Title: The non-magnetic nucleus of comet 67P/Churyumov-Gerasimenko

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Abstract: Knowledge of the magnetization of planetary bodies allows far-reaching conclusions on their formation processes, and the conditions in the solar nebula at that time. Based on magnetic field measurements during the descent and subsequent triple landing of the ROSETTA lander PHILAE on comet 67P/Churyumov-Gerasimenko, we show that no global magnetic field was detected within the limitations of analysis. The ROMAP suite of sensors measured an upper magnetic field magnitude of less than 2 nT at the cometary surface at multiple locations with the upper specific magnetic moment being $< 3.1 \cdot 10^{-5} \text{ Am}^2/\text{kg}$ for meter-size homogeneous magnetized boulders and the maximum dipole moment of 67P/Churyumov-Gerasimenko is $1.6 \cdot 10^8 \text{ Am}^2$. We conclude that on this scale magnetic alignment in the pre-planetary nebula is of minor importance.

One Sentence Summary: High-precision magnetic field measurements obtained during the triple landing of ROSETTA's lander PHILAE demonstrate that the Jupiter family comet 67P/Churyumov-Gerasimenko is unmagnetized ($< 3.1 \cdot 10^{-5} \text{ A m}^2/\text{kg}$).

Main Text: Comets are believed to have been formed in the outer solar nebula beyond the snow line, where icy aggregates can grow in size to form larger bodies (1-3). Both the Kuiper belts as well as the Oort cloud are possible reservoirs of comets, with different processes leading to their formation (3). The dust-to-ice ratio of comets is of the order 1 (4, 5). Thus, a large fraction of cometary material is refractory material. Analysis of Stardust samples indicates a high contribution of Fe to this refractory material (6, 7). Up to 1% of the Fe content can be present as magnetite. Processes like accretional remanent magnetization (8) or detrital remanent magnetization (9) are possible candidates to form larger scale magnetic dust grains and cometesimals. These in turn allow the possibility for a comet to possess a larger scale remanent magnetic field.

Detection of any cometary magnetization is difficult as a dipole field decreases with the cube of the distance from the object. Global magnetization of small solar system bodies can be detected either by spacecraft flybys or direct measurements on the surface. Whereas the flybys of the Galileo and Deep Space spacecraft at asteroids 951 Gaspra and 9969 Braille suggested the possibility of notable magnetization of these bodies (10,11), the distant flybys of the ROSETTA spacecraft (12) at asteroids 2867 Steins and 21 Lutetia provided an upper limit on the specific magnetic moment of $10^{-6} \text{ Am}^2/\text{kg}$ (13, 14).

Magnetic field measurements obtained during the flyby of the Giotto spacecraft at comet 1P/Halley offered an opportunity to estimate cometary magnetization as they revealed an almost magnetic field free ($< 50 \text{ pT}$) region around the nucleus (16, 17). Taking into account the closest approach distance of 596 km to Halley's nucleus this corresponds to a formal dipole magnetic moment of $< 5 \cdot 10^{13} \text{ Am}^2$ or an upper specific magnetic moment of $< 0.25 \text{ Am}^2/\text{kg}$, an unreasonably large value indicating the limitations of the observation. Other spacecraft encounters with comets did not allow any reliable estimate of an intrinsic cometary magnetic moment due to the perturbed magnetic field induced by the comet-solar wind interaction (18-20).

These inferences, however, are based on measurements acquired on distant flybys and have necessarily relied on modelling the modification of the solar wind magnetic field at rather

large distance from the asteroids. To determine if planetary bodies are magnetized requires measurements of magnetic fields on their surfaces. Pioneering such an observational situation was the NEAR-Shoemaker's spacecraft fluxgate magnetometer (21). Near surface measurements at asteroid 433 Eros provide an upper limit of the global remanent magnetic dipole moment of $1.3 \cdot 10^{10} \text{ Am}^2$ and a maximum specific magnetic moment for Eros of $1.9 \cdot 10^{-6} \text{ Am}^2/\text{kg}$. Eros is therefore a remarkably non-magnetic object (21).

We present combined space and near-surface measurements from ROSETTA and the subsequent multiple touches of its lander PHILAE on the surface of comet 67P/Churyumov-Gerasimenko. Both ROSETTA and PHILAE are equipped with fluxgate magnetometer instruments. The magnetometer of the ROSETTA Plasma Package, RPC-MAG (22, 23), serves as a solar wind monitor for the ROMAP measurements taken during descent, hopping and landing on the nucleus. The ROMAP instrument (24) is a highly integrated plasma and magnetic field sensor assembly. Both fluxgate magnetometers allow measuring the magnetic field at a resolution of about 30 pT at a cadence of up to 32 Hz during the PHILAE phase of the ROSETTA mission. [The combined measurements onboard the two spacecraft allow separation of the field of local sources from temporal field variations.](#)

PHILAE was released from ROSETTA on November 12, 2014 at 08:35 UTC. Both magnetometers were powered on a few hours before, and thus were able to monitor the release and successful deployment of the ROMAP boom at 08:43 UTC. RPC-MAG measured a maximum change of the magnetic field magnitude by about 20 nT indicating the successful release of the probe. During release PHILAE was put into a rotational state around its Z-axis by its Mechanical Support System (MSS), [the rotation frequency \(period\) being 3.3 mHz \(300 s\).](#) After the deployment of the landing gear [PHILAE's rotation frequency changed to 2 mHz \(500 s\).](#) Rotation at these frequencies was clearly identifiable in the ROMAP magnetic field measurements.

During the ROMAP boom deployment the field magnitude decreased from 2022 nT to 155 nT, indicating a substantial PHILAE-generated bias magnetic field present in pre-deployment measurements. The first touch-down was recorded by the magnetometer at 15:34:04 UTC. Due to its inertia, the boom was partly folded back into its stored position at touch-down and tilted up again. Touch-down was detected by a clear change of the field magnitude due to PHILAE's spacecraft bias field. Initiated by the touch-down sensors, the control electronics of PHILAE's fly wheel was turned off, and during the following 2400 s the flywheel transferred its angular momentum to the lander as PHILAE was lifted off the cometary surface. As a result the [spin rate changed to 76.9 mHz \(13 s\),](#) again monitored by the magnetometer.

PHILAE's rotation and nutation induced by descent and touch-down was advantageous: the rotations permitted precise in-flight calibration for all three magnetic field components. Further lander-biased field changes ($\delta B_x = +3 \text{ nT}$, $\delta B_y = +9 \text{ nT}$, $\delta B_z = -7 \text{ nT}$) occur mainly during the first three hours after separation as a result of temperature variations. At the time of all four surface contacts, temperatures were almost constant and the magnetometer offsets changed by only $\sim 1 \text{ nT}$.

At 16:20 UTC ROMAP measurements provide clear evidence that PHILAE touched a cliff structure. This was not an actual landing as no vertical deceleration of the boom was detected. After this encounter with an as yet unknown surface structure PHILAE started to tumble, no longer rotating about the z axis. This complex dynamical motion - rotation and nutation dominated - caused a more complex magnetic field variation. The main [rotation](#)

frequency changed to 41.7 mHz (24 s). At 17:25:26 UTC a second touch-down was recorded by ROMAP, and at 17:31:17 UTC, probably only a few meters away, the final landing position was reached.

As the actual surface of the nucleus is highly structured we use a spherical surface as a reference for any further height information as well as to display the locations where PHILAE had ground contact and finally landed (Fig. 1). The center of this sphere is the center of mass of the comet that is the origin of the CHEOPS system (25). The positive Z-axis of the CHEOPS system is pointing along the cometary rotation axis, and the X-axis is in the equatorial plane, parallel to the longest axis of the nucleus, in the direction of the small lobe of the nucleus. The Y-axis completes the right-handed system; the X-axis prime meridian is through the CHEOPS boulder (26). The radius of the reference sphere is determined as $R_{\text{sphere}} = 2393$ m, the radial distance of the first touch-down point in the CHEOPS system.

Fig. 1: PHILAE's preliminary trajectory on the surface of 67P/Churyumov-Gerasimenko. The mosaic from OSIRIS images displays the horizontal path of PHILAE (top). The ballistic trajectory (dark blue) as well as the surface profile (black) relative to reference sphere indicates the shallow flight of PHILAE above the surface (bottom).

Based on the position of the first touch-down as determined by the Rosetta Mission Operation Center (RMOC) and considering the direction of flight after the first touch-down as indicated by OSIRIS camera (27) observations, preliminary coordinates of the touch-down points are $TD_1=(2.133, -0.963, 0.500)$ km and $TD_{2,3}=(2.482, -0.063, -0.185)$ km in CHEOPS coordinates. The distance between the second and third touch-down point is only a few meters.

The point of contact with the cliff structure is estimated at $C=(2.361, -0.668, -0.009)$ km. This position has been determined from the collision time as seen in the ROMAP measurements, the OSIRIS determined flight direction and speed as well as searching for a surface structure

in OSIRIS pictures suitable for a collision. The collision time determined for this structure using the OSIRIS determined PHILAE speed agrees very well with the ROMAP determined collision time. With respect to the reference sphere the heights of the four points are: $h_1=0$ m, $h_{2,3}=97$ m, and $h_c=61$ m.

To reconstruct the lander trajectory between the points of ground contact ballistic trajectories are assumed. With a preliminary nucleus mass value of 10^{13} kg (28) the local gravity was estimated as $g = 10^{-4}$ m/s². The distance between the first touch-down and the cliff contact points is about 631 m, the maximum height reached by PHILAE being 123 m. The distance to the second touch-down point is 641 m, with a maximum flight height 240 m. The final landing point is probably very close to the second touch-down point. From the ballistic trajectory determination we infer for the collision point descent and ascent velocities of 0.26 m/s and 0.25 m/s, respectively. This is in agreement with PHILAE flying up-hill towards TD_{2,3}.

From this preliminary flight trajectory determination we infer that ROMAP is able to provide very precise magnetic field measurements not only at the two touch-down points, the contact point and the final landing side, but also at a range of heights above the nucleus surface (Fig. 2). Furthermore, measurements during both descent and ascent are available, different from measurements at 433 Eros where only descent observations were possible (21).

Figure 2: Magnetic field [magnitude](#) measurement during descent and hopping. The blue curve gives the magnitude during each descent, the red during ascent. Panel TD1 displays measurements taken during descent towards TD₁ and ascent to the first apex, COL shows data taken from the first apex down to the cliff collision point and the second apex, TD2 gives the observations from the second apex to the second touch-down point and the third apex, and panel TD3 displays measurements taken along the short trajectory to the final landing side. As an example of increased external magnetic activity the event at 17:21:30 UTC is marked in TD2.

Due to the dynamics of the landing process, the precise height of the ROMAP instrument above the surface is not known. In its deployed state, the boom mounted sensor has a nominal height above the plane (defined by the three landing gear feet) of 1.2 m. At the final

landing site, we estimate the distance of the sensor to the closest cometary surface structure to be less than 0.4 m, derived from CIVA pictures (29).

Moving towards and away from the first touch-down point TD₁ clearly demonstrates no large spatial variation in the observed field. The field measured at and close to the surface is dominated by the solar wind magnetic field transported to the surface by the solar wind flow. Observed variations of up to 10 nT in magnitude, over frequency range of 100 mHz to 1 mHz are inherent to the interaction-modified interplanetary magnetic field (30). The average field magnitude is 4 nT for both descent and ascent.

No significant spatial variation in field magnitude is observed along the path from the first touch-down to the cliff contact point COL either. The field measured in the vicinity of the surface is identified as the solar wind magnetic field, with no clear indication of a field attributed to the nucleus.

The segment COL-TD₂ exhibits a pronounced set of field variations close to the surface at a height below about 20 m, between 17:21 and 17:23 UTC during descent. As no ascent measurements are available we use RPC-Mag data to rule out any radial magnetic field variation caused by a putative local magnetic anomaly. During the PHILAE landing ROSETTA was positioned above the landing area at a distance of about 17 km. Magnetic field measurements taken by RPC-MAG exhibit field variations similar to those detected by ROMAP (Fig. 3). These are to ultra-low frequency waves seen in the inner coma (30). For the time interval 17:21-17:23 UTC the correlation coefficient between both time series is $r=0.78$ with a lag of -2 s. Space truth provided by RPC-MAG thus supports our conclusion that the field variations recorded by ROMAP are due to variations of the interplanetary magnetic field, and not caused by spatial variations related to a magnetized cometary crust.

Figure 3: Magnetic field magnitude determined from measurements from ROMAP measurements onboard the lander PHILAE (red line) and RPC-MAG of the ROSETTA orbiter (blue line) for the time interval just before the second touchdown. For reason of enhanced visibility the RPC-MAG data are shifted by 10 nT.

A more detailed investigation of the near surface field is provided in the Supplementary Materials, also on component level. No spatial variation of the magnetic field strength during descent and ascent to the surface is observed in any of the magnetic field components. The

mean value between 10 m and touchdown of the averaged absolute values for descent and ascent is used as an error estimate. It varies between 0.6 nT and 1.9 nT. Therefore we use the value 2 nT as a conservative estimate for the magnetic field caused by local surface magnetization.

For a nucleus dipole-generated field <2 nT, measured at a distance of 2.5 km, the distance of the observation sites from the center of gravity of the nucleus, a magnetic dipole strength of $< 1.6 \cdot 10^8 \text{ Am}^2$ is determined.

A lower bound for the magnetization required to cause an observed field value can be estimated using Parker's optimal magnetization criteria (31). However an upper bound for the magnetization requires a different treatment. A worst case scenario is a randomly oriented distribution of magnetic dipoles of uniform strength M . In such a frustrated dipole situation field compensation of neighboring dipoles requires a larger magnetization to generate a given surface magnetic field. Furthermore, our measurements were not made directly at the surface. This limits the horizontal spatial resolution to about 1 m. Also, descent and ascent trajectories were not along the local surface normal. To account for all these effects model calculations have been performed (see the Supplementary Materials) assuming a set of rectangular prisms with uniform magnetization magnitude, but random orientation. With these model calculations we reason a magnetic dipole $\vec{M}$ in 2. Gaussian position to provide a suitable estimate for the magnetic field:

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi} \frac{\vec{M}}{r^3},$$

where μ_0 denotes the vacuum permeability and r the distance of the measurement to the dipole center. With $|\vec{M}| = m \cdot D^3$, where m is the magnetization and D the scale of the rectangular prism, we set an upper bound

$$m \leq m_{\text{Upper}} = \frac{4\pi}{\mu_0} \cdot \left(\frac{h}{D} + \frac{1}{2} \right)^3 \cdot B.$$

For D , the granularity of the magnetization distribution, we chose $D=1$ m, the spatial resolution of our measurements. With $B=2$ nT, and $h=0.4$ m we estimate $m_{\text{Upper}}=0.0146 \text{ A/m}$, or using the cometary density of 466 kg/m^3 (28) an upper value for the specific magnetic moment of $3.1 \cdot 10^{-5} \text{ Am}^2/\text{kg}$. For larger homogeneously magnetized grains ($D \gg h$) the upper value for the specific magnetic moment decreases to $5.4 \cdot 10^{-6} \text{ Am}^2/\text{kg}$. Of course, we cannot rule out the possibility that boulders with a stronger magnetic moment are present at larger distances from the observational points.

As a comparison lunar material is characterized by a specific magnetic moment in the range $2.5 \cdot 10^{-5} - 10^{-3} \text{ Am}^2/\text{kg}$ (32). The natural remanent specific magnetic moment of meteorites collected in the Atacama Desert ranges between $10^{-4} - 7 \cdot 10^{-3} \text{ Am}^2/\text{kg}$ (33). The weakest magnetization of achondrites and SNC meteorites is reported as $5 \cdot 10^{-4} \text{ Am}^2/\text{kg}$ and $2 \cdot 10^{-5} \text{ Am}^2/\text{kg}$ (34). The specific magnetic moment we report here for cometary material, depending on granularity $< 3.1 \cdot 10^{-5} \text{ Am}^2/\text{kg}$ to $< 5.64 \cdot 10^{-6} \text{ Am}^2/\text{kg}$, is significant smaller than that of lunar and meteoritic planetary material. Therefore much like Eros, Churyumov-Gerasimenko is a remarkably non-magnetic object.

The magnetization found at 67P/Churyumov-Gerasimenko is much too low to enforce alignment of 10^{-1} m and larger cometesimals in a pre-planetary nebular. The orientation of such grains and bodies may be determined mainly by gas drag.

If comet 67P/Churyumov-Gerasimenko is representative of cometary nuclei, magnetic forces are unlikely to play a role in the accumulation of planetary building blocks on [scales > 1 m](#), that is in the critical diameter range 10^{-1} to 10^2 m (35).

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Supplementary Materials for

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Materials and Methods

Supplement 1: Data Analysis

Supplement 2: Modeling

Supplement 1: Data Analysis

Figure S1-1: The averaged absolute descent and ascent values of the three magnetic field components X, Y and Z measured by ROMAP plotted for the final 10m before/after touchdown 1 (black line). The mean value, representing the variation level, is plotted as dashed line. The field decay caused by an assumed surface magnetization of $m = 2 \cdot 10^{-5} \text{ Am}^2/\text{kg}$ (derived from the model described in suppl. 2) for a volume element of 3m and shifted by the field mean value is plotted in red.

Figure S1-2: The averaged absolute descent and ascent values of the three magnetic field components X, Y and Z measured by ROMAP plotted for the final 10m before/after the collision (black line). The mean value, representing the variation level, is plotted as dashed line. The field decay caused by an assumed surface magnetization of $m = 2 \cdot 10^{-5} \text{ Am}^2/\text{kg}$ (derived from the model described in suppl. 2) for a volume element of 3m and shifted by the field mean value is plotted in red.

Figure S1-3: The averaged absolute descent and ascent values of the three magnetic field components X, Y and Z measured by ROMAP plotted for the final 10m before/after touchdown 2 (black line). The mean value, representing the variation level, is plotted as dashed line. The field decay caused by an assumed surface magnetization of $m = 2 \cdot 10^{-5} \text{ Am}^2/\text{kg}$ (derived from the model described in suppl. 2) for a volume element of 3m and shifted by the field mean value is plotted in red.

Figure S1-4: The averaged absolute descent and ascent values of the three magnetic field components X, Y and Z measured by ROMAP plotted for the final 10m before/after touchdown 3 (black line). The mean value, representing the variation level, is plotted as dashed line. The field decay caused by an assumed surface magnetization of $m = 2 \cdot 10^{-5} \text{ Am}^2/\text{kg}$ (derived from the model described in suppl. 2) for a volume element of 1m and shifted by the field mean value is plotted in red.

The above figures show the three magnetic field components for the individual touchdowns. For the first two touchdowns and the Collision (fig. 1 – fig. 3), the absolute values for descent and ascent were averaged to gain statistical significance. For the final touchdown only descent values are available, therefore fig. 4 only shows the absolute values observed during descent.

Additionally modeled magnetic field profiles (retrieved from the model described in supplement 2) are shown. The model represents the expected magnetic field depending on the distance to the surface based on a given specific magnetic moment. For the first three contacts the model is based on a block edge length of $l_b = 3\text{m}$ and a specific magnetic moment of $m = 2 \cdot 10^{-5} \text{ Am}^2/\text{kg}$. For the last touchdown the block edge length was decreased to $l_b = 1\text{m}$. To account for the background field caused by the solar wind comet interaction, the mean values of the individual components were added to the modeled profiles and illustrated by the dashed lines in the figures.

	TD1 (nT)	COL (nT)	TD2 (nT)	TD3 (nT)
X	0.7	1.5	1.9	1.6
Y	0.9	1.8	1.3	1.6
Z	0.6	0.8	1.9	1.6
Magnitude	1.3	2.5	3.0	2.8
RPC-Magnitude	1.3	2.8	2.7	2.8

Table S1-1: Mean values of the individual magnetic field components for the four ground contacts as plotted in Fig.S1-1 – Fig.S1-4 and the mean value of the magnitude, together with the mean magnitude of simultaneous RPC-MAG observations, derived by the same method and given for comparison

The individual component mean values are given in table 1. The overall mean magnitude is $\bar{B} = 2.4 \text{ nT}$ with a variance of $\sigma^2 = 0.58 \text{ nT}^2$. To ensure this background field is caused by the interaction of the cometary plasma with the solar wind, these values can be compared with the mean value obtained from identically treated simultaneous RPC-MAG observations. The overall mean value is $\bar{B}_{RPC} = 2.4 \text{ nT}$ with a variance of $\sigma^2_{RPC} = 0.54 \text{ nT}^2$, which is nearly identical to the ROMAP results.

This leads to the conclusion that the variations seen by ROMAP are dominated by ambient field fluctuations. Based on these results, the upper threshold for any field contributions due to comet magnetization are estimated to be less than 2 nT. As this threshold amounts to 80% of the mean total field variation (as mentioned above dominated by ambient field variations) and is above any of the mean values of the individual components, it can be considered as a very conservative assumption.

Supplement 2: Modeling

The purpose of the modeling is to quantify the relation between the measured field on the decent trajectory and the magnetization of the near surface material.

The magnetized material is modeled by a set of randomly oriented dipoles. The dipoles, representing homogeneous magnetized cubes, are placed within a three dimensional lattice. The material of the cubes is assumed as the same for the whole lattice. The dipole moment $\vec{M}$ of each cube can be derived from magnetization of the material m and its volume D^3 .

$$|\vec{M}| = m D^3 = M_{sp} \rho D^3$$

Where M_{sp} denotes the specific magnetic moment and ρ the density.

The resulting magnetic field at a certain position is computed as a sum of fields generated by all dipoles.

$$\vec{B} = \frac{\mu_0}{4\pi} \sum_i \left(\frac{3\vec{r}_i (\vec{M}_i \cdot \vec{r}_i)}{|\vec{r}_i|^5} - \frac{\vec{M}_i}{|\vec{r}_i|^3} \right)$$

Where $\vec{r}_i$ is the spatial vector from the i^{th} dipole to the measurement position.

In order to have a representative profile of the magnetic field during the descent a set of trajectories above the lattice surface are defined. The trajectories have foot points in an area on the lattice surface within a square of width equal to quarter of the lattice dimension. The foot points within this area are randomly chosen from a uniform distribution as well as the tilt of the trajectories (limited to $\pm 45^\circ$).

Figure s2-1: Lattice with 10^6 dipoles randomly oriented (blue arrows). The red lines show profile trajectories for computation of the magnetic field.

For each of the trajectories the magnetic field profile is computed. Cyan solid lines in Figure s2-2 indicate the profiles. The averaged field of all profiles (blue line) is taken as a representative profile of the magnetic field during the descent.

The black lines show the magnetic field profile along a vertical trajectory above a single dipole located at depth of $D/2$ below the surface with a vertical magnetic moment $\vec{M}_v$ (the 1st Gaussian orientation, dash-dotted black line) and a horizontal magnetic moment $\vec{M}_h$ (the 2nd Gaussian orientation, dashed black line).

Figure s2-2: Computed magnetic field profiles along random tilted trajectories above a set of 10^6 dipoles located in a cubic lattice. Cyan solid lines indicate the magnetic field profiles along randomly selected trajectories. The blue solid line shows the average profile. The black dash-dotted (dashed) line represents vertical profile above a single dipole in the 1st (2nd) Gaussian orientation respectively (see text for details). The cube dimension D has been set to 1 m, the specific magnetic moment to $10^{-5} \text{ Am}^2/\text{kg}$ and the density to 466 kg/m^3 .

The 2nd Gaussian situation for a single dipole at the center of a single *cube* is a conservative approximation for measurement heights greater than 10% of the cube size. Therefore we are using this case for estimating the magnetization independence on cube size D and measurement height h by the equation

$$m = \frac{4\pi}{\mu_0} \cdot \left(\frac{h}{D} + \frac{1}{2} \right)^3 \cdot B.$$

Figure s2-3 shows the results for specific measurement heights and a maximum B of 2nT (for justification see supplement 1).

Figure S2-3: Threshold for determination of local magnetization independence on the size D of homogeneous magnetized volume elements. The blue curve shows the threshold for a measurement in a distance to the surface of 1.2m, the red one for a magnetic field measurement at a distance of 0.4m.