more distant orbit for safety reasons, making further radio contact nearly impossible. On June 13, 2015 a short signal from Philae was received by the Rosetta orbiter, indicating that Philae was still healthy and now, closer to the Sun, enough solar power was available for scientific operations. To increase the likelihood of further radio communications, the orbit and pointing of Rosetta was adapted based on the estimated location and attitude of Philae (Heinisch et al. 2016). After several successful contacts, attempts to activate scientific instruments failed and after July 9, no further communication was possible. On July 27, 2016 the Philae radio transceivers onboard Rosetta were switched off, officially ending Philae operations.

2.3 Comet 67P/Churyumov–Gerasimenko

67P is a short-period Jupiter family comet, discovered by Klim Churyumov and Svetlana Gerasimenko in 1969. The discovery itself and the orbital parameters are described in detail by Krolikowska (2003) and Lamy et al. (2007). 67P has a heliocentric perihelion distance of approximately 1.3 AU and an aphelion distance of 5.7 AU with an orbital period of 6.55 years. It rotates around an axis of largest moment of inertia with a period of 12.4 h (Mottola et al. 2014). While initial remote observations of 67P by Lamy et al. (2006), using the Hubble space telescope, suggested an elongated shape, similar to a potato, images taken by the Rosetta spacecraft revealed a much more intricate bi-lobed structure. Fig. 2.2 shows an image of the comet, taken by Rosetta at a distance of 154 km in July 2015 as an example. The smaller upper lobe is approximately 2.6 km by 2.3 km and has a height of 1.8 km, while the bigger bottom lobe is 4.1 km by 3.3 km and 1.8 km high (Mottola et al. 2014). This unexpectedly irregular shape made it much more difficult than initially expected to find a suitable landing site for Philae during the landing site selection process as explained by Ulamec et al. (2015) and Jurado et al. (2016). This was not only caused by the complex gravitational field of such an object, but also due to significant self shadowing. Entire regions of the comet were inaccessible to Philae as high cliff-like structures blocked possible trajectories. Because of the shape of 67P and orientation of the rotation axis, several different regions experienced polar day and night during the progression along the orbit of the comet. This led to inhomogeneous erosion of these areas and further complicated the selection of a landing site. Starting from an initial set of ten possible landing sites, the search was narrowed down to five sights with the best possible scientific return while at the same time providing the highest likelihood of longer-term lander survival. These possible areas are illustrated in Fig. 2.3. During the landing site selection process in fall 2014, site “J” was finally chosen as primary landing site for Philae.

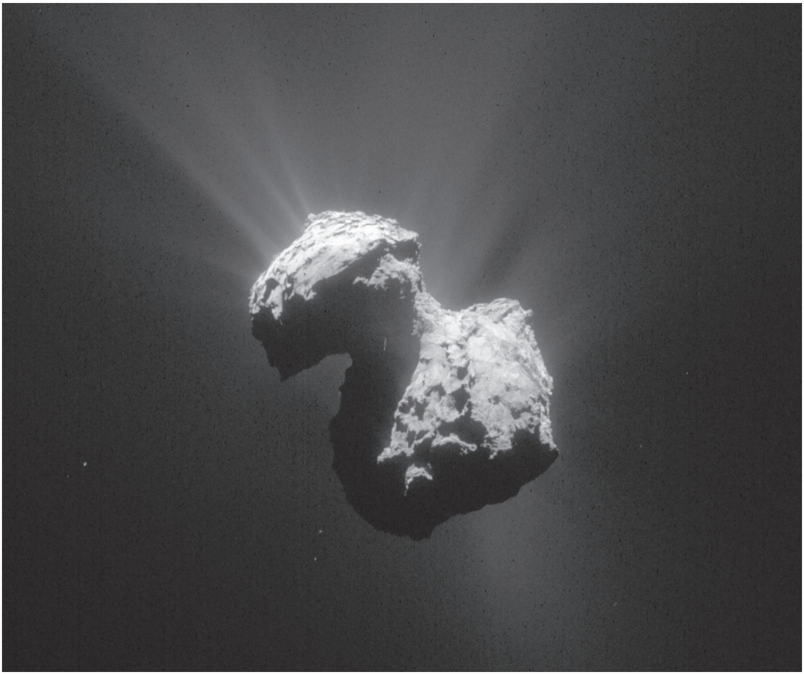

Figure 2.2: Image of comet 67P/Churyumov–Gerasimenko taken by Rosetta on July 7, 2015 from a distance of 154 km (ESA/Rosetta/NAVCAM, this image was published under the Creative Commons Attribution Share Alike 3.0 license).

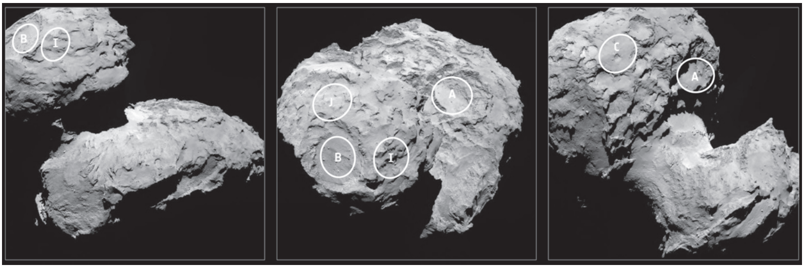

Figure 2.3: Five possible landing sites selected during the landing site selection process in 2014, site “J” was selected as primarily landing site for Philae (released for publication by ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA).

Figure 2.4: Rendering of the Rosetta spacecraft showing the (primarily) Sun-facing site. Image provided by ATG medialab for ESA (this image was published under the Creative Commons Attribution Share Alike 2.0 license).

Perturbations of Rosetta's orbital velocity allowed an accurate determination of the mass and bulk density. Using this approach Pätzold et al. (2016) derived a mass of $9.98 \cdot 10^{12}$ kg and an average bulk density of 533 kg/m^3. A total volume of 18.7 km^3 was estimated from camera images (Jorda et al. 2016), while an overall porosity of 75% to 85% was determined from radar observations (Kofman et al. 2015). By combining these results with observations from several other Rosetta instruments Davidsson et al. (2016) and Blum et al. (2017) independently concluded, that 67P most likely formed as a primordial rubble pile. This means that the comet was created by agglomeration of smaller pebbles and not as a collisional fragment of a larger parent body as suggested for example by Morbidelli and Rickman (2015). The nature of 67P makes it an ideal target to study the evolution of remnants of the early solar system.

2.4 The Rosetta Spacecraft

The Rosetta spacecraft was purpose-build for the very specific demands of a cometary mission. Reliable operation for at least ten years and thermal management and power systems capable of supporting spacecraft survival in deep space at more than 5 AU were the main requirements. To accomplish this without the use of nuclear power systems, Rosetta was equipped with 64 m^2 of solar cells, which was the largest solar array ever flown (D'Accolti et al. 2002) up to this point. The main spacecraft bus was build by Astrium (now Airbus) and measured 2.8 m by 2.1 m with a height of 2 m and a total mass of approximately 2900 kg. Fig 2.4 shows a rendering of the spacecraft, illustrating the dimensions and the prominent solar arrays.

After launch on March 2, 2004 Rosetta performed several gravity assist maneuvers at Earth and Mars and flew past Asteroids 2867 Steins (Schulz 2010) and 21 Lutetia (Schulz et al. 2012) in September 2008 and and July 2010 respectively. In June 2011 Rosetta