Induction signatures at 67P/CG

D. Constantinescu[1,2] K-H. Glassmeier[2] I. Richter[2] U. Auster[2]
P. Heinisch[2]

[1]Institute for Space Sciences, Bucharest

[2]Institute for Geophysics and Extraterrestrial Physics, Braunschweig

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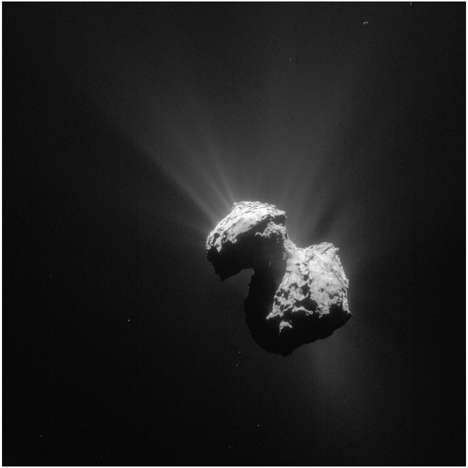
Comet Churyumov-Gerasimenko

Two-lobes Jupiter family comet discovered in 1969



- aphelion: 5.7 AU
- perihelion: 1.2 AU
- orb. period: 6.4 yr
- rot. period: 12.4 h
- density: $400\,kg/m^3$
- escape vel.: $1\,m/s$
- lobe1: $2.5 \times 2.5 \times 2\,km$
- lobe2: $4 \times 3 \times 1.5\,km$

Image from Rosetta Navigation Camera, July 7 2015

The Rosetta mission

Two subsystems: Rosetta orbiter and Philae lander

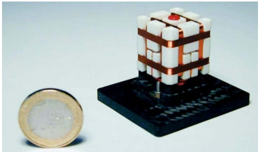
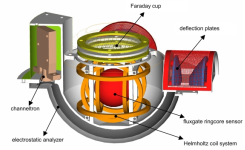
- Launch: Mar. 2004
- Arrival: Aug. 2014
- Landing: Nov. 2014

- 25 experiments
  - fields
  - particles
  - cameras
  - dust
  - spectrometers

Image credit: ESA

The Rosetta and Philae magnetometers

Three-axial fux-gate developed by TUBS, IWF, and MPE

	orbiter (RPC-MAG)	lander (ROMAP)
		
digital resolution	30 pT	10 pT
NS sampling rate	1 Hz	1 Hz
BS sampling rate	20 Hz	64 Hz

- NS Nyquist frequency: 0.5 Hz
- BS Nyquist frequency: 10 Hz

Skin depth and conductivity

Consider:

- half-space with permeability μ_0 and conductivity σ
- primary field: $\boldsymbol{B}_{\text{prim}} = \boldsymbol{B}_0 e^{-i\omega t}$
- Diffusion equation: $\nabla^2 \boldsymbol{B} = \sigma \mu_0 \dfrac{\partial \boldsymbol{B}}{\partial t}$

$\Rightarrow$ solution: $\boldsymbol{B}_{\text{sec}} = \boldsymbol{B}_0 e^{-\frac{z}{\delta}} e^{-i(\omega t - \frac{z}{\delta})}$

characteristic length (skin depth): $\delta = \sqrt{\dfrac{2}{\sigma \mu_0 \omega}}$

Skin depth and conductivity (cont.)

For skin depths larger than the object dimmension, the object becomes "transparent"

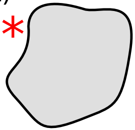
σ (S/m)		δ (km) at 0.5 Hz	δ (km) at 10 Hz
10^{-3}	(rock)	22	5
10^{-1}	(sea ice)	2.2	0.5
4	(sea water)	350×10^{-3}	80×10^{-3}
10^{+5}	(Fe_xS_y meteorites)	2×10^{-3}	0.5×10^{-3}

For km - range objects, induction signatures are observable above ice conductivity

Two point induction methods

$\boldsymbol{B}_{\mathrm{tot}}(\mathrm{t}) = \boldsymbol{B}_{\mathrm{prim}}(\mathrm{t}) + \boldsymbol{B}_{\mathrm{sec}}(\mathrm{t})$

$\boldsymbol{B}_{\mathrm{prim}}(\mathrm{t})$

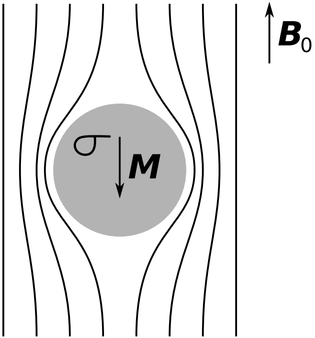


- compare $\boldsymbol{B}_{\mathrm{prim}}(t)$ with $\boldsymbol{B}_{\mathrm{tot}}(t)$
- two approaches:
  - time domain — for non periodic perturbations
  - frequency domain — for periodic perturbations

$\Rightarrow$ mean conductivity or conductivity radial distribution

Time domain: transient response

Sphere with radius R and uniform conductivity σ
Switch-on scenario: $\boldsymbol{B}_{\text{prim}}$ is the step function



- induced magnetic moment: $\boldsymbol{M}(t) =$

$$-\frac{2\pi}{\mu_0}\boldsymbol{B}_0 R^3 \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left\{-\frac{n^2\pi^2}{\mu_0\sigma R^2}t\right\}$$

- induced dipol:

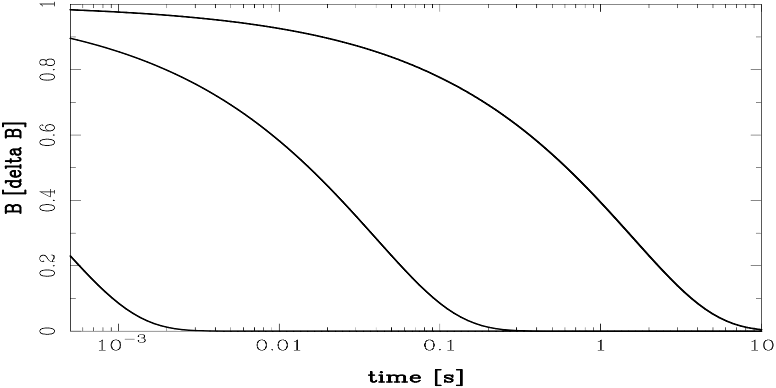
$$\boldsymbol{B} = \frac{\mu_0}{4\pi}\frac{1}{r^3}\left[3(\boldsymbol{M}\cdot\hat{\boldsymbol{r}})\hat{\boldsymbol{r}} - \boldsymbol{M}\right]$$

Surface field at $t = 0$ (or $\sigma \to \infty$): only tangential component

- at the poles: $\boldsymbol{B}_{\text{tot}} = 0$
- at the equator: $\boldsymbol{B}_{\text{tot}} = 1.5\boldsymbol{B}_0$

Time domain: surface field decay

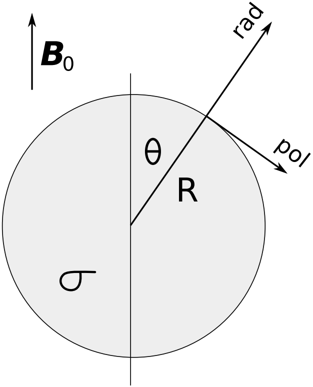
rock (10^{-3}), ice (0.1), and water (4 S/m) surface field for $R = 2$ km



- sudden field variation is necessary
- an estimate can be made if conductivity is high
- method used for the Moon, Europa and Callisto

Frequency domain: Model

Linear polarised wave: $\boldsymbol{B}_{\text{prim}} = \boldsymbol{B}_0 e^{-i\omega t}$
The z axis is given by the polarization direction



- The induced magnetic moment is phase delayed:

$$\boldsymbol{M} = Ae^{i\phi}\boldsymbol{B}_{\text{prim}}\frac{4\pi}{\mu_0}R^3$$

-

$$Ae^{i\phi} = \frac{J_{5/2}(Rk)}{J_{1/2}(Rk)} \quad ; \quad k = \frac{1-i}{\delta}$$

At the surface:

$$\boldsymbol{B}_{\text{sec}} = Ae^{-i(\omega t - \phi)}B_0(3\cos\theta\hat{\boldsymbol{r}} - \hat{\boldsymbol{e}}_z)$$

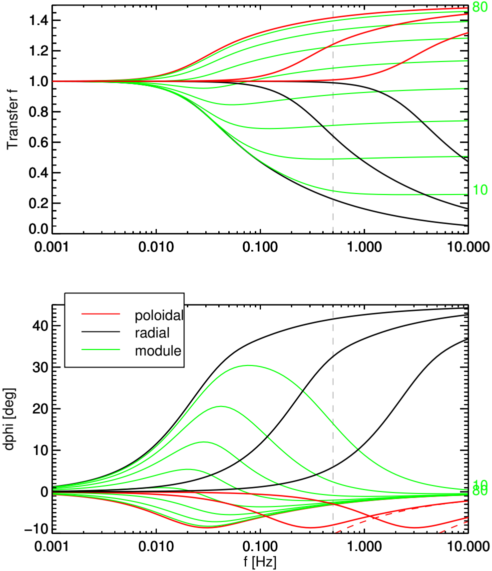
Transfer functions and phase differences

For each component and for the magnetic field intensity we define:

$$\mathcal{T}_j(\sigma, \omega, \hat{\boldsymbol{r}}) = \left. \frac{B^j_{\text{prim}} + B^j_{\text{sec}}}{B^j_{\text{prim}}} \right|_{\text{surface}} \quad ; \quad j = \text{rad, pol, abs}$$

- $\mathcal{T}_{\text{rad, pol}}$ depend only on the radius and R and skin depth $\delta(\sigma, \omega)$
- $\mathcal{T}_{\text{abs}}$ depends also on the angle θ
- Transfer function: $T_j(\delta) = |\mathcal{T}_j|$
- Phase difference: $\phi_j(\delta) = \text{phase}(\mathcal{T}_j)$

TF and $\Delta\phi$ for $R = 2\,\textbf{km}$, $\sigma = 10; 1; 0.1\,\textbf{S/m}$



- abs dep. on θ
- rad, pol indep.

low frq limit:

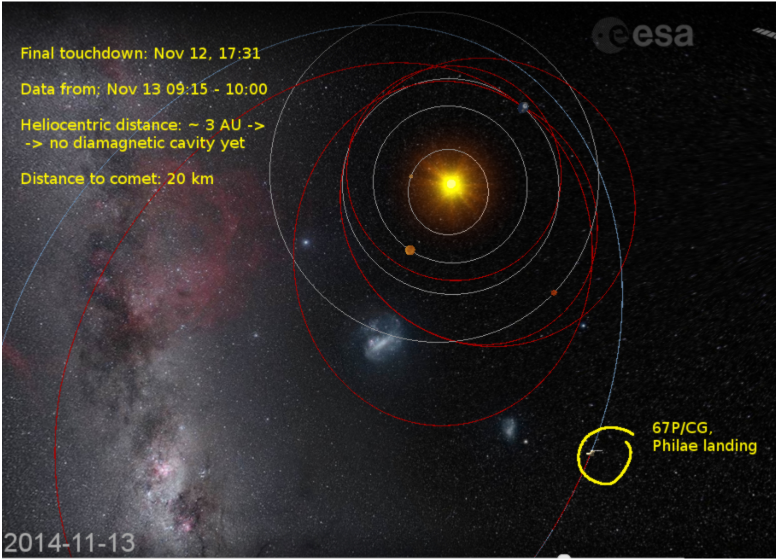
- $T_\mathrm{j} \to 1$
- $\Delta\phi_\mathrm{j} \to 0$

high frq limit:

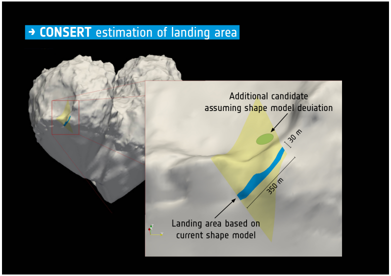
- $T_{rad} \to 0$
- $T_{pol} \to 1.5$
- $\Delta\phi_\mathrm{rad} \to \pi/4$
- $\Delta\phi_\mathrm{pol} \to 0$
- $\Delta\phi_\mathrm{abs} \to 0$

strategy: measure T_abs and $\Delta\phi_\mathrm{abs}$

Measurements: comet position



Measurements: lander position



- radial and poloidal directions: difficult to determine
- we will use the module

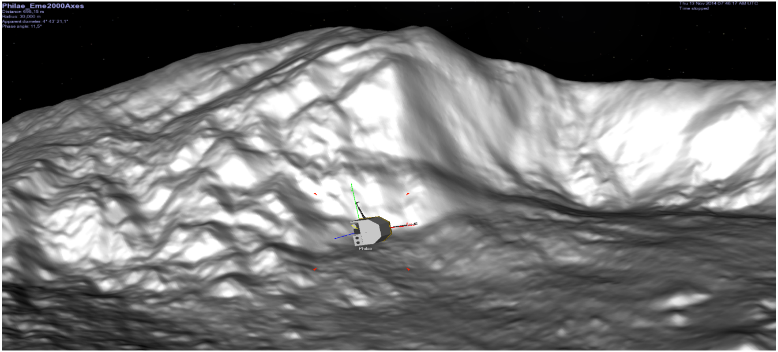
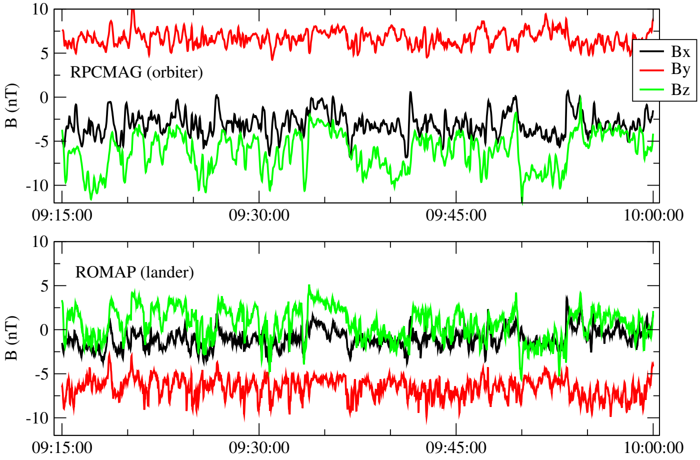


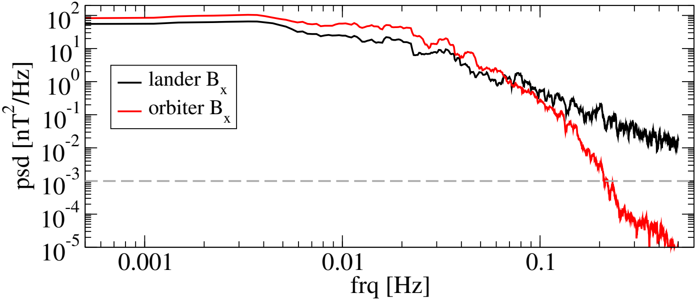
Image from Heinisch et al 2015

Measurements: CSEQ magnetic field



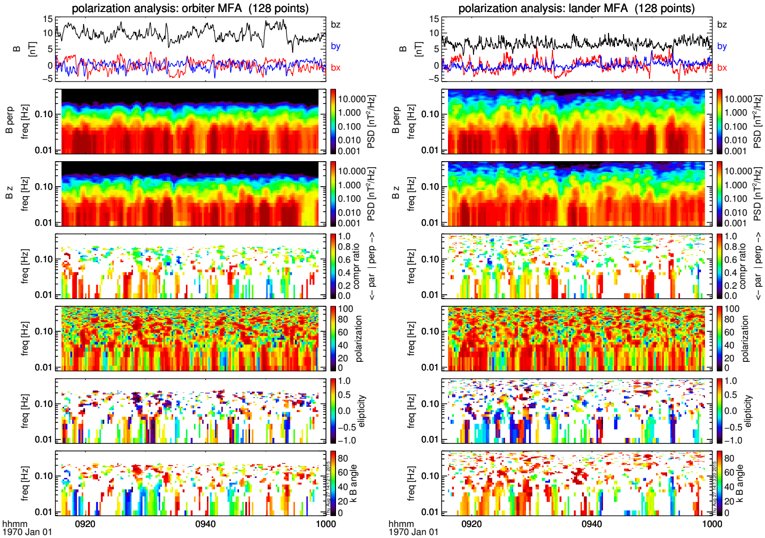
- Data from Nov. 13, 09:15 – 10:00 (16 hrs after landing)
- CSEQ: x sunward; $z \perp$ ecliptic; y completes the system
- acquisition rate: 1 Hz

Wave properties: Power Spectral Density



- no outstanding dominant frequency
- fast decrease of wave power at orbiter above 0.1 Hz
- noise threshold $10^{-3}\,nT^2Hz^{-1} \Rightarrow$ max. usable frequency 0.2 Hz

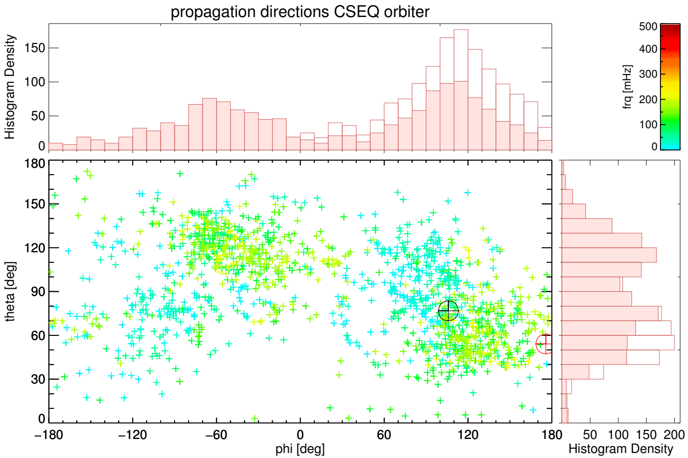
Waves properties: Polarization



filter:

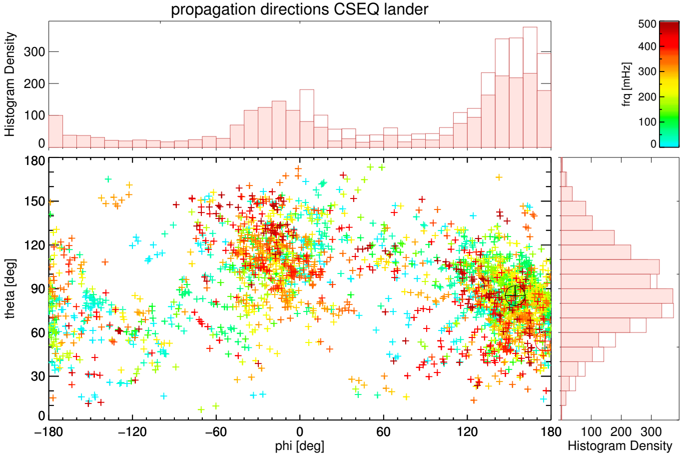
plolarization $>$ 50%; power $> 10^{-3}\,\mathrm{nT^2Hz^{-1}}$; eigenvalue ratio $>$ 5

Waves propagation directions at the orbiter



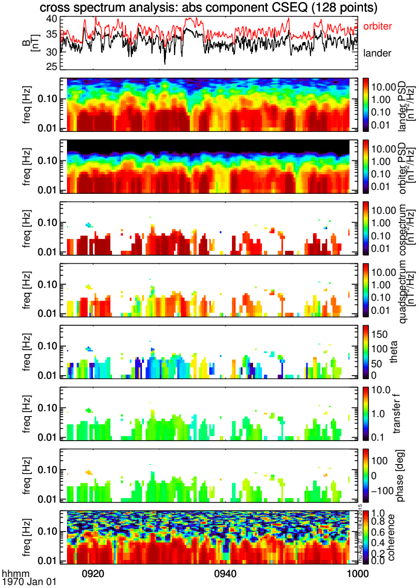
$$\widehat{\boldsymbol{kr}} = 66^\circ; \qquad \theta = 76^\circ; \qquad \varphi = 105^\circ$$

Waves propagation directions at the lander



$\widehat{\boldsymbol{kr}} = 37°$; $\theta = 85°$; $\varphi = 154°$; $\widehat{\boldsymbol{k}_{|}\boldsymbol{k}_{\circ}} = 50°$

Cross spectrogram for the field module

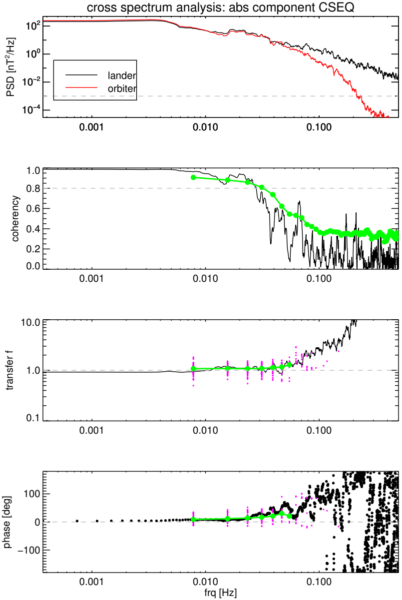


window length: 2min

filtered for:

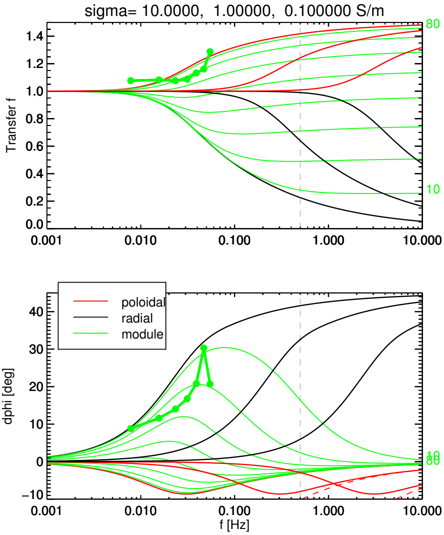
- power $> 10^{-3}\,\mathrm{nT}^2\mathrm{Hz}^{-1}$
- coherence > 0.9

Cross spectrum for the field module



- black and red:
  entire 45 min interval
- magenta:
  filtered 2 min intervals
- green:
  avg of filtered intervals
- max usable frq: 60 mHz
- different θ angles (!)

Comparison with the model



- red line:
  model for poloidal
- black line:
  model for radial
- green line :
  model for module
- green dots:
  measured for module
- minimum estimated conductivity:

  $\sigma > 10\,\mathrm{S/m}$

Data Caveats

- The offsets influence the transfer function
- The orbiter onboard digital filter reduces the PSD above 50 mHz
- Synchronization can be wrong as much as 1 s

Summary

- A minimum conductivity of 10 S/m, (larger than the conductivity of Terrestrial ocean water) has been estimated for 67P/CG.
- 1 Hz magnetic field data from the Rosetta orbiter and the Philae lander have been used.
- Data was acquired shortly after landing at about 3 AU heliocentric distance.
- Distance between the Rosetta orbiter and the comet was about 20 km.
- Assumptions made:
  - Spherical uniform conductivity model
  - No diamagnetic cavity
  - No other phase altering processes