Cometary Dust and Plasma

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Cometary dust and plasma: an Introduction

- Comet exhibit a multiphase outer environment (gas, dust, plasma) not gravitationally-bounded to its nucleus.

- Comets → Natural laboratory for dusty plasma effects.

Comet Hale-Bopp observed over Boulder, Colorado
Additional credit: Niescja Turner and Carter Emmart

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Cometary dust and plasma: an Introduction

- Dust – plasma interactions at comets:
  - Solar wind interaction with the **dust tail**.
    - e.g. Interaction between comet tails and heliospheric current sheet (sector boundary crossing) and formation of **striae** in the dust tail.

[Horanyi & Mendis 1986
Mendis & Hornyi 2013
Price & al 2019, 2023]

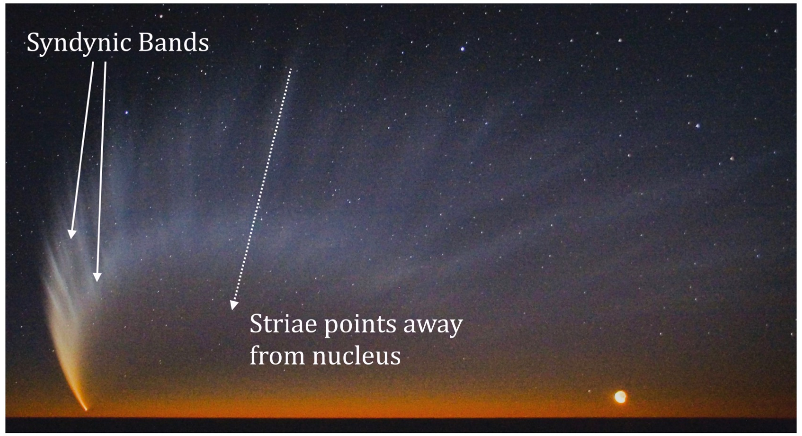

Figure 2.3: Striae and Syndynic bands seen in the dust tail of C/2006 P1 McNaught, as observed from the European Southern Observatory on the 21st January 2007. Image credit: S. Deiries.

Comet Hale-Bopp observed over Boulder, Colorado
Additional credit: Niescja Turner and Carter Emmart

Cometary dust and plasma: an Introduction

- Dust – plasma interactions at comets:
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  - **In the inner coma?**
  - **At the comet nucleus surface?**

Where cometary dust and plasma are densest
Expect more efficient dust-plasma interactions
[Mendis & Horanyi 2013]
➔ Dust lifting?
➔ Electrostatic disruption?
➔ Plasma depletion from dust charging?
➔ Ultra LF waves from collective charged dust motion?

Comet Hale-Bopp observed over Boulder, Colorado
Additional credit: Niescja Turner and Carter Emmart

Cometary Dust and Plasma:
from Rosetta to Comet Interceptor

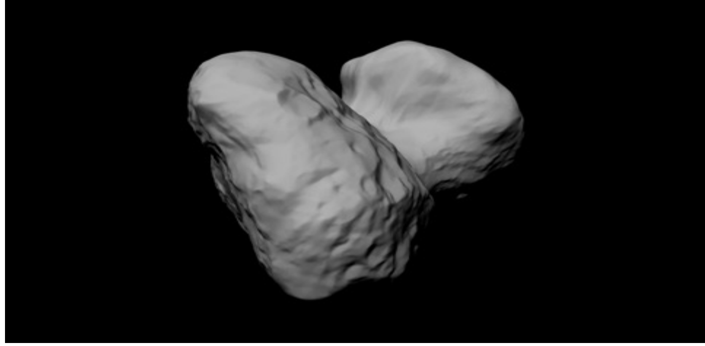
Content

1. **Cometary plasma seen by Rosetta**

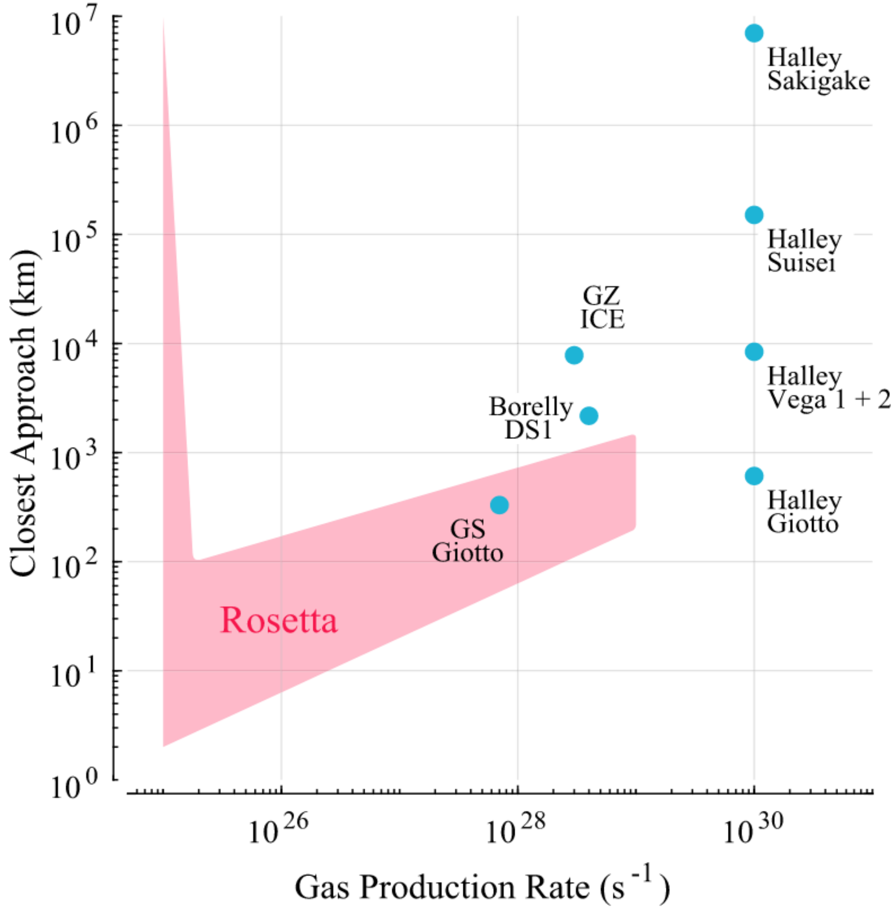
2. Cometary (charged) dust seen by Rosetta

3. Cometary dusty plasma studies with Comet Interceptor

The Rosetta mission



- *Target comet: 67P/CG (Jupiter-family comet)*
- *Launched in 2004, cometary operations in 2014-2016*
- *Data available on:*
  - *ESA Planetary Science Archive (PSA)*
  - *NASA Planetary Data System (PDS)*
- *First comet "monitoring" mission, following the comet during part of its orbit around the Sun (1.2 → 3.8 A.U.)*
- *Low velocity (m/sec), close to the nucleus (surface to 1500 km)*



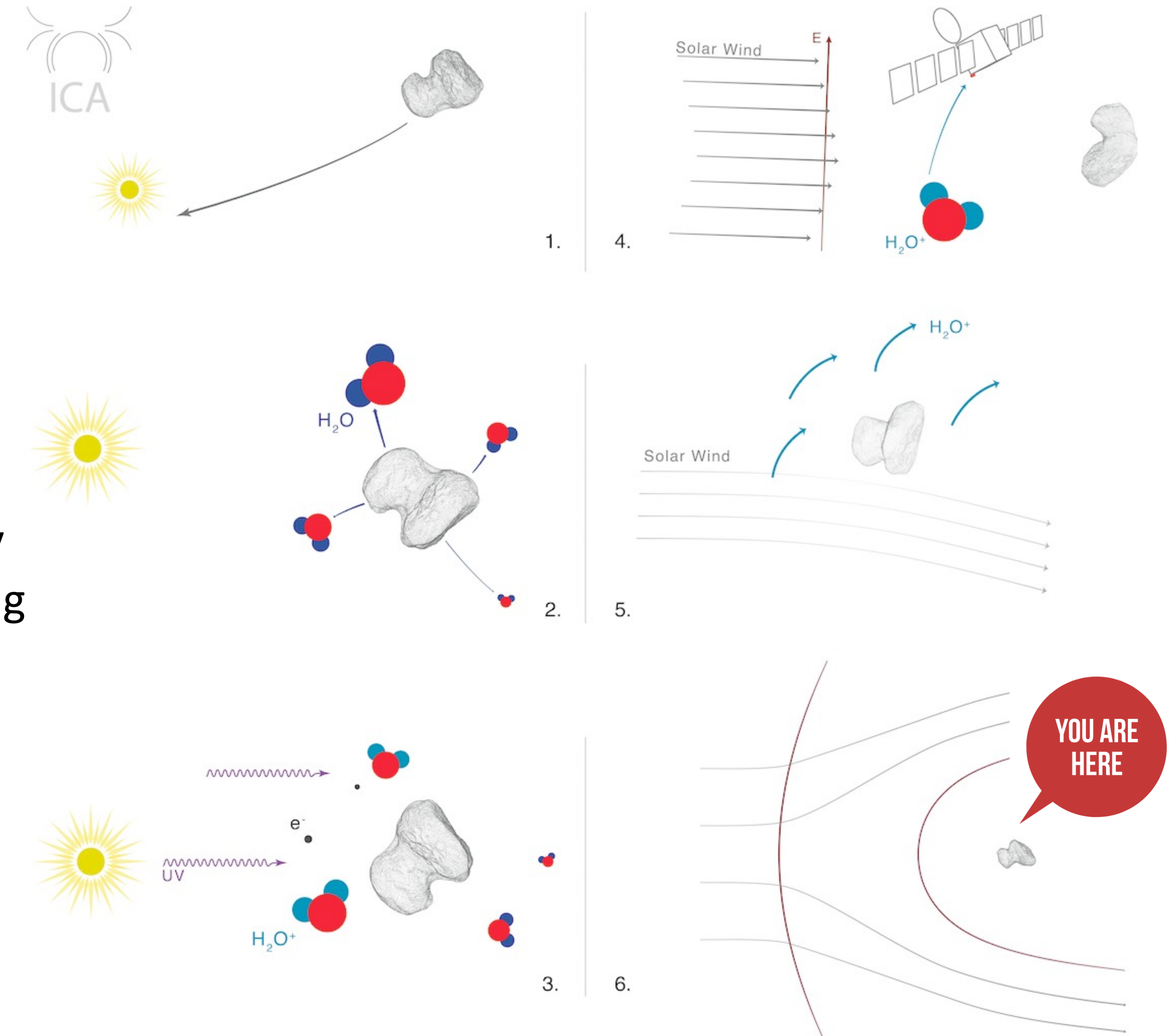
[Goetz et al, 2022]

Formation of the induced magnetosphere of a comet

Heating of comet nucleus

Sublimation of cometary volatiles (H_20, $C0_2$)
Expanding cometary atmosphere (carrying cometary **dust**)

Ionisation of cometary neutral



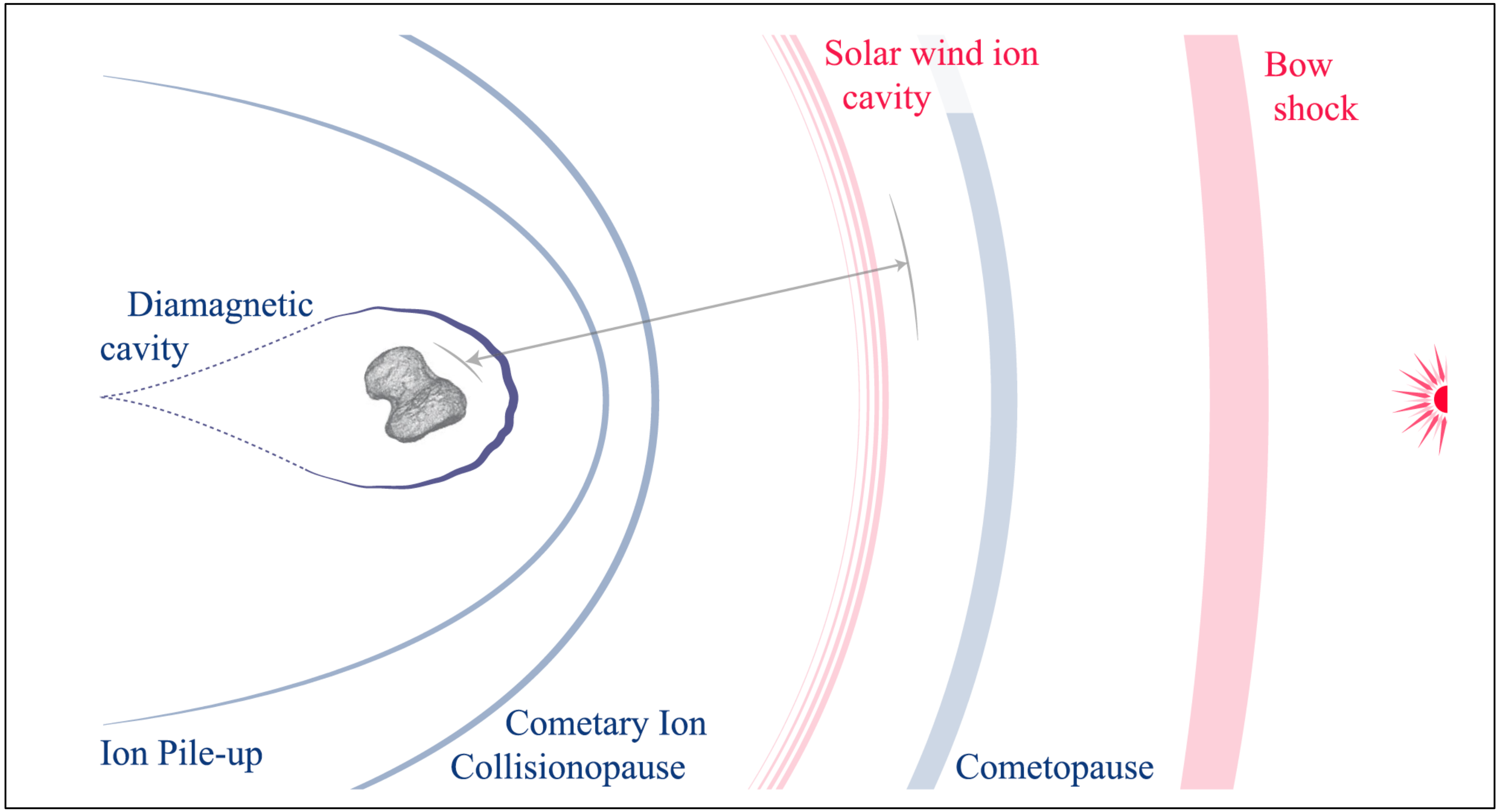
Cometary ions picked up in the solar wind

Deflection of solar wind ions

Formation of an **induced magnetosphere**

[Béhar et al.]

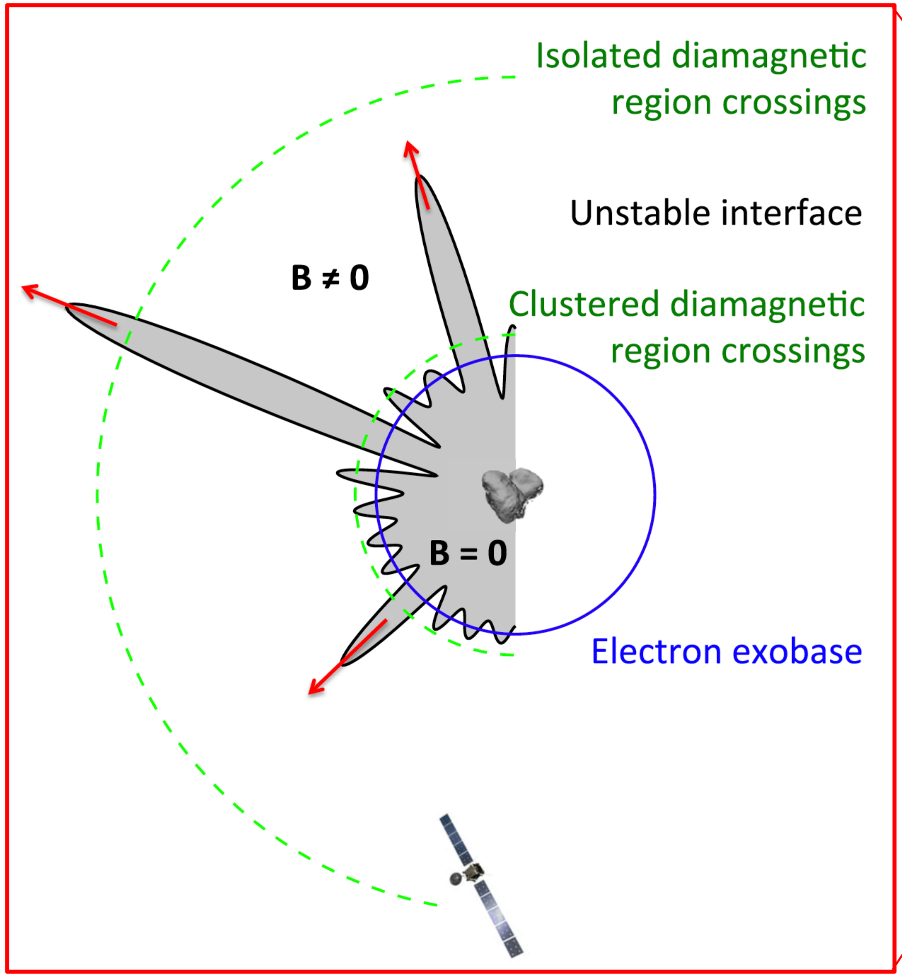
The plasma environment of a comet



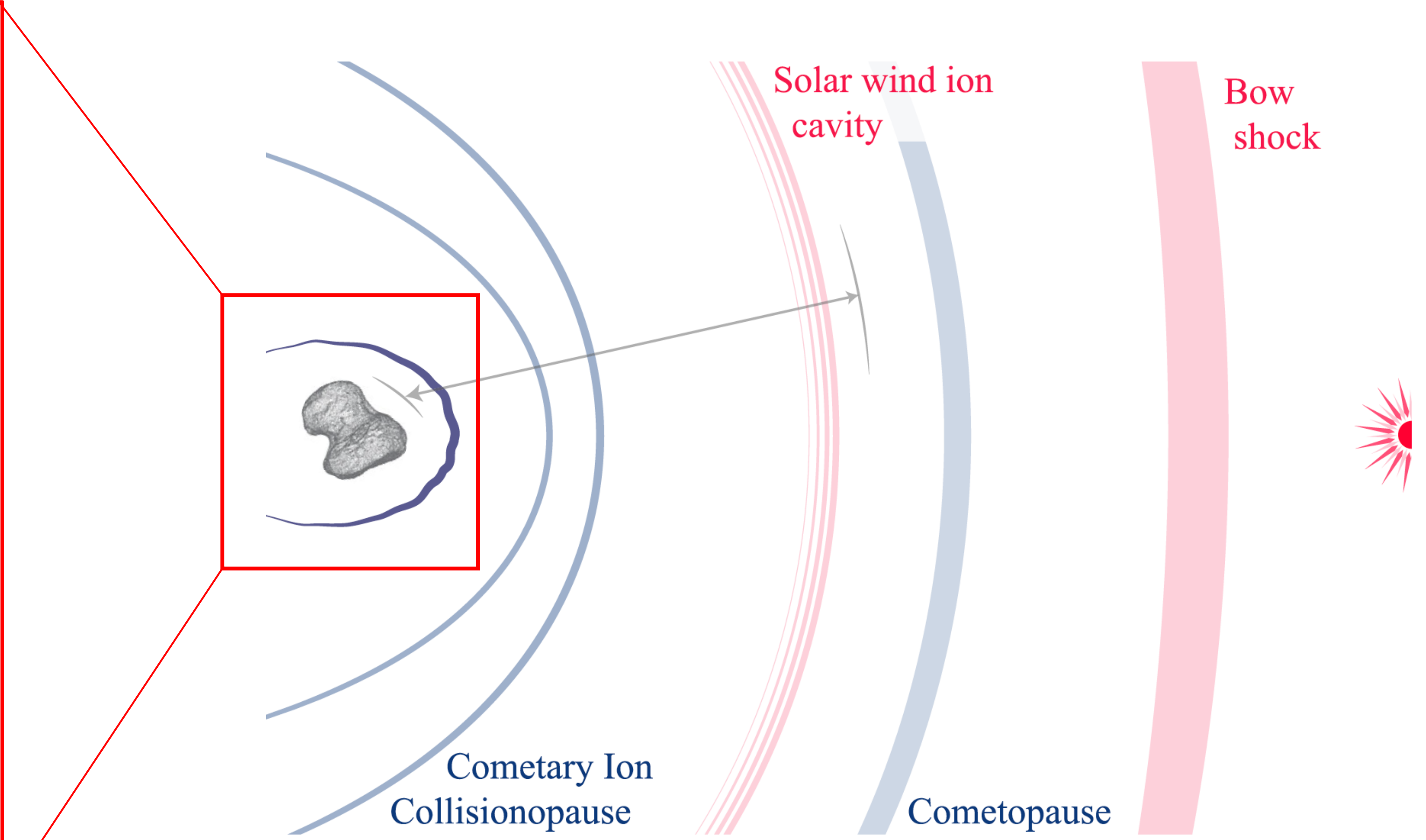
[Goetz et al., SSR, 2022]

The plasma environment of a comet

Inner coma



[Henri et al, 2017]



[Goetz et al., SSR, 2022]

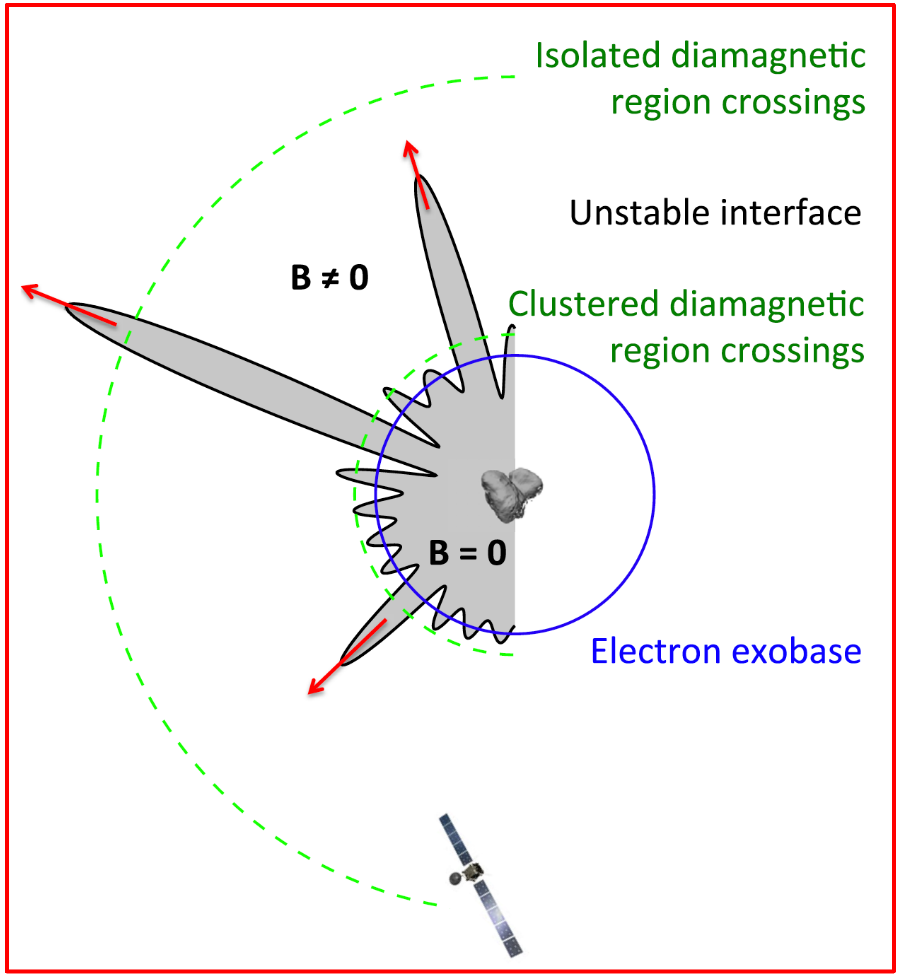
The plasma environment of a comet

Today: focus on two particular aspects of the cometary plasma that are essential for dust-plasma interactions:

- **Electron flux:** key parameter for *dust charging*
- **Electric fields:** key for charged *dust dynamics*

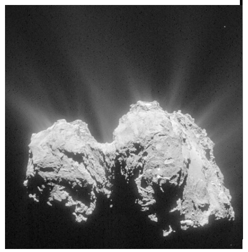
The plasma environment of a comet: electron populations

Inner coma



[Henri et al, 2017]

Vertical profile



Electrons:

warm (5 eV)
+ **hot** (30-200 eV)

[Broiles et al. 2015, Clark et al. 2015, Madanian et al. 2016, 2017, Myllys et al., 2019]

Electron exobase

warm (5 eV)
+ cold (<0.1 eV)

[Eriksson et al. 2017, Gilet et al. 2017, 2020, Wattieaux et al, 2020 etc…]

Magnetic field:

Piled-up
(few 10 nT)
& draped

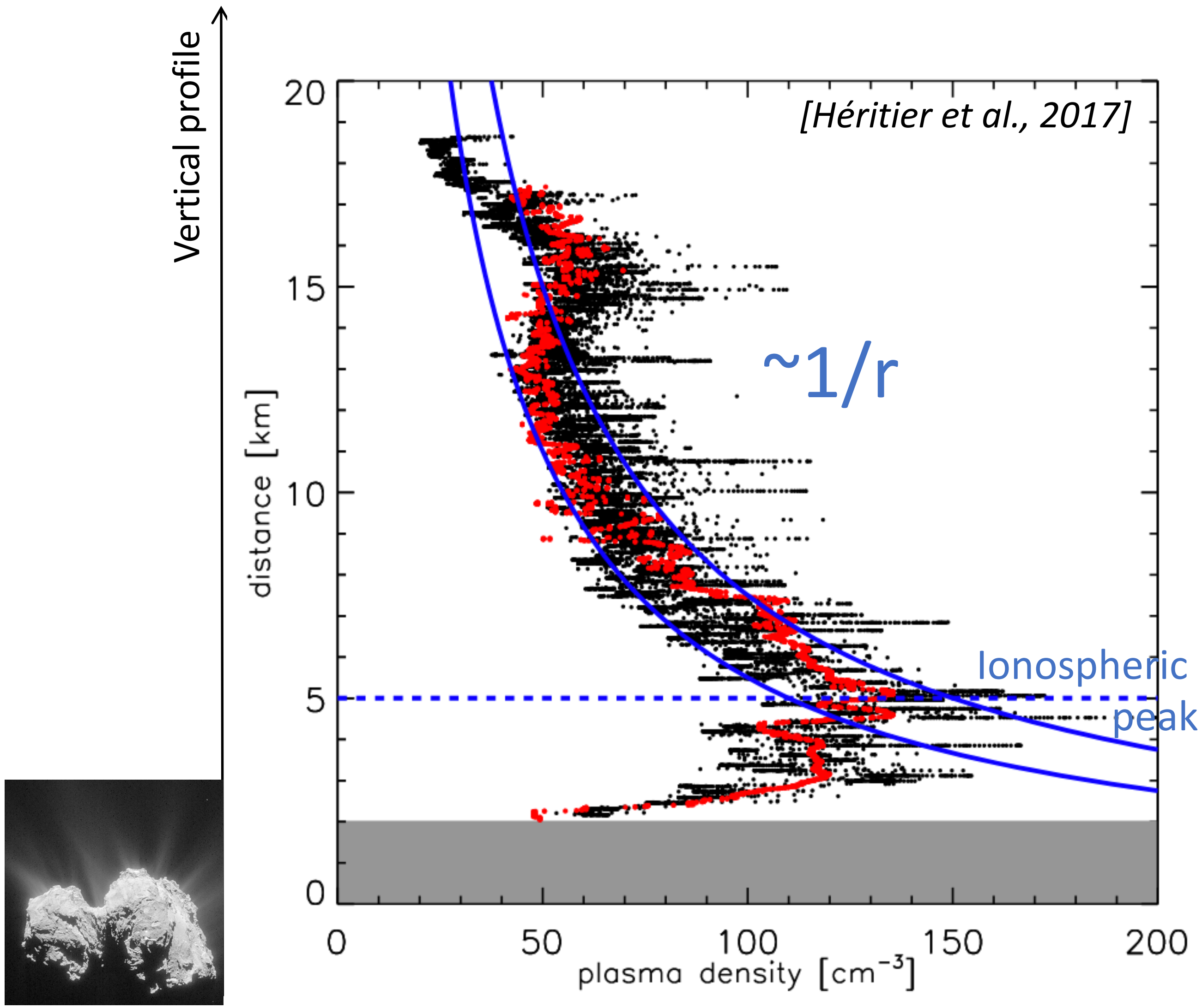
diamagnetic cavity/regions

No magnetic field

[Goetz et al. 2016ab, Nemeth et al. 2016, Madanian et al. 2017, Henri et al. 2017, Hajra et al. 2018]

The plasma environment of a comet: electron populations

Inner coma



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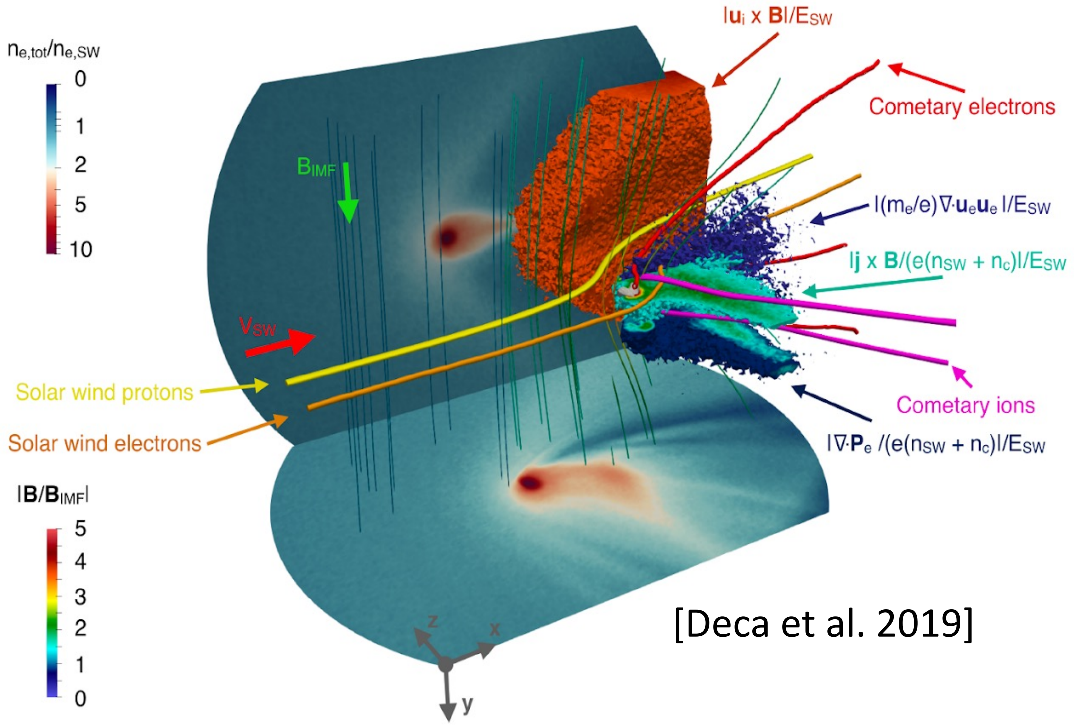
The plasma environment of a comet – Electric fields

- *Convective, Hall, Ambipolar [Deca et al. 2019], polarization [Nilsson et al. 2018]*
- *Focus on **ambipolar electric field** [Madanian et al. 2017; Deca et al 2017, 2019, Divin et al 2020]*



[Deca et al. 2019]

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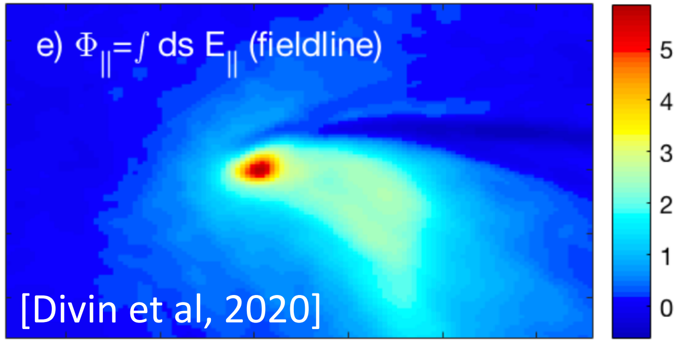
Ambipolar electric potential



➔Potential well
for electrons

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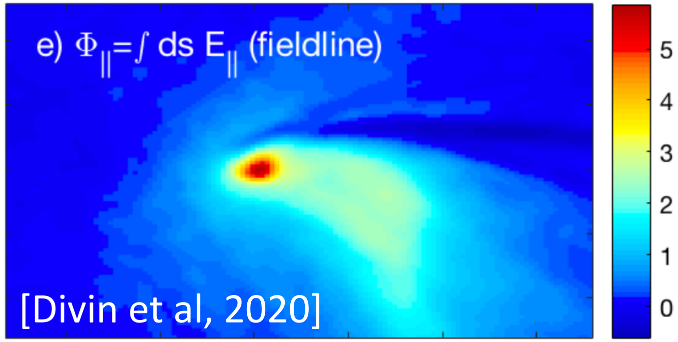
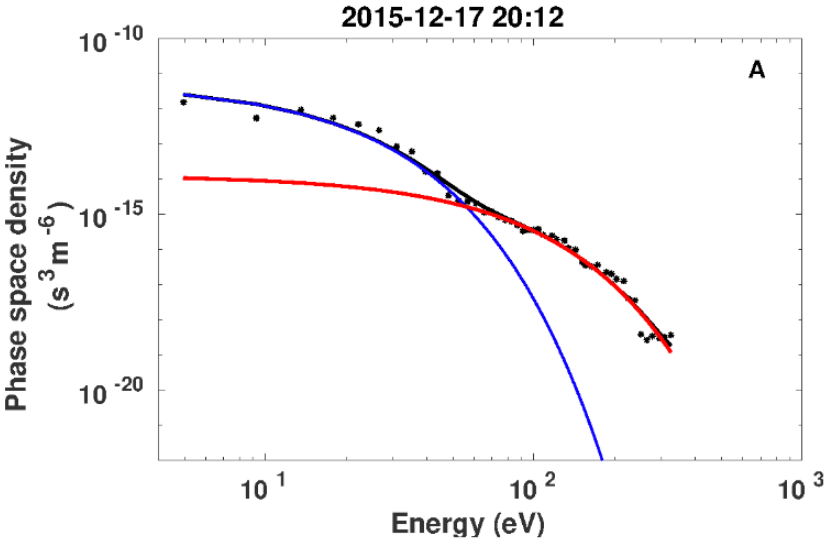


➔Potential well for electrons

Hot electrons
(30-200 eV)

Electron acceleration → heating



[Myllys et al 2019]

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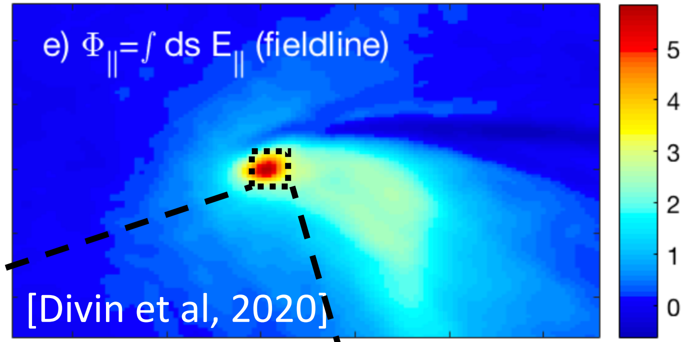
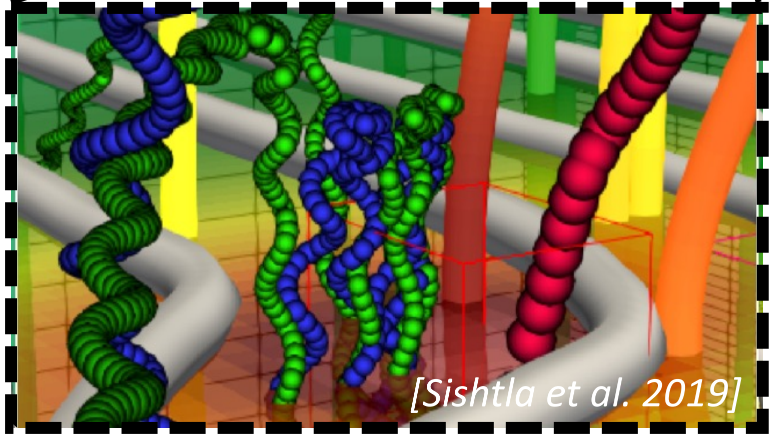
Ambipolar electric potential

Cold electrons (<0.1e eV)

Hot electrons (30-200 eV)

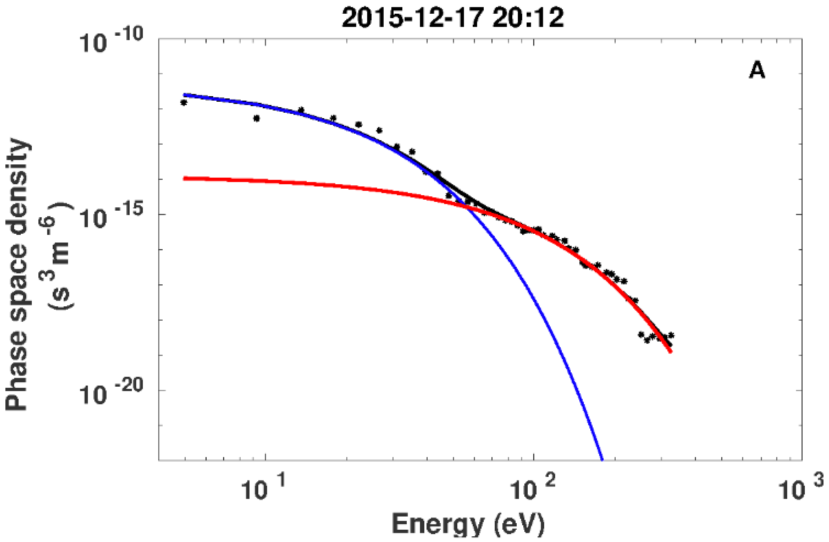


Electron trapping in the inner coma
➔ Electron-neutral collisions increase
➔ efficient cooling



Test-particules : PIC + Collisions (Monte-Carlo) *[Stephenson et al., 2022]*

Electron acceleration → heating



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Ambipolar electric potential

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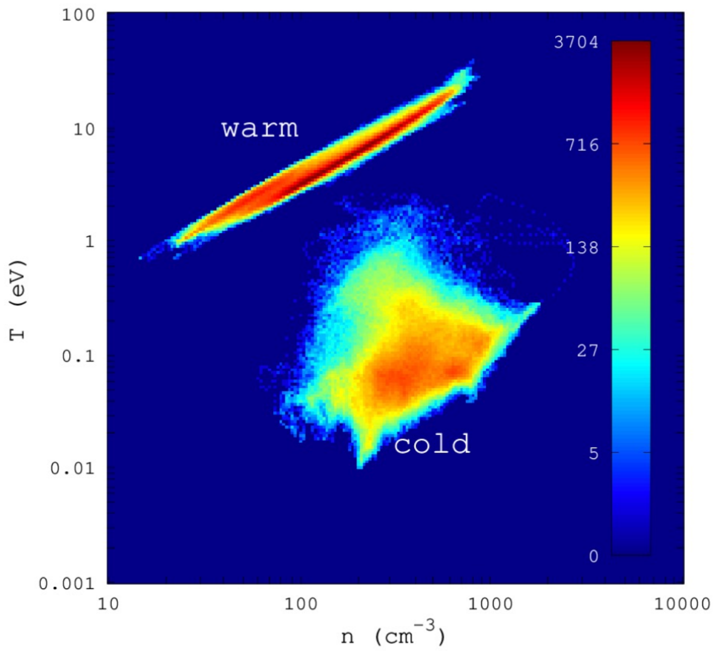
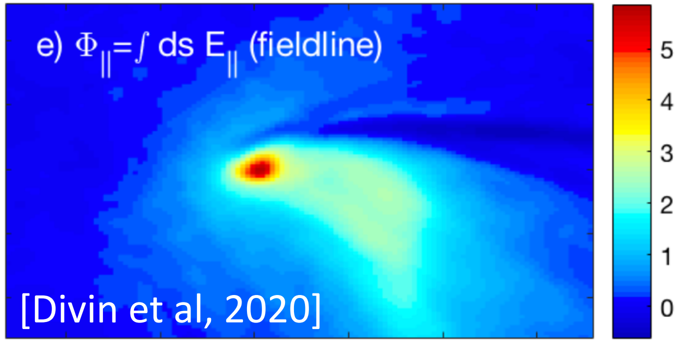
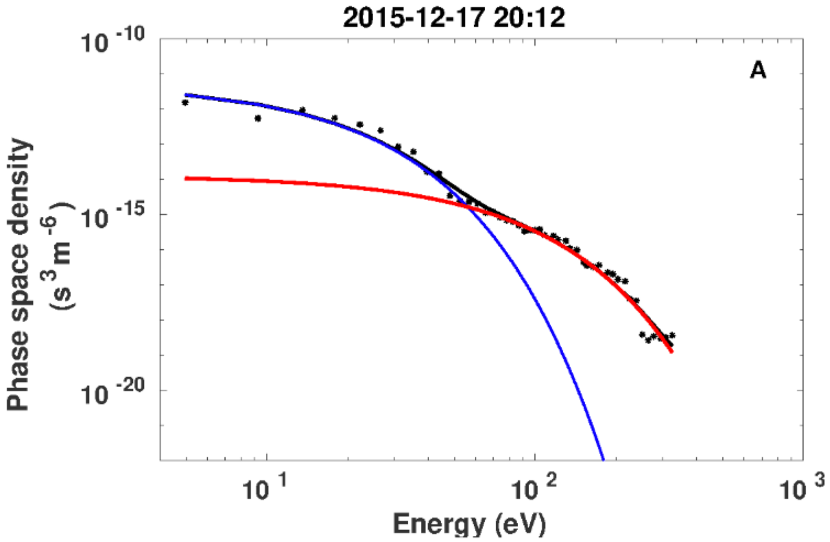


[Wattieaux et al. 2020]

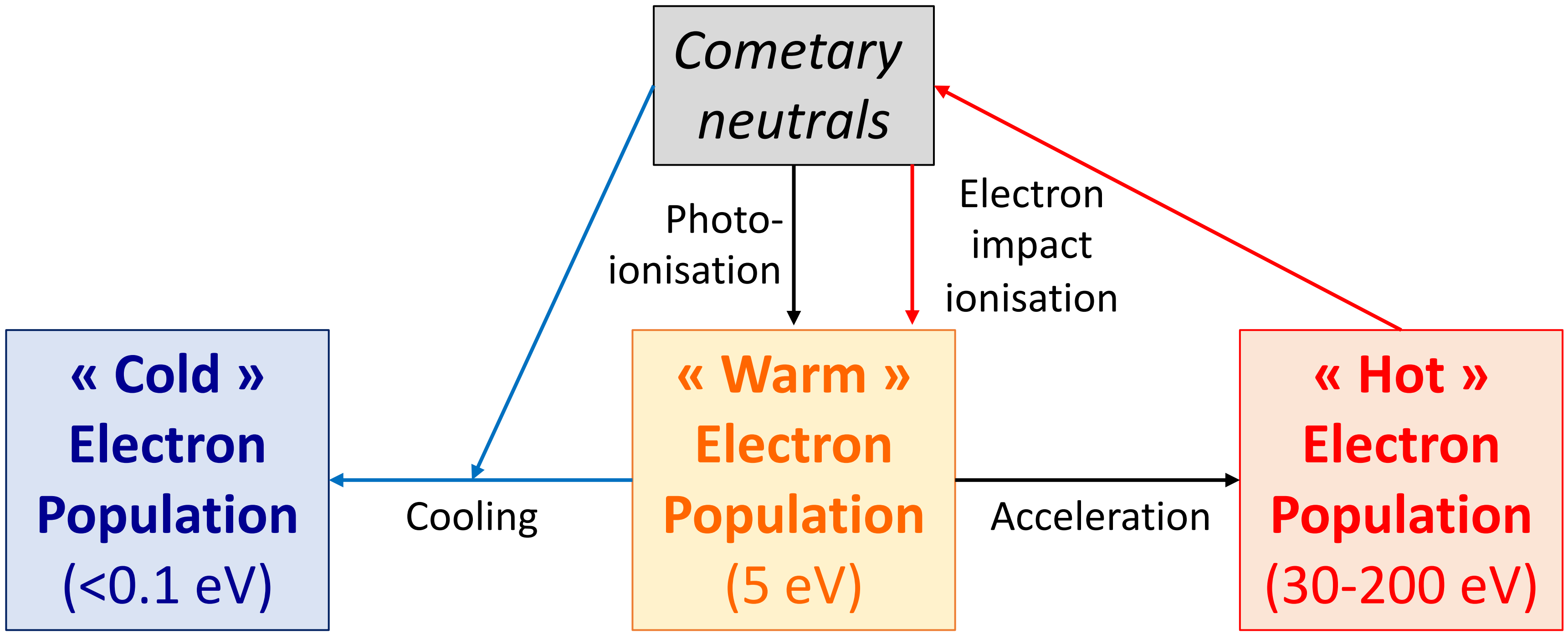


Electron acceleration → heating



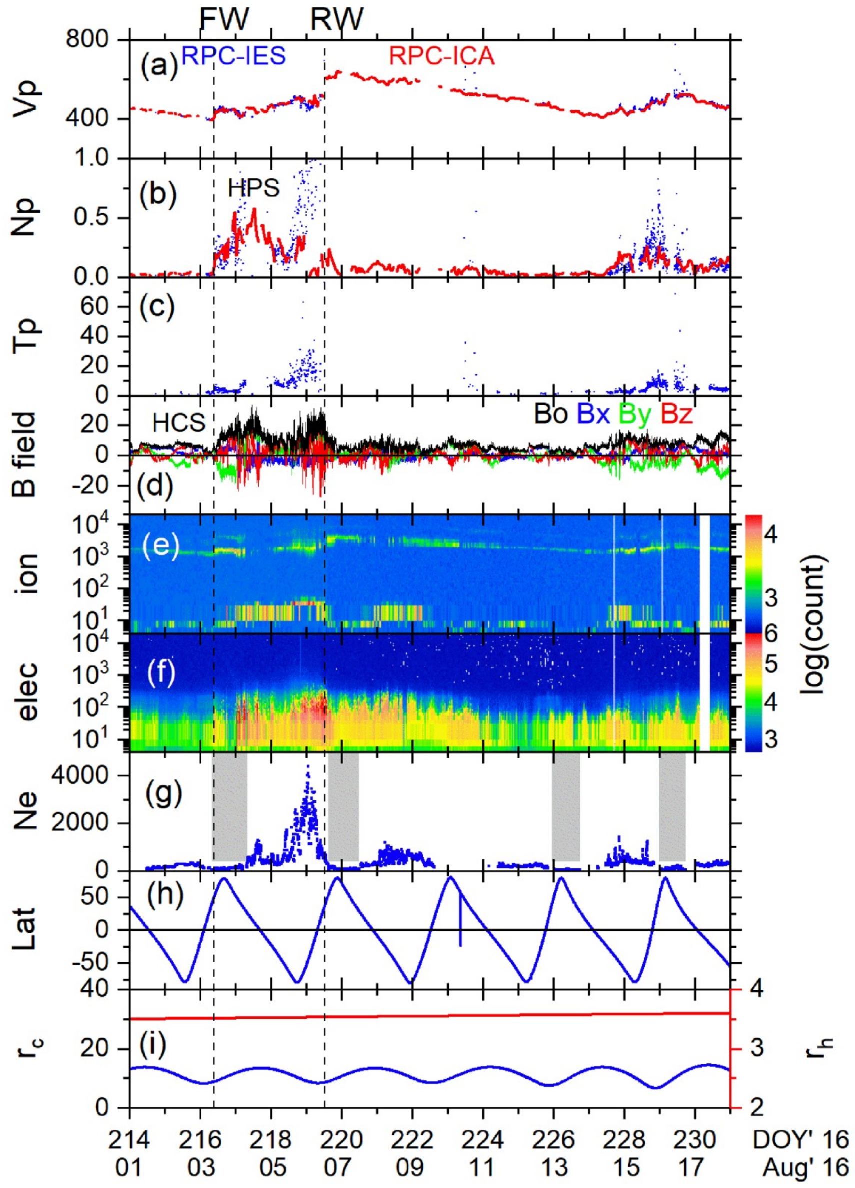
[Myllys et al 2019]

Cometary Electron Populations

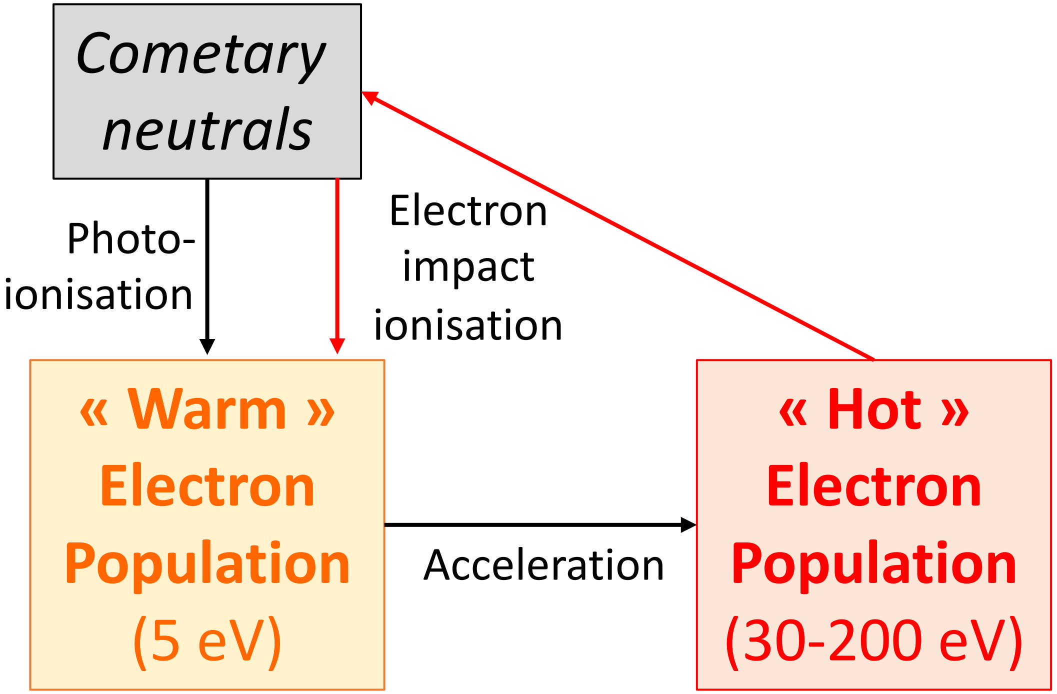


➔ Cometary dust charging processes to be controlled by the flux of those electron populations

Cometary Electron Populations



[Hajra et al. 2018]



Example: CME or CIR impact on a comet

→ ~~Compression~~ but <u>expansion</u> of the induced cometary magnetosphere

Cometary Dust and Plasma: from Rosetta to Comet Interceptor

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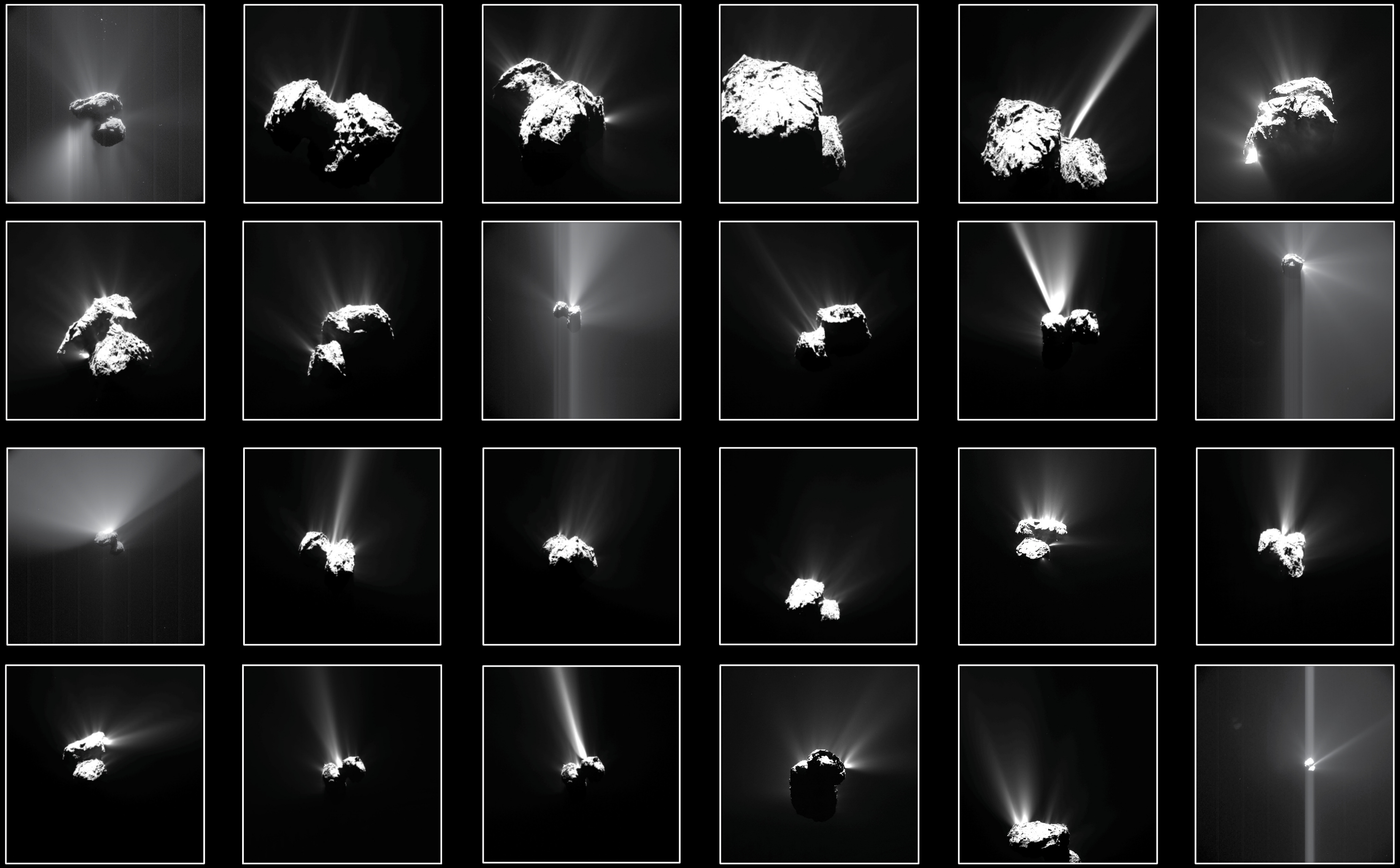
Cometary Dust Outbursts



Credits: OSIRIS: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; NavCam: ESA/Rosetta/NavCam

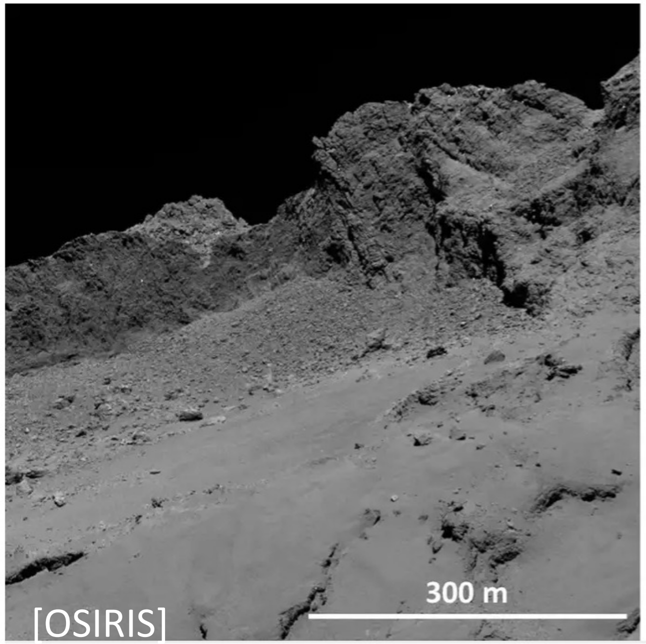
Cometary dust observations by Rosetta

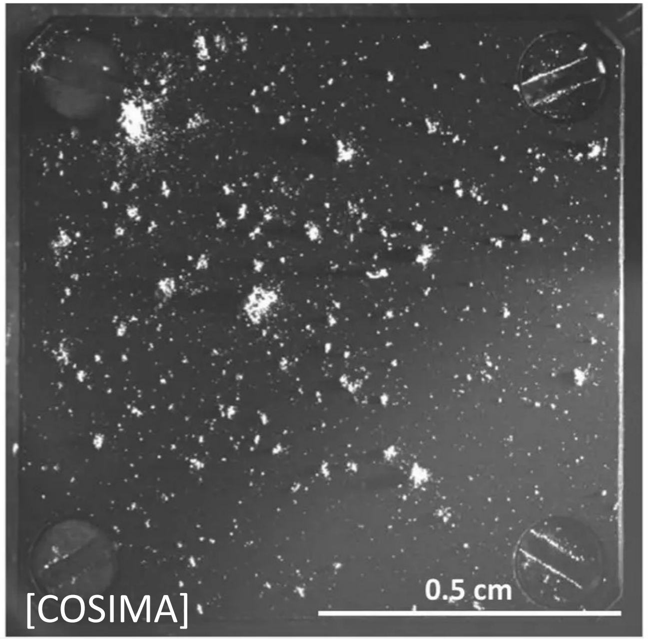
- **Many** observations of dust

[Some reviews: Hilchenbach et al 2017, Levasseur-Regourd et al 2018, Vincent et al., 2019, Guttler et al. 2019, Choukroun et al 2020, etc]

  - *COSIMA:* secondary ion mass spectrometer equipped with a dust collector and camera
  - *GIADA:* Grain Impact Analyser and Dust Accumulator
  - *MIDAS:* atomic force microscope for dust micro-imaging

  - *OSIRIS* (cometary dust imaging, e.g. dust size distribution *Marschall et al., 2020*)
  - *VIRTIS* (Visible and Infrared Thermal Imaging Spectrometer)
  - *IES* (Ion and Electron Spectrometer)





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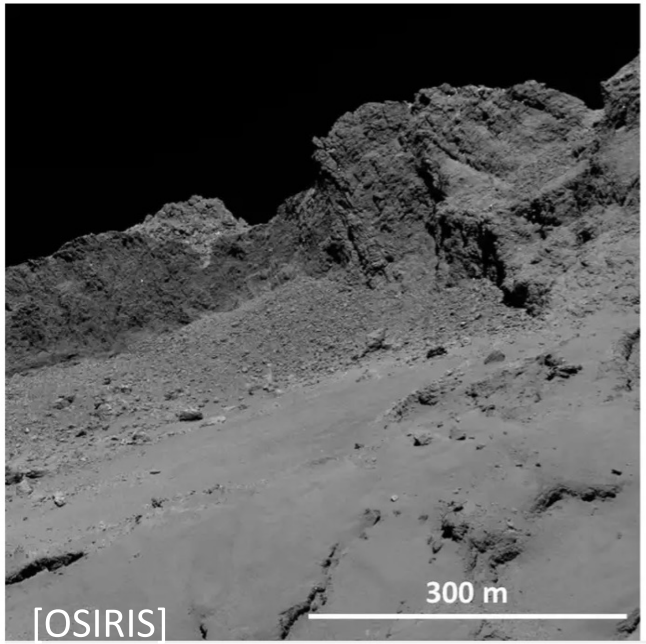
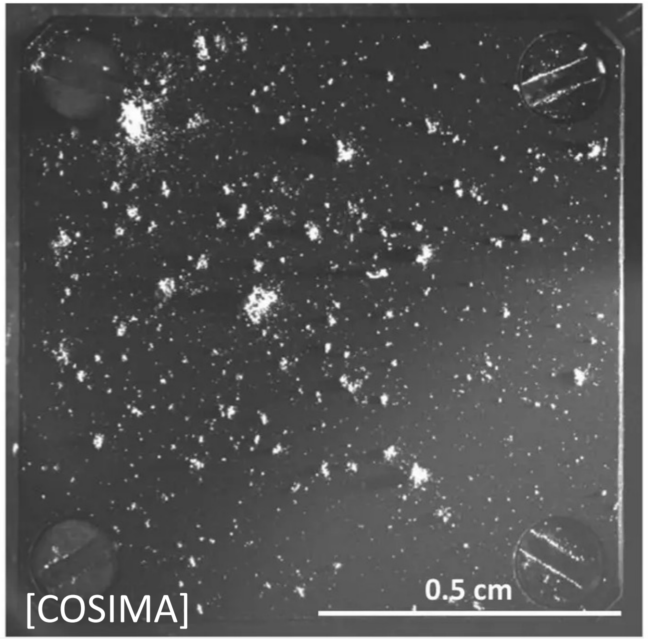
	MIDAS	COSIMA	GIADA	OSIRIS	VIRTIS	Stardust
Porous group - Porosity 10–95% - Aggregate - Low strength	1–50 μm	14–300 μm on target; up to mm range parents	0.1–0.8 mm	~100 μm-1 m, dominant scatterers	Dominating size distribution (diff. slope –2.5 to –3)	Particle creating track A with multiple terminals or track B 1–100 μm
Fluffy group - Porosity >95% - Likely fractal - Very low strength	fractal: 15–30 μm $D_f = 1.7 \pm 0.1$ constituent particles: <1.5 μm	No indication	0.1–10 mm $D_f < 1.9$, ~23% of GDS detections	Not dominant scatterers	Not excluded, consistent with moderate super-heating in normal activity	Particle creating bulbous tracks (B for coupled, A* or C for fluffy GIADA detections), aluminum foil clusters. Up to 100 μm
Solid group - Porosity <10% - Consolidated - High strength	50–500 nm fragments collected on tip	CAI candidate and specular reflection 5–15 μm	0.15–0.5 mm ~4000 kg m^{-3}	No indication	Outburst: temperature requires 0.1 μm particles	Particle creating track A with single or multiple terminals, tens of nm, 1–100 μm

[Guttler et al. 2019]

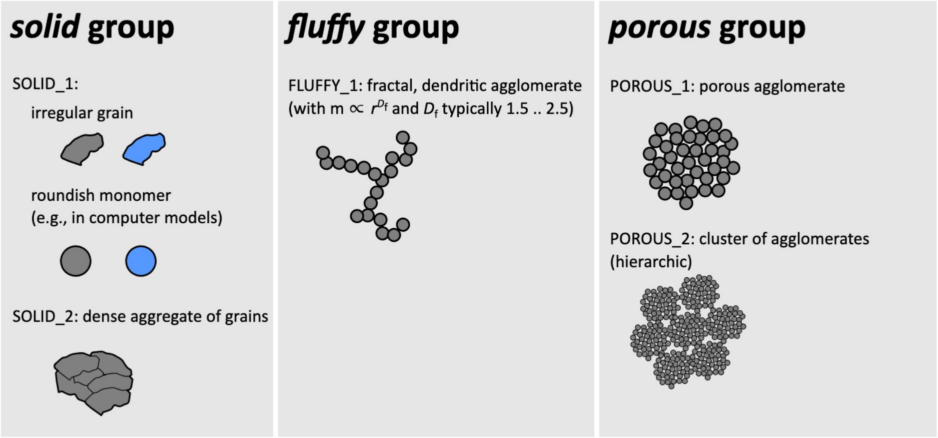




Cometary dust observations by Rosetta

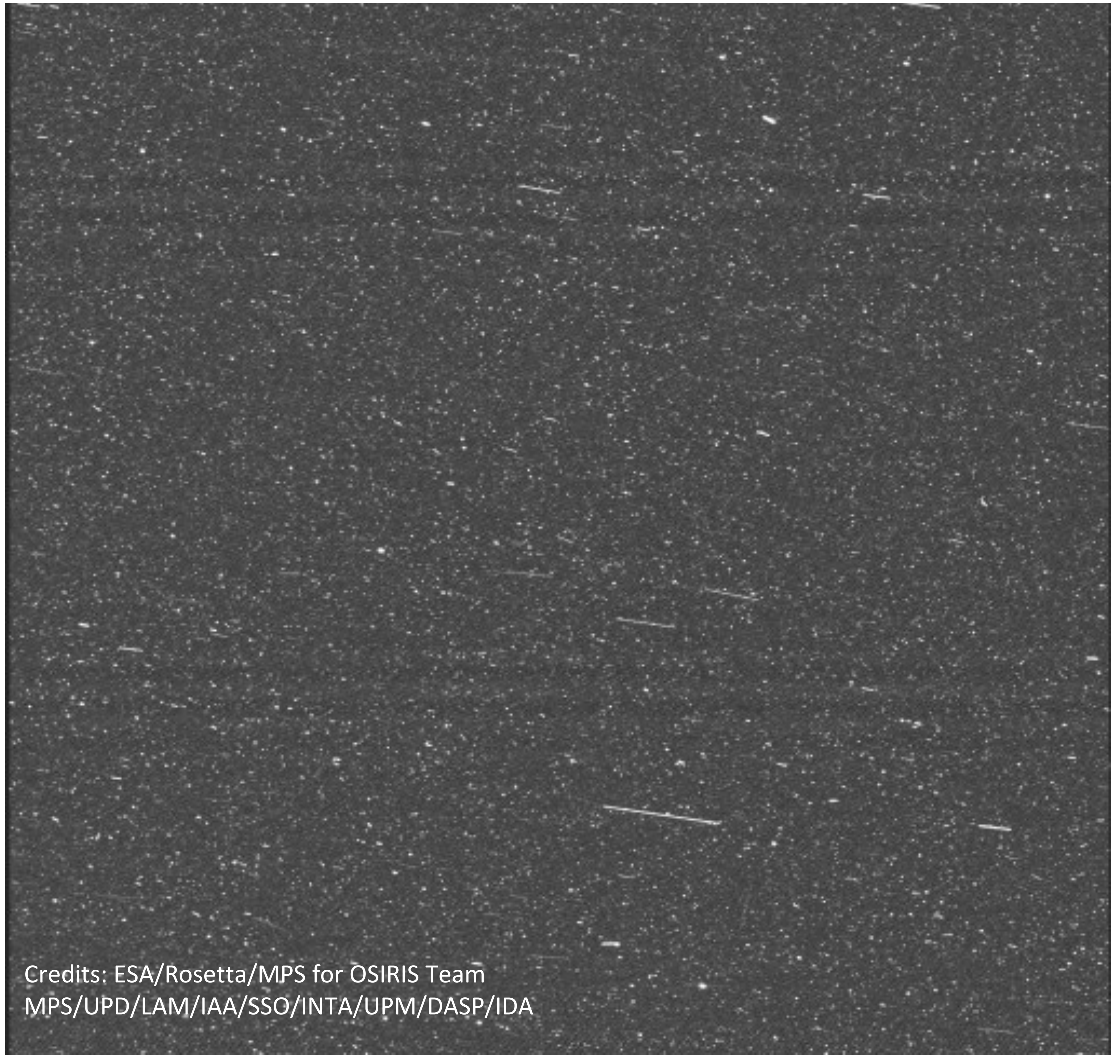
- **Composition**

- **Morphology** aggregates of grains
  (dense aggregates and porous agglomerates)

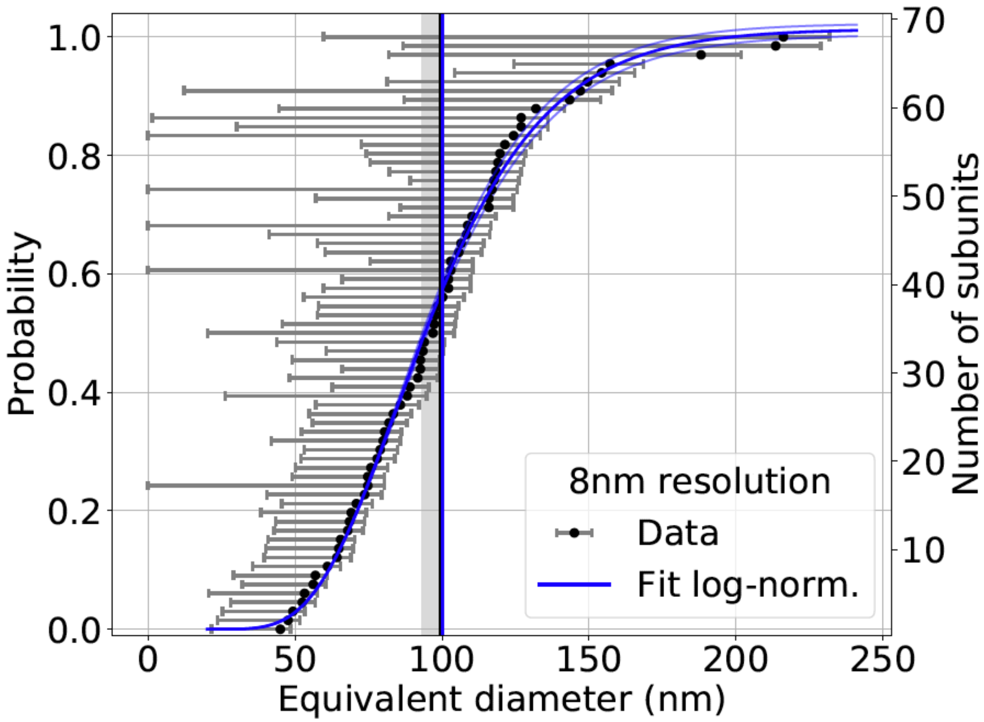


[Guttler et al. 2019]

- **Velocity**: dust at ~1 to 100 m/sec
  (mostly larger than escape velocity)



Cometary dust observations by Rosetta



[Mannel et al 2019]

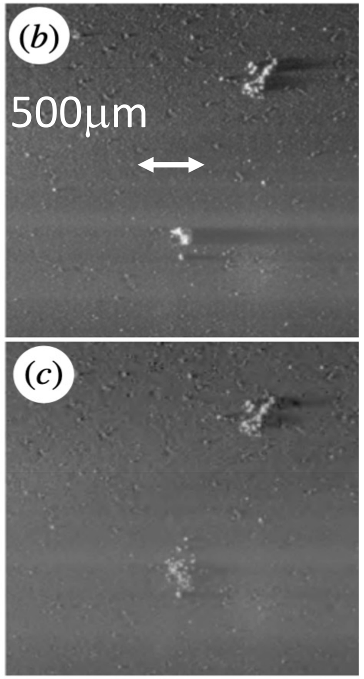
Size distribution:

Dust aggregates observed from 100 μm to mm-size: **power law with index -3 to -4**

Dust grains of few to few 10 μm, with subunits with sizes following a log-normal distribution with a mean of from 1 μm to **100 nm**

→ *Could those subunits fragmentate and form nm grains?*

*What about **charged** cometary dust?*

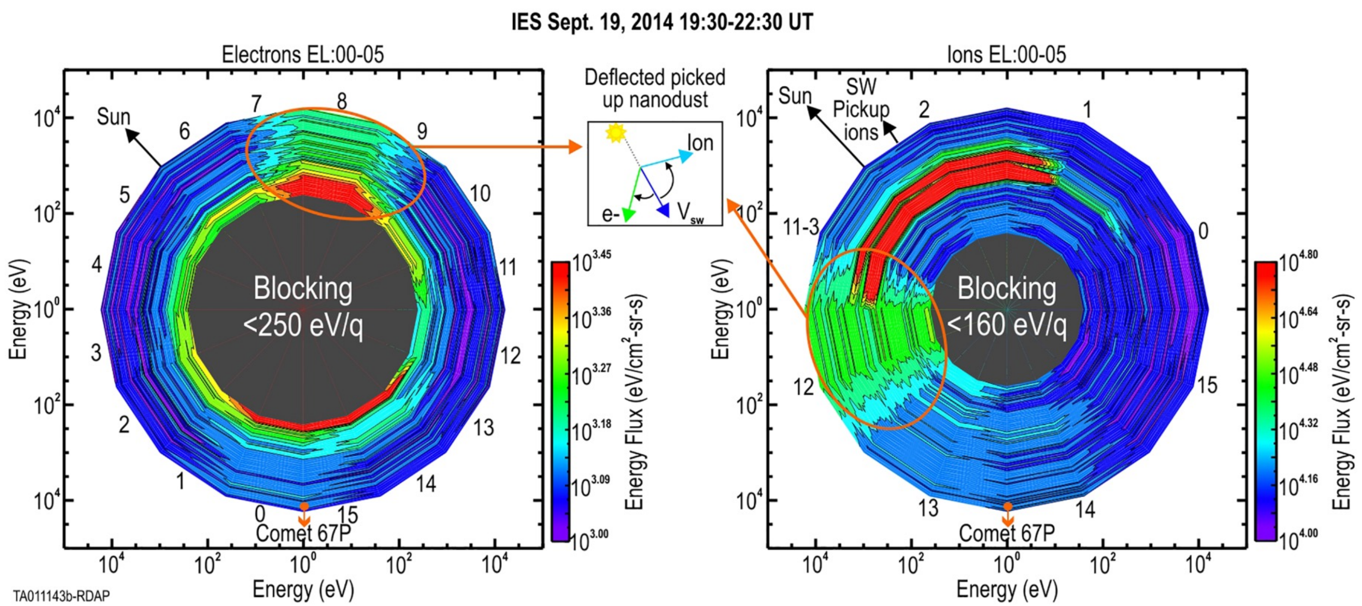


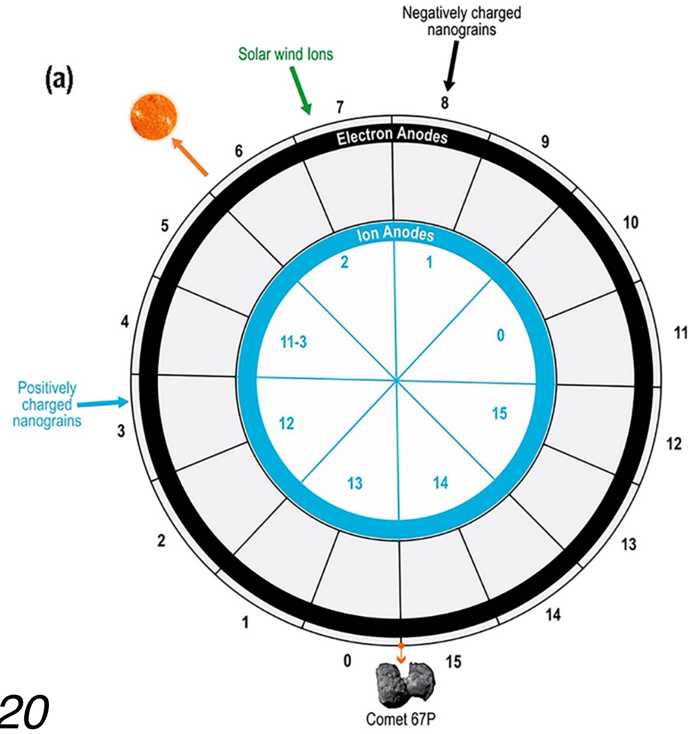
[Hilchenbach et al. 2017]

[Bentley et al., 2016; Mannel et al 2019]

Cometary *charged* dust observations by Rosetta

- Few observations of charged dust, with the Ion and Electron Spectrometer *[Burch et al. 2015 ; Llera et al. 2020]*
- Model for charged nanodust dynamics consistent with IES nanodust observations *[Gombosi et al. 2015]*





Llera et al. 2020

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- Model for charged nanodust dynamics consistent with IES nanodust observations *[Gombosi et al. 2015]*

- **What about charged dust at the comet nucleus surface?**
  - Outgassing activity observed at large heliocentric distances (at least up to 3.8 A.U) ➔ dust lifting appeared dominated by gas sublimation.
  - "Asteroid-like" comet behavior not observed by Rosetta.
  - Indirect signature of electrostatic lifting of charged dust on surface images during early part of the mission?

Cometary charged dust observations by Rosetta

Feedback from cometary charge (nano)dust on cometary plasma composition and dynamics? How much charge is carried by cometary (nano)dust ?

Enough to generate an electron / an ion depletion? (as in Enceladus plume *[Morooka et al. 2011; Hill et al. 2012]* and Titan's ionosphere *[Coates et al. 2007; Shebanits et al. 2013])*

Unfortunately, no reliable measurements of ion densities (instrumental limitations associated with low orbital velocity of Rosetta).

Models predicting: **no observable electron or ion depletion expected** from cometary nanodust *[Vigren et al. 2021, Vigren et al. 2022].*

➔**Dusty plasma waves** unlikely (no reported observation of ultra LF waves).

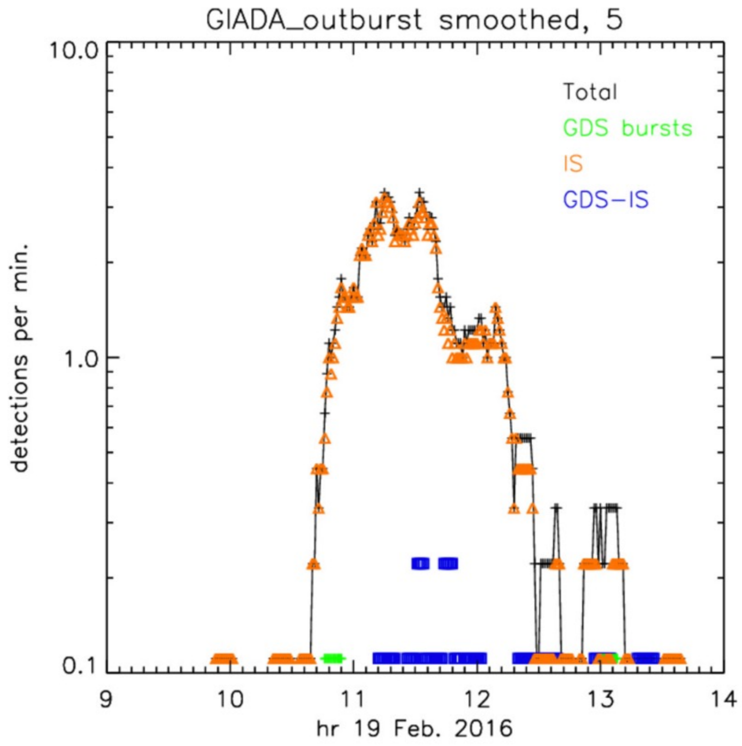
➔What about during **outburst**?

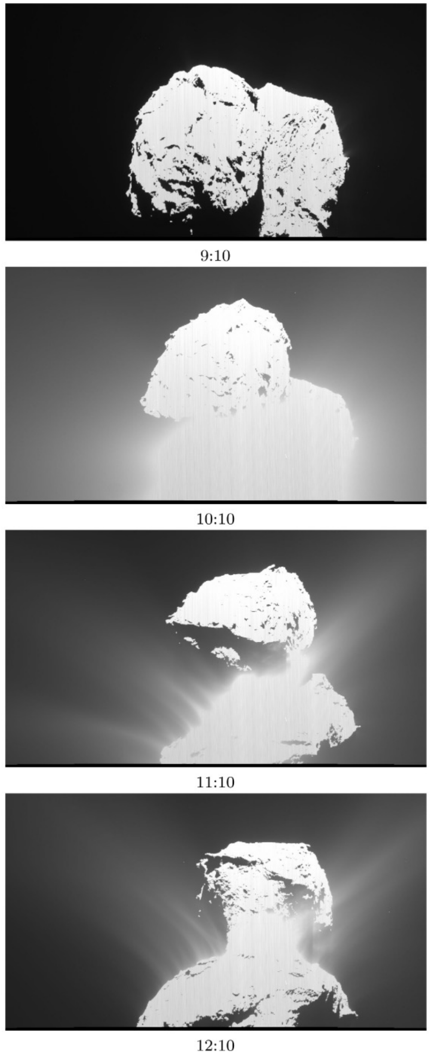
Dust & plasma observations during cometary outburst

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **462,** S220–S234 (2016) doi:10.1093/mnras/stw2088
Advance Access publication 2016 August 25

The 2016 Feb 19 outburst of comet 67P/CG: an ESA Rosetta multi-instrument study

Grün et al, 2016





A&A 607, A34 (2017)
DOI: 10.1051/0004-6361/201730591
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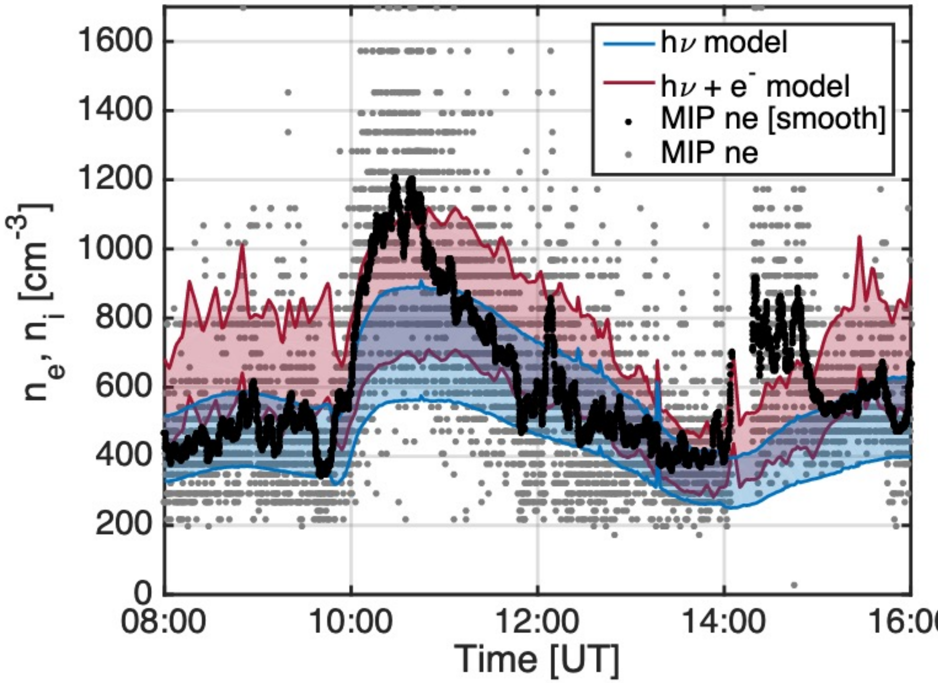
Astronomy & Astrophysics

Impact of a cometary outburst on its ionosphere

Rosetta Plasma Consortium observations of the outburst exhibited by comet 67P/Churyumov-Gerasimenko on 19 February 2016

R. Hajra[1], P. Henri[1], X. Vallières[1], M. Galand[2], K. Héritier[2], A. I. Eriksson[3], E. Odelstad[3], N. J. T. Edberg[3], J. L. Burch[4], T. Broiles[4], R. Goldstein[4], K. H. Glassmeier[5], I. Richter[5], C. Goetz[5], B. T. Tsurutani[6], H. Nilsson[7], K. Altwegg[8], and M. Rubin[8]



Exceptional dust detection. Stronger electron density enhancement than expected. No charged dust detection on spectrometers

Cometary charged dust observations by Rosetta

Summary of Rosetta dust and plasma observations at comet 67P :

- Plasma effect on dust: **ok** (but probably more to dig from the data)
- Dust feedback on plasma: **not found yet** (if any)

➔ The inner coma of comet 67P was likely more in the *dust-in-plasma* regime than the *dusty plasma* regime.

Final word?

➔Mostly dust-only and plasma-only studies so far.
Dusty plasma studies to come next
(but require experts in the field ➔ You!)

From Rosetta to Comet Interceptor

Motivations for a new cometary mission:

1) Significant surface processing even after few passages within inner solar system

➔ Need to visit a **dynamically-new comet**

(i.e. 1st passage within inner solar system)

2) Single s/c measurements do not enable to disentangle local dynamics from

➔ Need **multi-s/c measurements**

➔ **Comet Interceptor** selected as first ESA F-class mission, multi-s/c mission to a dynamically new comet.

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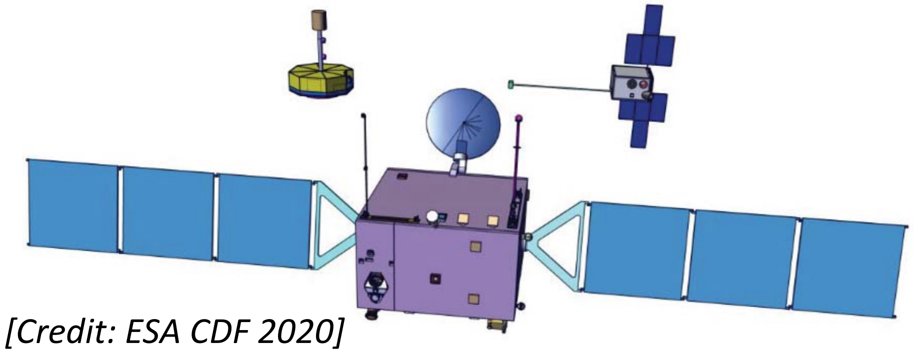


[Credit: ESA CDF 2020]

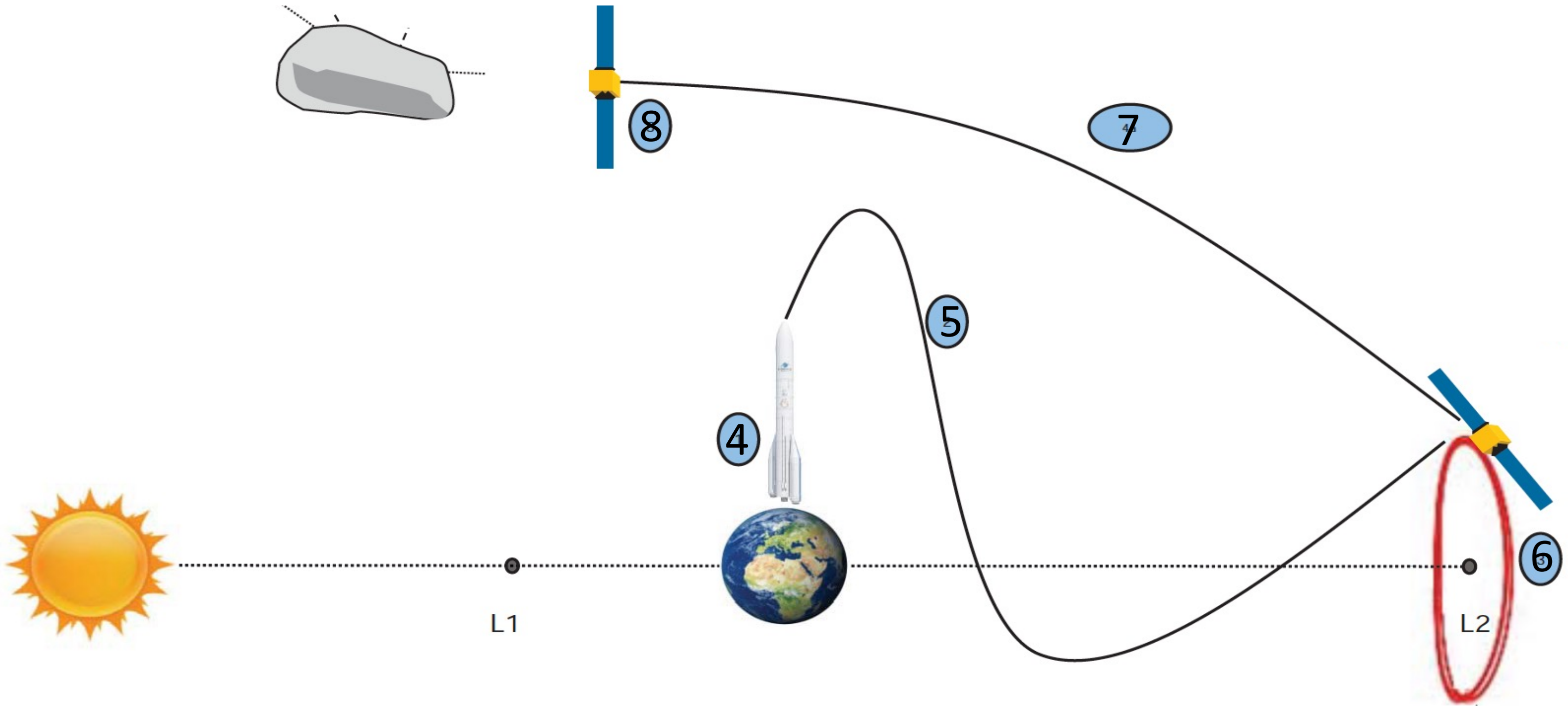
Comet Interceptor

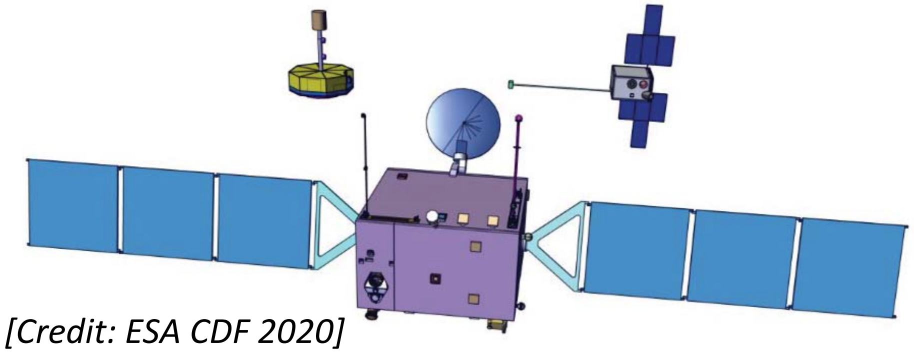
- Dynamically-new comet
- Multi-spacecraft mission

Unknown comet target yet
Fly-by mission

<u>Mission timeline :</u>

1) Mission adoption in 2022
2) *Today: Instrument critical design review.*
3) Instruments delivery in 2026
4) Launch in 2029 (ARIEL piggyback)
5) Transfert to L2
6) Parking
7) Cruise
8) Fly-by





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- Dynamically-new comet
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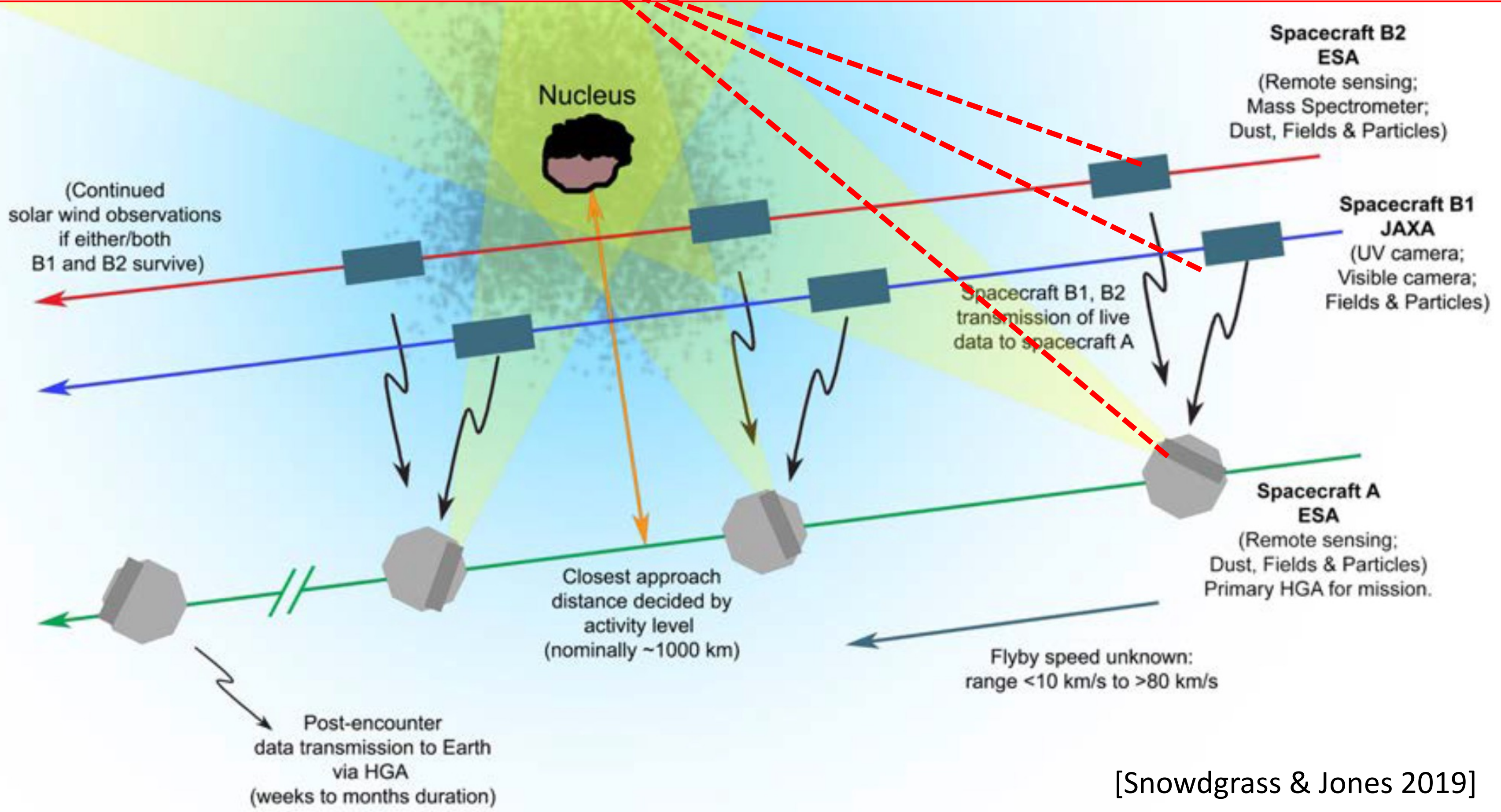
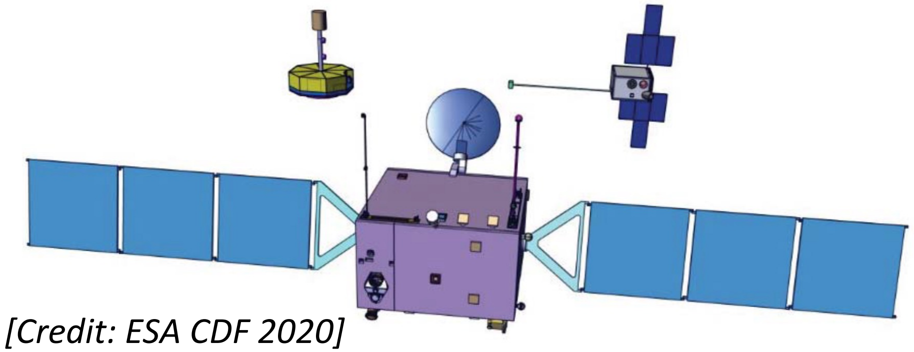


[Snowdgrass & Jones 2019]



[Credit: ESA CDF 2020]

Comet Interceptor

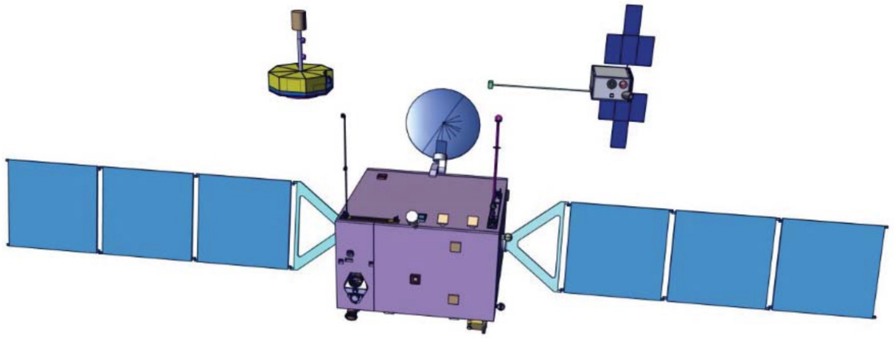
Dust and plasma measurements by Comet Interceptor to be provided by two instrumental consortia:

1) **Dust Field Plasma (DFP) consortium**:

- Magnetometer
- **Combined Langmuir and Mutual Impedance Probe, with nanodust detection**
- **Ion and energetic neutral mass spectrometer**
- **Electron spectrometer**
- **Dust impact sensor and counter**

2) **Plasma Suite (PS)**:

- Magnetometer
- **Ion spectrometer**



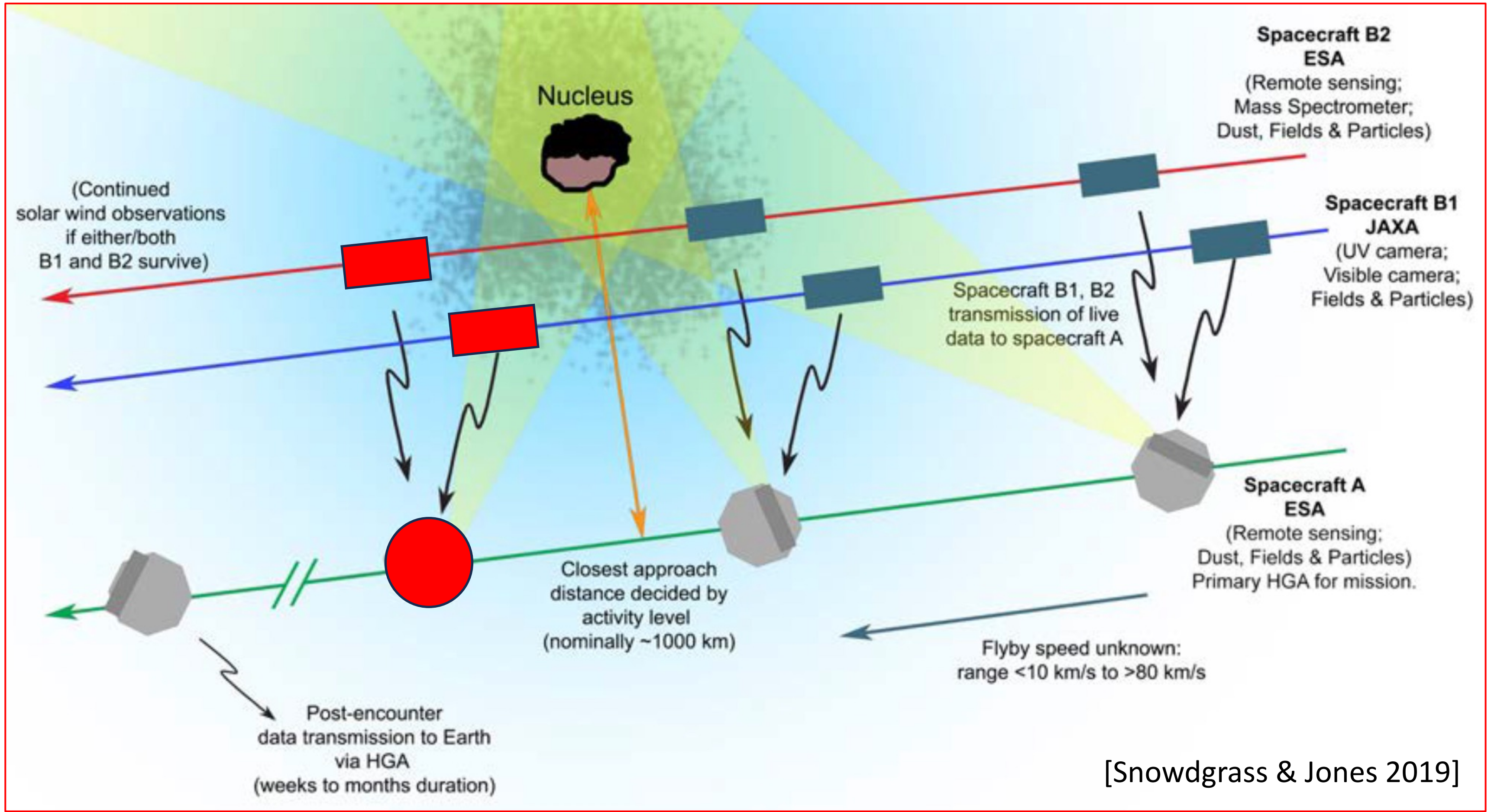
Comet Interceptor

- Dynamically-new comet
- **Multi-spacecraft** mission

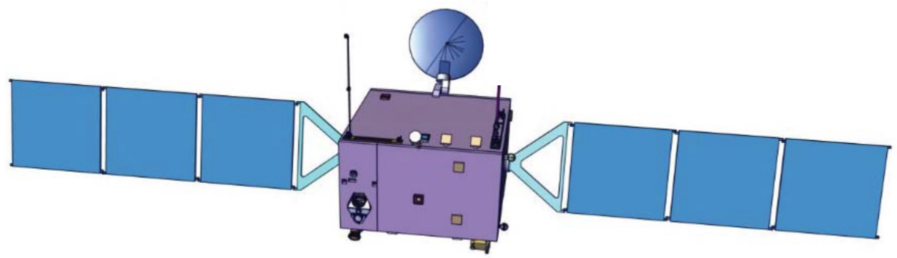
Magnetic field *(3 s/c)*

Plasma *(2 s/c)*
Dust *(2 s/c)*

Electric field *(1 s/c)*



[Snowdgrass & Jones 2019]



Comet Interceptor

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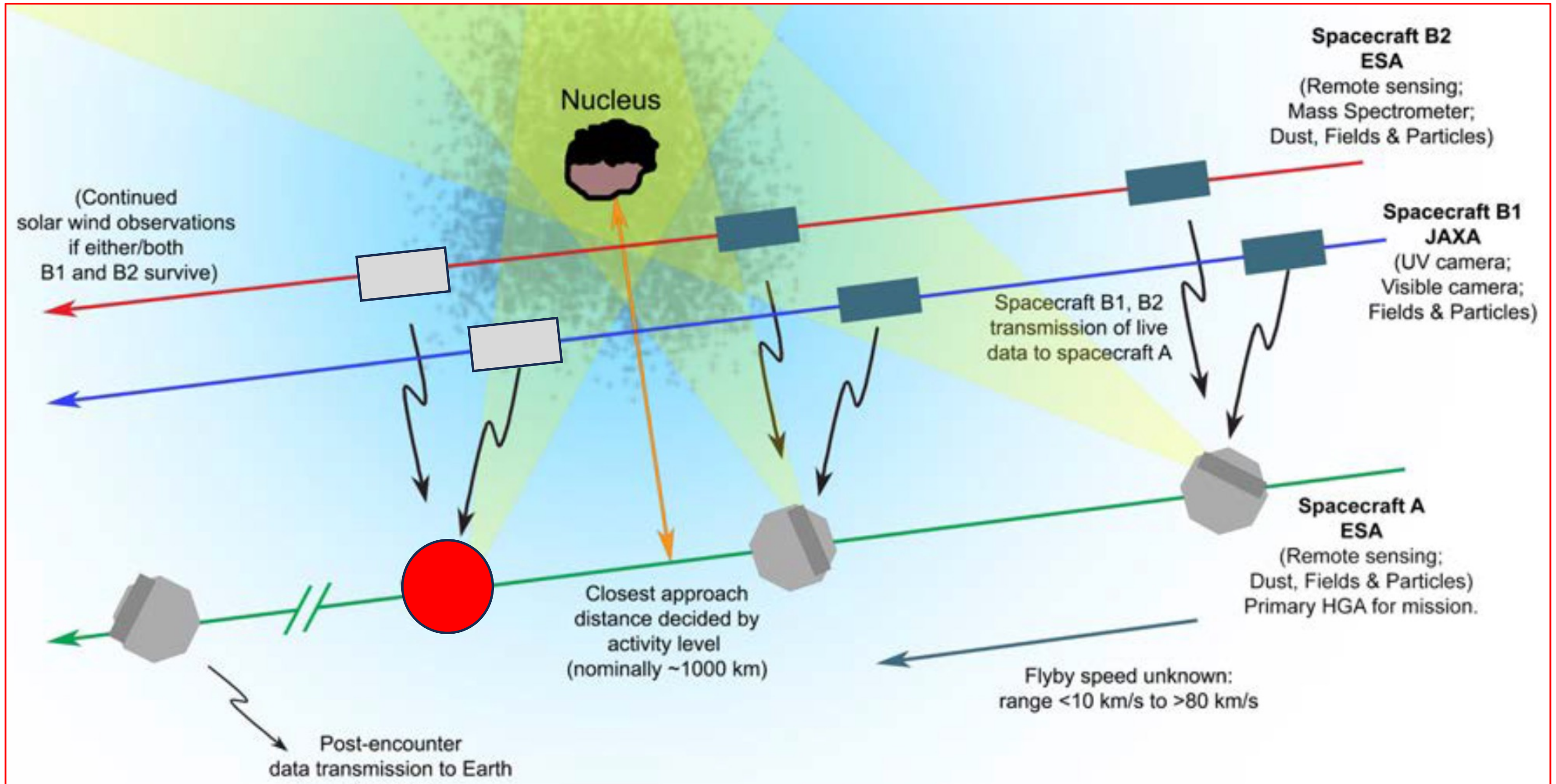
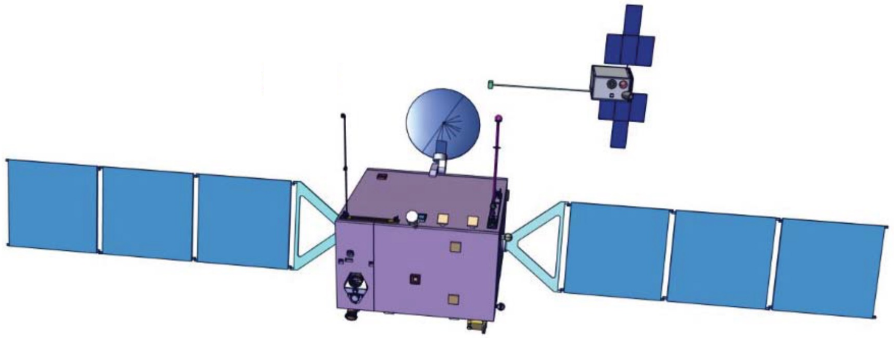


[Snowdgrass & Jones 2019]

Comet Interceptor



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- **Multi-spacecraft** mission

Magnetic field *(3 s/c)*

Plasma *(2 s/c)*

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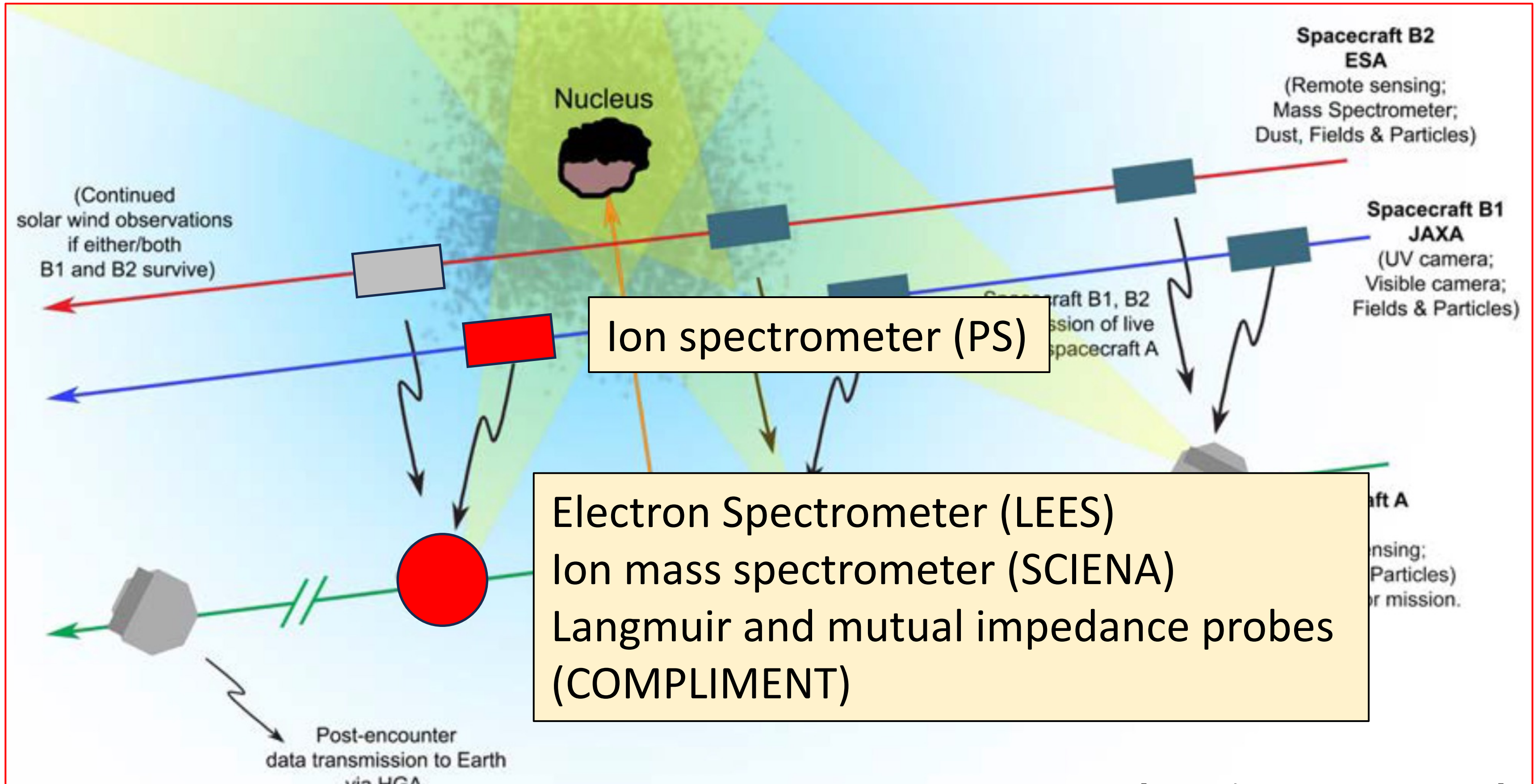
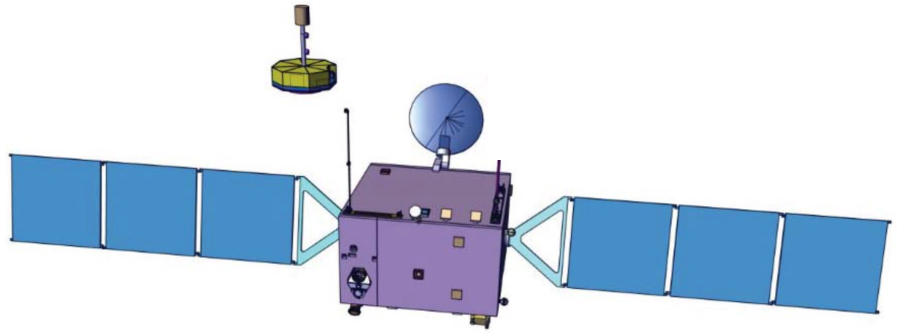


[Snowdgrass & Jones 2019]



Comet Interceptor

- Dynamically-new comet
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Dust *(2 s/c)*

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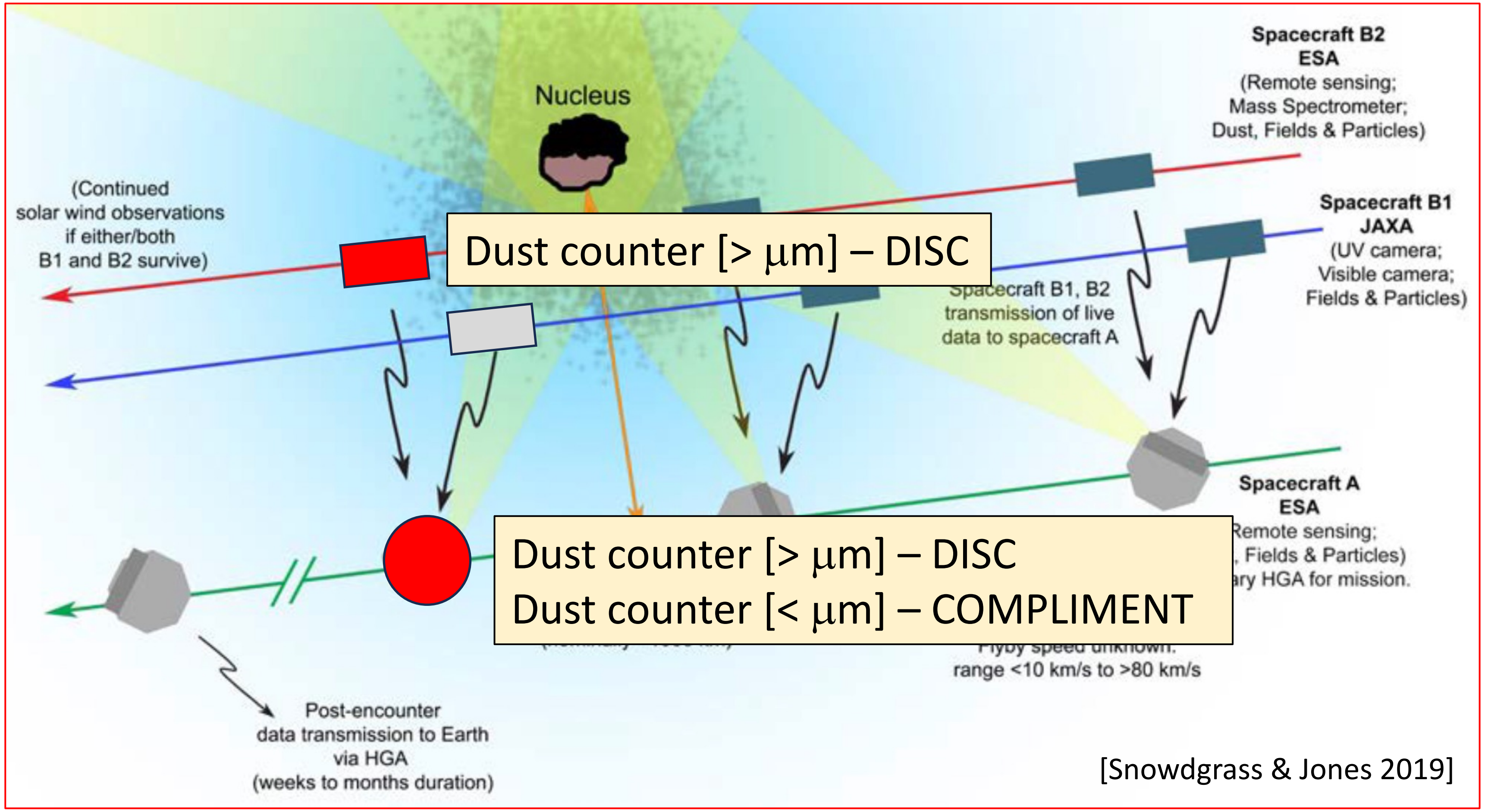
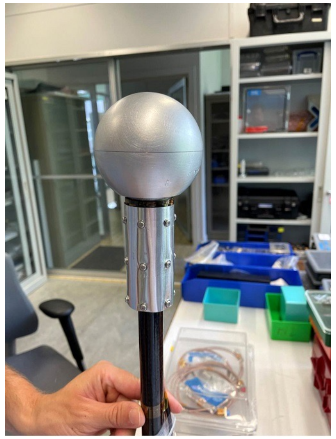
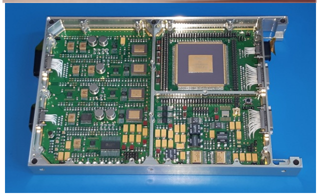


COMetary Plasma Light InstruMENT (COMPLIMENT)

Electric instrument combining **mutual impedance probe** + **Langmuir probe** + **electric antenna** to measure:

- **Plasma** (independent electron and ion **densities** at 2 sec, plasma density up to 10 msec, electron **temperature** at 1 sec)
- **Electric field** (1D, 1Hz-2MHz)
- **Nanodust detection capability**
- **S/c potential**





[COMPLIMENT engineering model]

Table 6.3.2. DFP-COMPLIMENT parameters

Measured Quantity	**Range**
Electric field component, δE(f)	1 Hz – 1.4 MHz ; 2μV/m/√Hz (>500Hz)
Electron density (N_e)	$10^2 – 10^5$ cm^{-3}
Density fluctuations (δn/n)	DC – 10kHz
Ion density (N_i)	10^2–10^5 cm^{-3}, <1 Hz
Electron temperature (T_e)	0.01 – 30 eV, <1Hz
Ion effective mass (amu)	1-100 amu
S/C potential (U_{sc})	Max ±850 V, <100 Hz
Integrated solar EUV flux	<1 Hz

PI: P. Henri
LPC2E (FR) + BIRA (BE) + IRF-U et IRF-K (SE)

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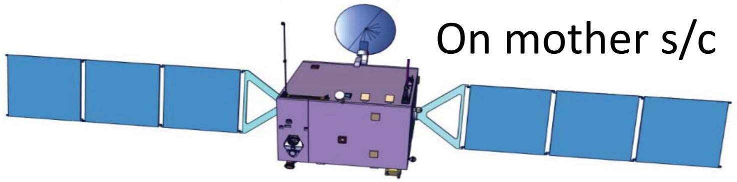
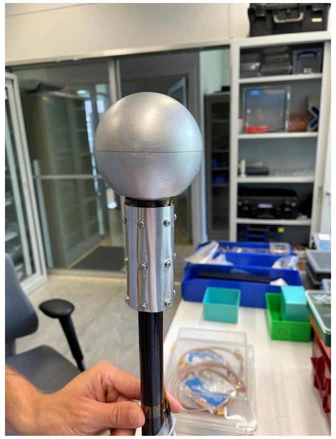
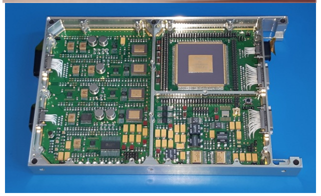


Cometary dust – plasma interactions





[COMPLIMENT engineering model]

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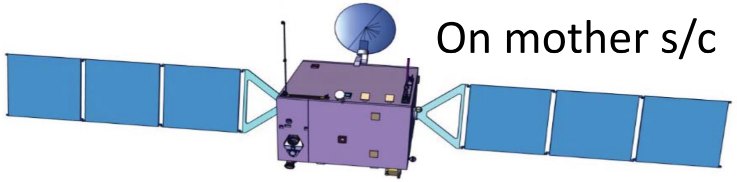
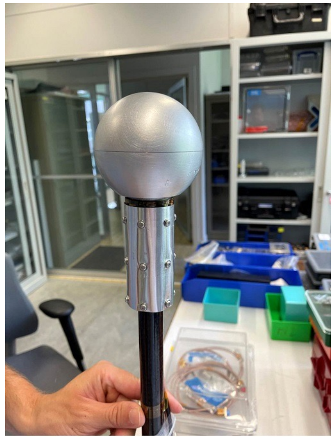
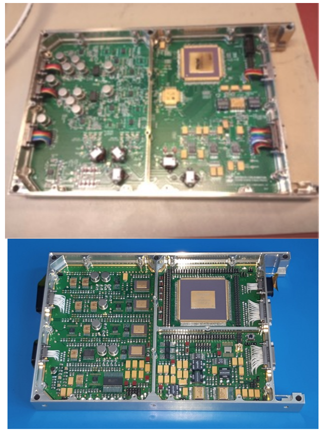


On mother s/c

Cometary dust – plasma interactions

NB: Strength and limitations of Rosetta : low s/c orbital velocity





[COMPLIMENT engineering model]

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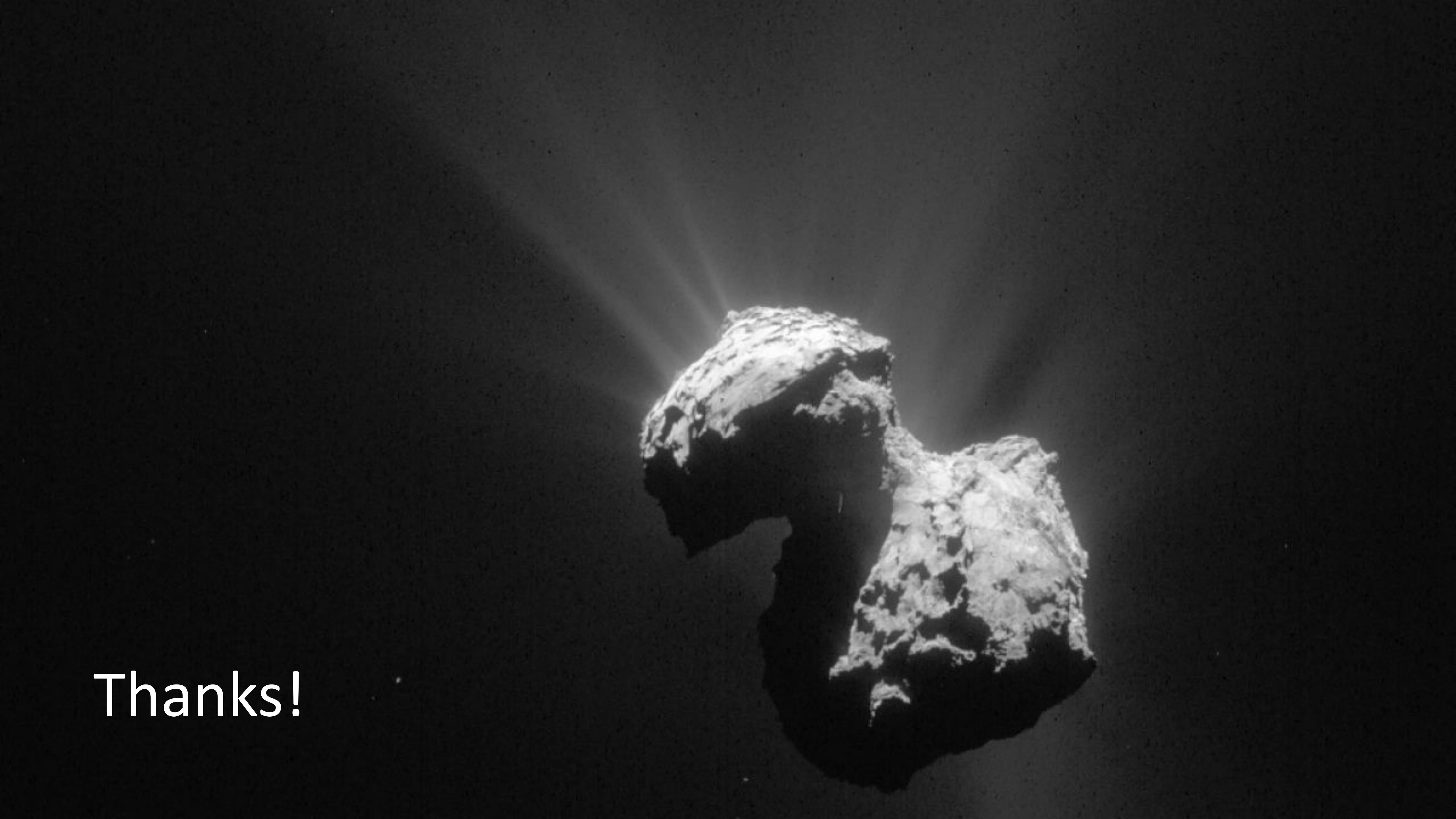
Conclusion

- Rosetta observations of cometary dust and cometary plasma **now mature for more specific dusty plasma studies**
- Fully calibrated data have been available since 2020, **would benefit to be revisited by dusty plasma / charged dust experts**
- **Comet Interceptor** mission to address outstanding issues after Rosetta mission
- Comet Interceptor measurements of dust and plasma to be provided by the same consortium, nanodust and plasma to be provided by the same instrument ➔ shall be more favorable to **dusty plasma studies**


Thanks!