Exploring the solar corona through observations of sungrazing comets with Solar Orbiter/Metis

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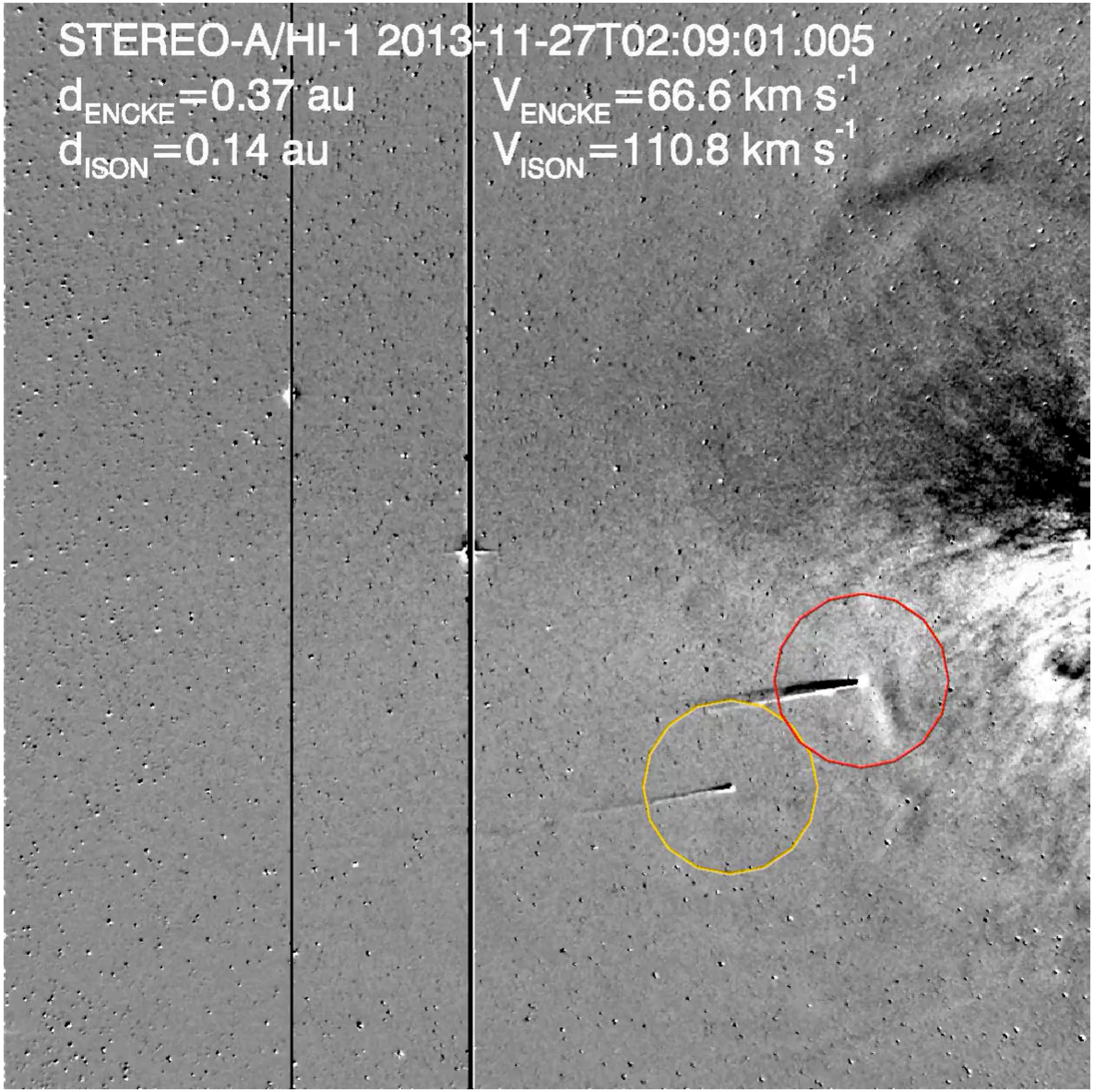
Abstract

Observations of comets with coronagraphs and heliospheric imagers reveal highly dynamic tails, which exhibit disconnections, wave-like motion, and respond to the solar wind flows and to the passage of coronal mass ejections [1, 2]. Furthermore, during the 25 years of the SoHO space mission, the LASCO coronagraphs have observed more than 3500 sungrazing comets plunging in the solar atmosphere [3]. Such comets can be exploited as probes of the corona and the near-Sun environment [4]. The study of comets is relevant to the coronagraph Metis of the Solar Orbiter mission, which will certainly provide observations of sungrazing comets with unprecedented spatial and temporal resolutions, and from very advantageous positions (minimum distance below 0.3 AU), both in the visible and UV wavelengths. Metis will accurately image the interaction of the comet tails with the local medium, observe how cometary ions are channelled along the local magnetic field lines, and allow diagnostics of the coronal plasma encountered by the sungrazing comets, e.g., by spectroscopy in the hydrogen Lyman-α line [5]. Here, we present the work of [6], who proposed that the observed transverse oscillations of comet tails are attributed to the formation of a Kármán vortex street, whose properties depend upon the characteristics of the comet itself and the local medium. Furthermore, we show simulations of trajectories for some groups of sungrazing comets in the METIS field-of-view during the different orbits of Solar Orbiter, in order to demonstrate plausible observational scenarios in connection with the further Solar Orbiter instruments (e.g., SolO-HI) and other space missions (e.g., Parker Solar Probe, Proba-3).

Observations of comets Encke and ISON with STEREO/SECCHI-HI A in 2013



(Online movie)

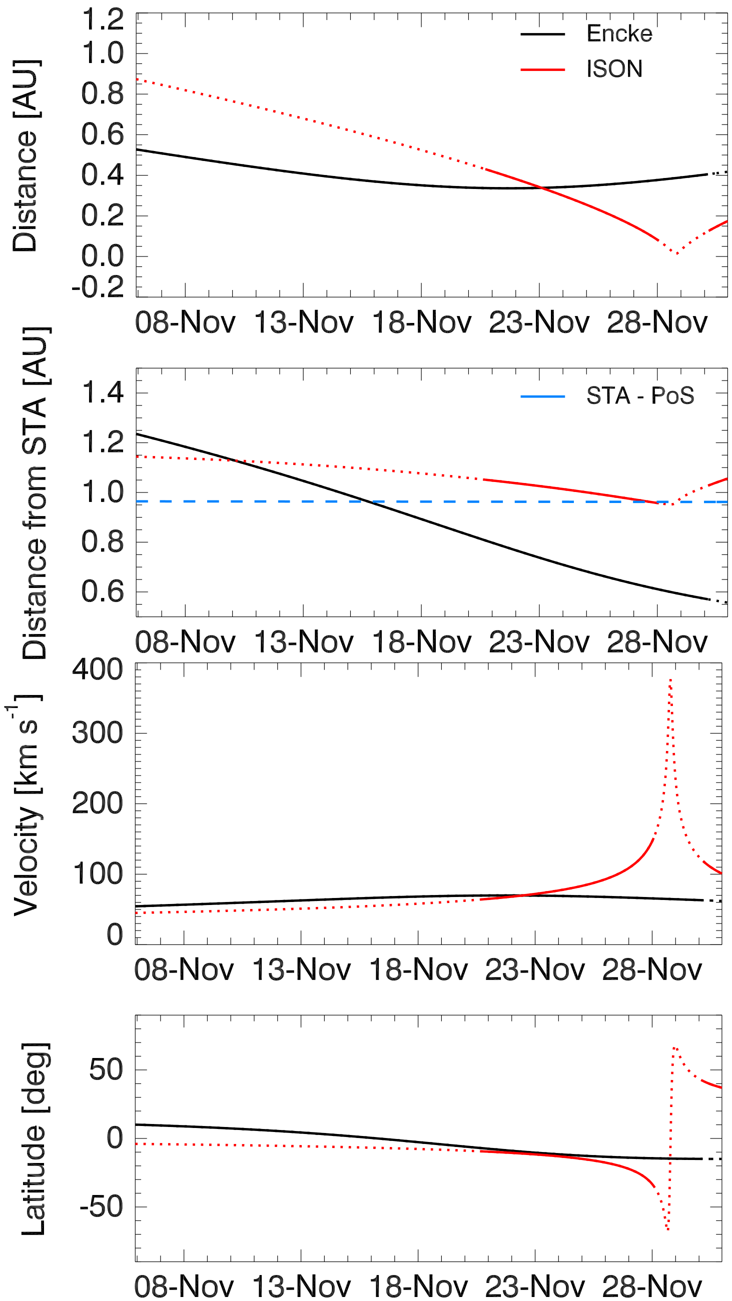
Comet Encke

- Aph = 4.11 AU
- Per = 0.33 AU
- Ecc = 0.8471
- Orb_{period} = 3.3 yr
- R = 4.8 km

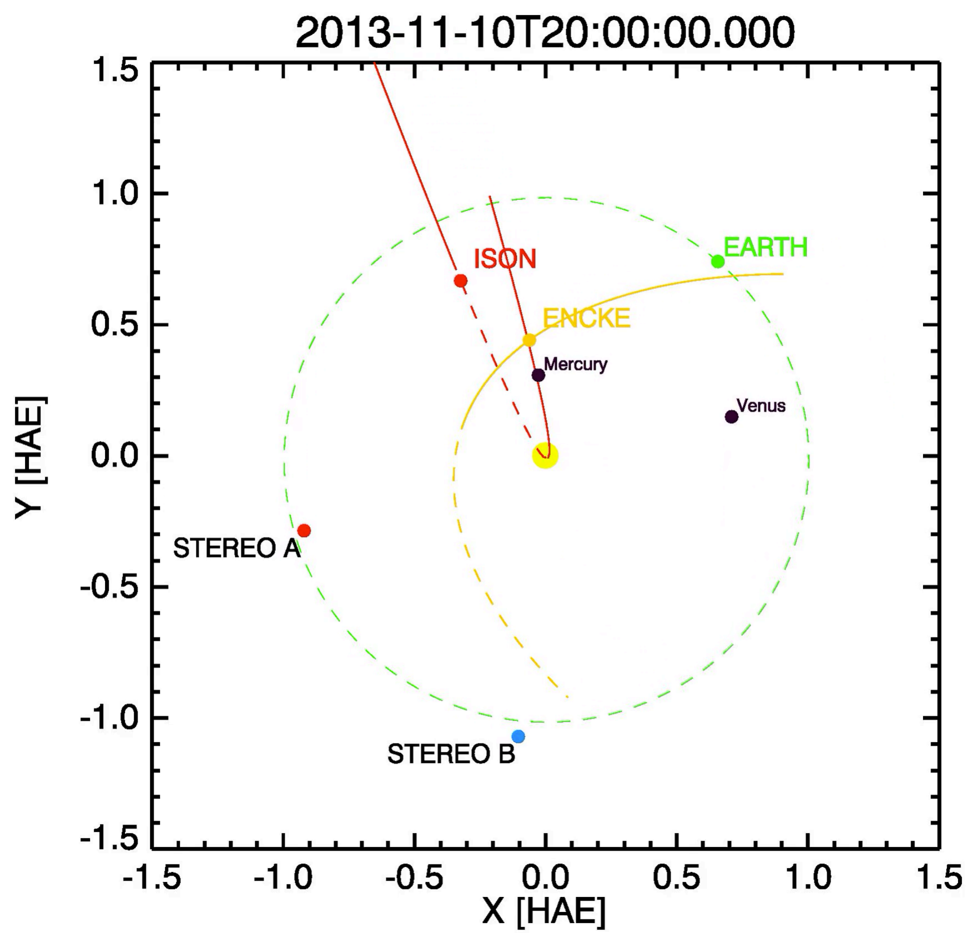
Comet ISON (International Scientific Optical Network)

- Discovery: 21 Sept 2012
- Perihelion = 0.01244 AU
(1.68 $R_\odot$ from the solar surface)
- Ecc = 1.02
- Incl = 62.4 deg

Orbital parameters of the comets



Despite appearing close in the HI-1A FoV, the trajectories of the comets are different. ISON was a sungrazing comet, passing at ~1.5 R_{Sun} from the solar surface.



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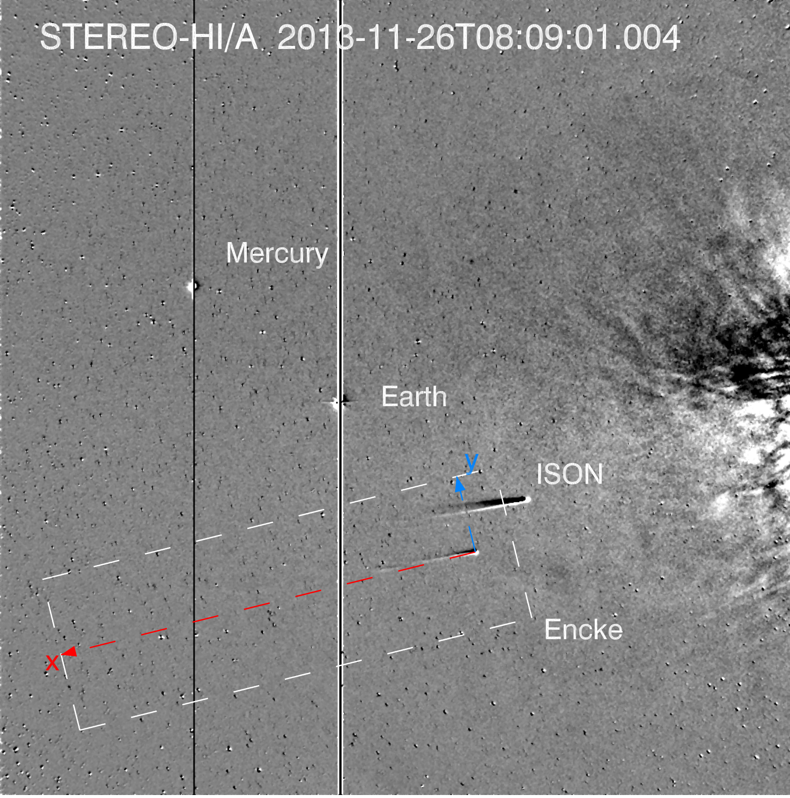


Motivations

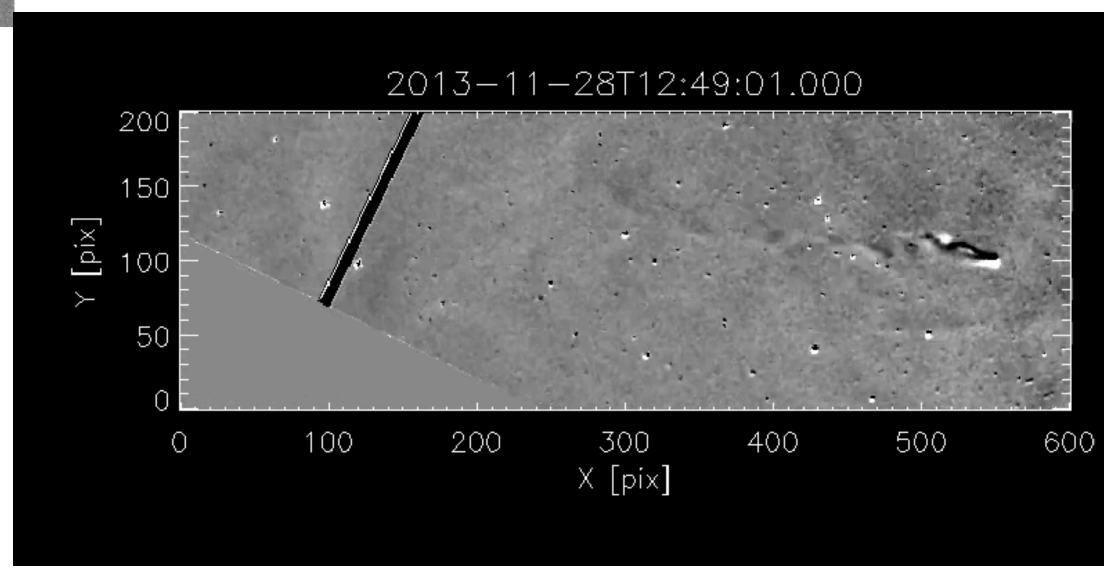
- Study of the evolution of the comet tail
- Investigation of the relationship between the tail and the local medium

Analysis

- Reference frame centered on the comet's nucleus
- Extraction of sub-images with the x-axis (red line) along the comet tail and the y- axis perpendicular to it (blue arrow).

Question

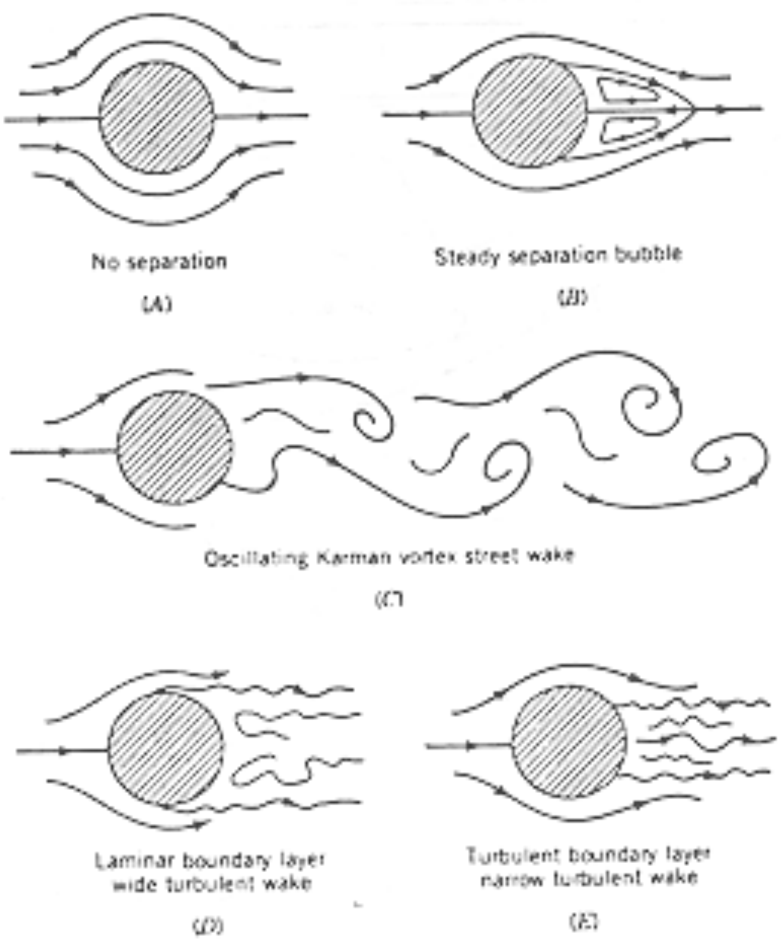
Which physical mechanism causes the observed oscillations in cometary tails?

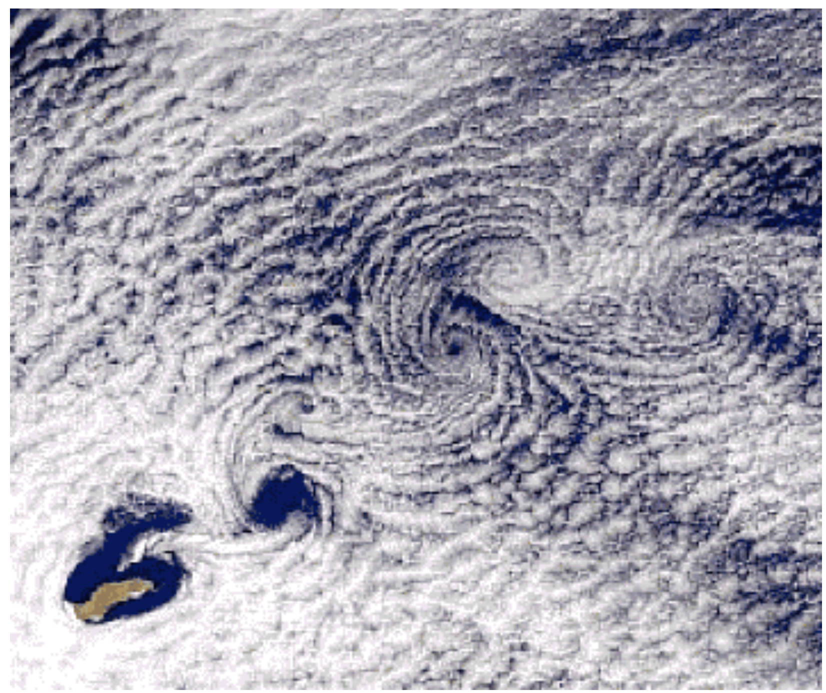


Flow past an obstacle (e.g. cylinder)

The comet coma acts as an obstacle in the solar wind flow (hydrodynamic approximation). The appearance of periodic downstream vortices (Kármán vortex street) leads to pressure fluctuations, hence an alternating force which acts perpendicularly to the comet tail [7].

In addition to the Reynolds number ($Re = VL/\nu$), the vortex shedding is quantified by the dimensionless Strouhal number $St = fL/V$, with f the frequency of the shed vortices, L the size of the obstacle, and V the relative flow speed. A typical value for St is 0.2. The task is to determine the Strouhal number for the observed comets.





(Example of vortex shedding in the Earth's atmosphere observed from space)

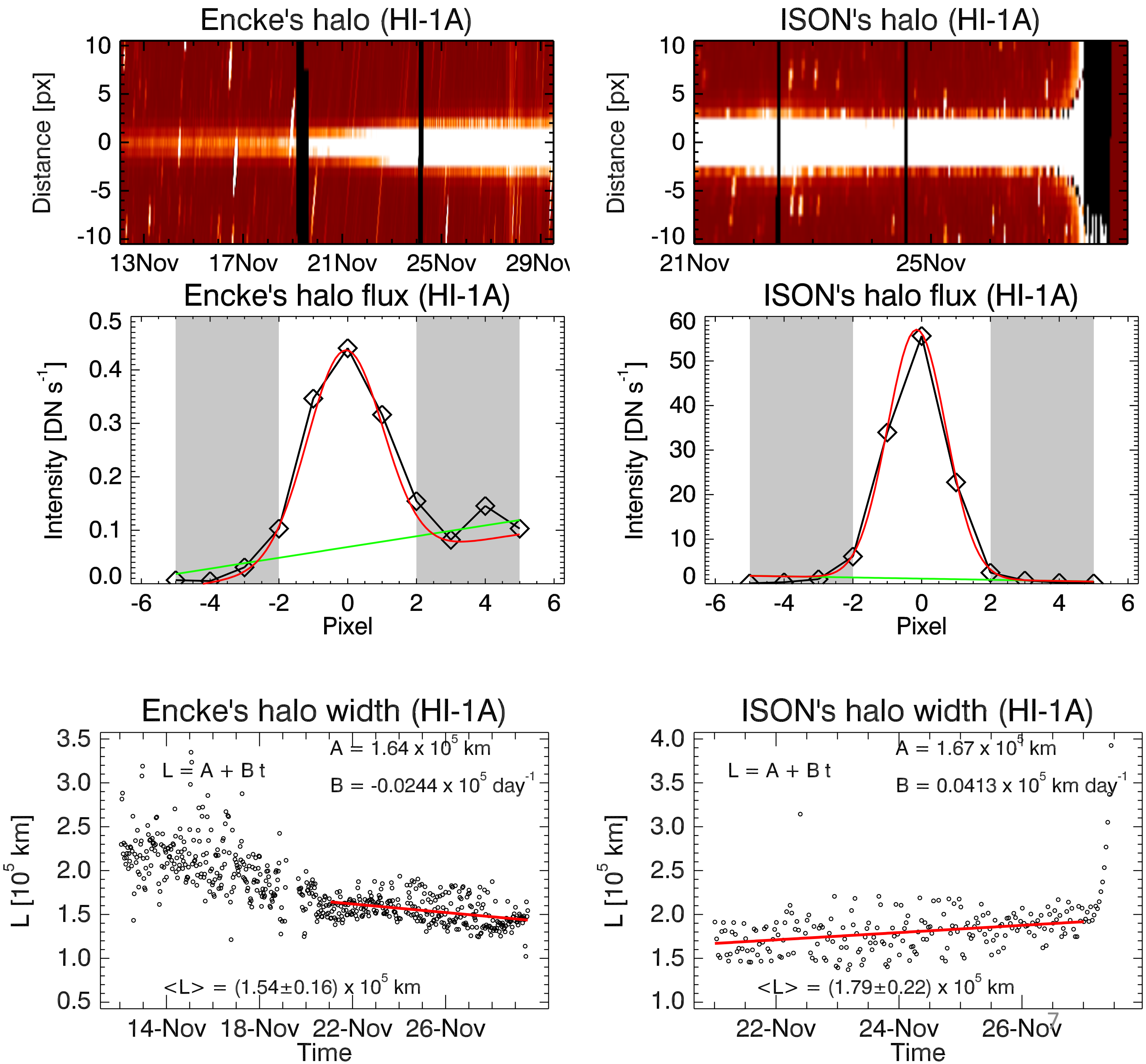
Determination of the Strouhal number for comets

a) Determination of the length L

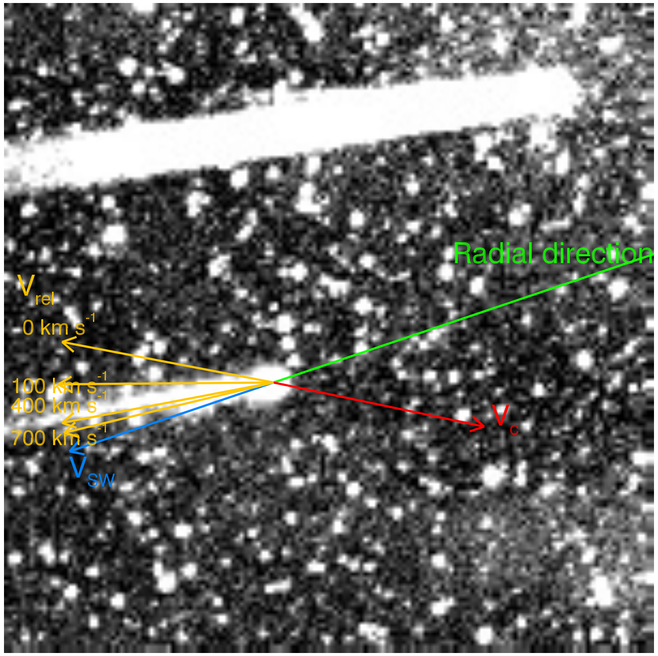
Gaussian fitting of the intensity profile across the cometary halo/coma.

Average value for the size of the halo/coma of the comets:

- Encke: $(1.54 \pm 0.16) \times 10^5$ km
- ISON: $(1.79 \pm 0.22) \times 10^5$ km



Determination of the Strouhal number for comets



b) Determination of the relative speed V

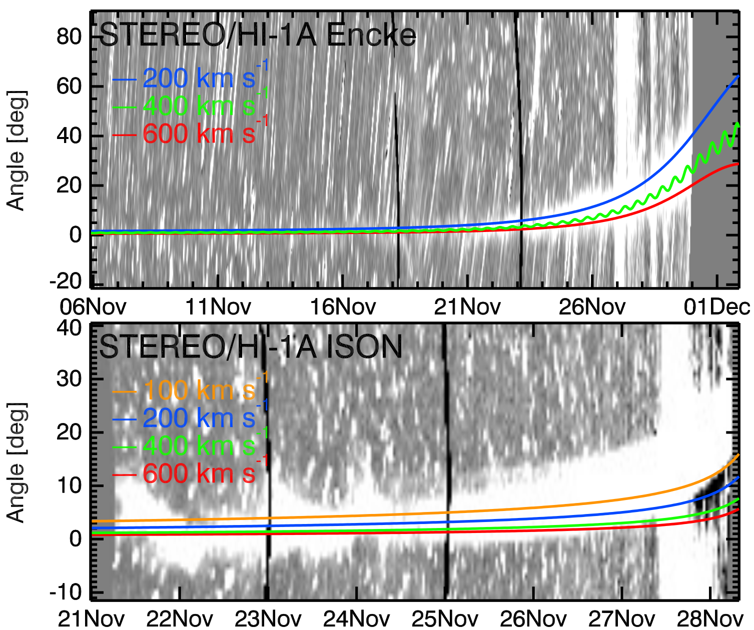
Radial speed for the solar wind (Parker's model). The tail is assumed to be directed along the relative speed **V,** determined as the vectorial sum of the solar wind speed $\mathbf{V}_{SW}$ and the comet speed $\mathbf{V}_C$ ($\mathbf{V} = \mathbf{V}_{SW} - \mathbf{V}_C$).

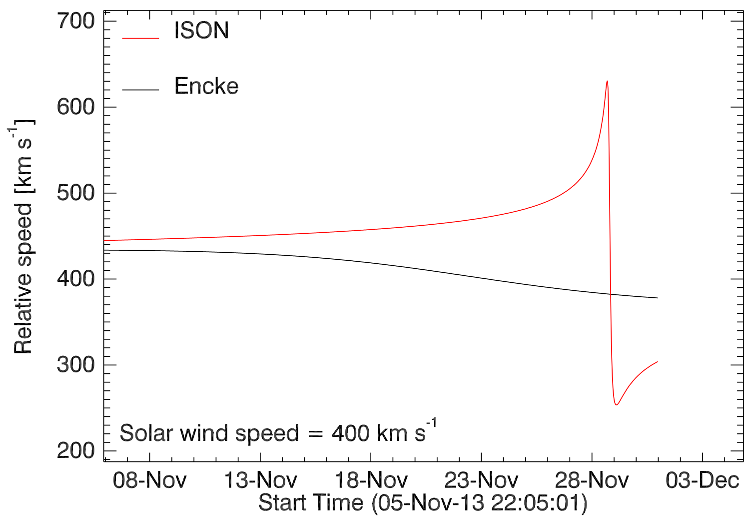
For any value of V_{SW}, we determine the aberration angle

$$\alpha = \cos^{-1}\left(\frac{\mathbf{V}\cdot\mathbf{V}_{SW}}{|\mathbf{V}||\mathbf{V}_{SW}|}\right)$$

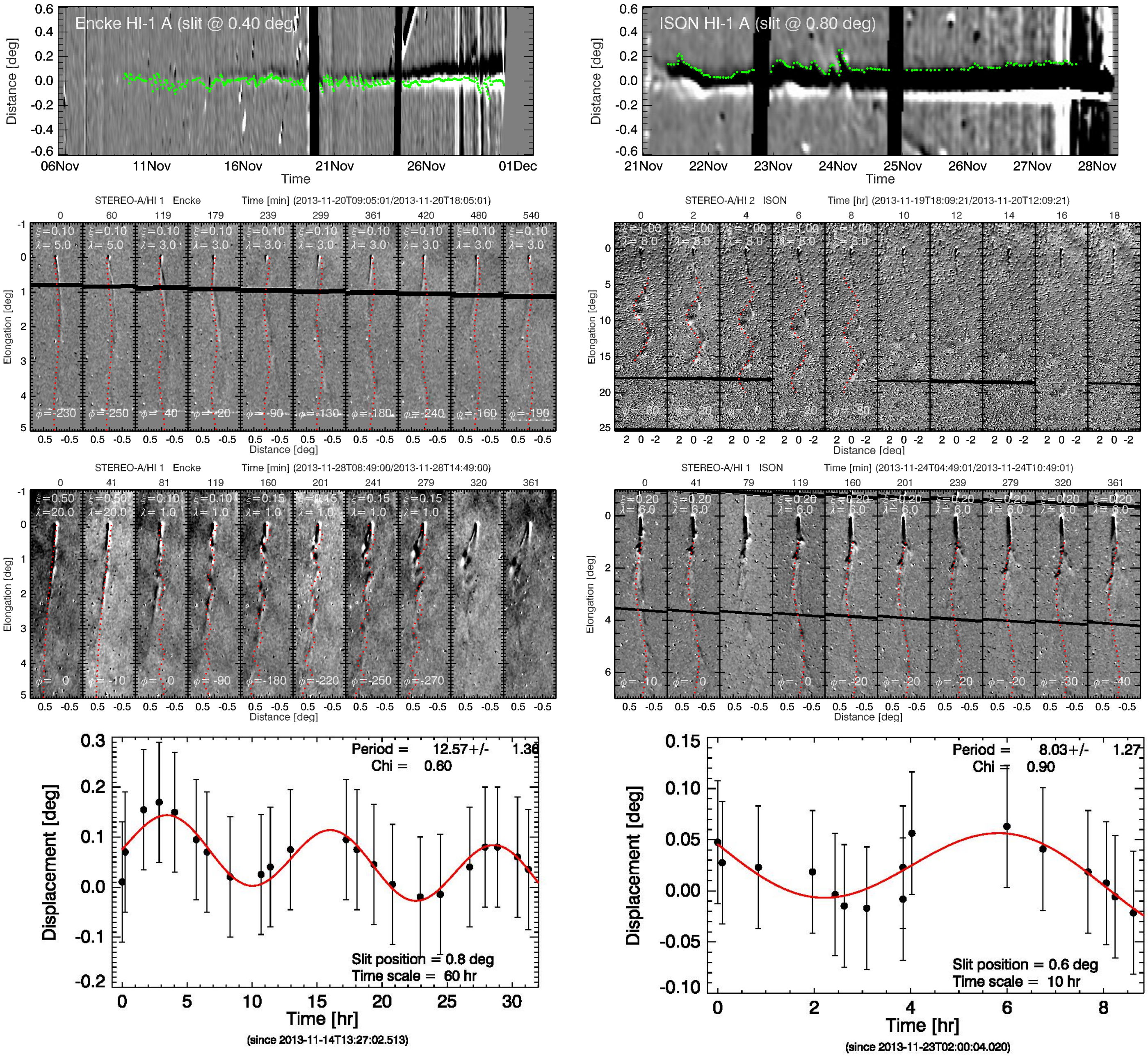
and visually fit the deviation of the comet tail from the radial direction. We found a good agreement for V_{SW} = 400 km s^{-1}. The magnitude of **V** during the observations is then found has

$$V = \sqrt{V_{SW}^2 + V_C^2 - 2(\mathbf{V}_{SW}\cdot\mathbf{V}_C)}$$





Determination of the Strouhal number for comets



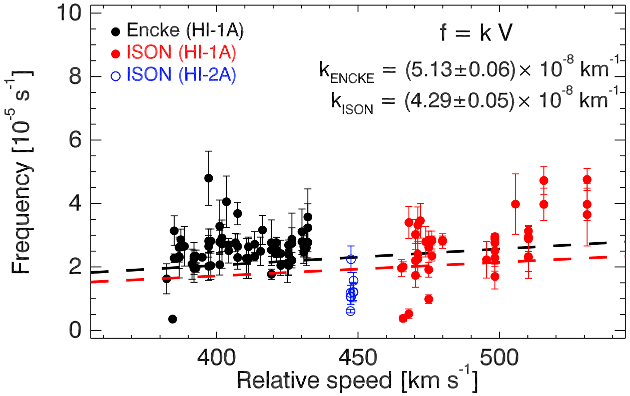
c) Determination of the period (frequency) of the oscillations of the tails

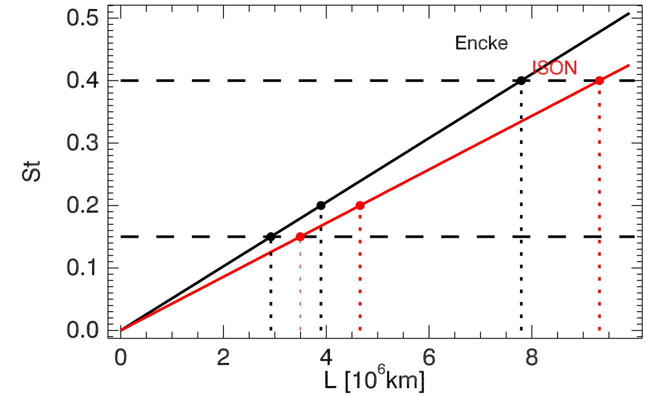
We extracted the oscillations from time-distance maps and we also used sinusoids which fits the tail profiles to estimates values of the period.

The period estimates range between 3-20 hrs

Determination of the Strouhal number for comets

Linear fit of f vs. V measurements. The coefficient k is equal to the ratio St/L. Given k, we extrapolate L for the interval St =[0.15,0.4], typical values for vortex shedding.

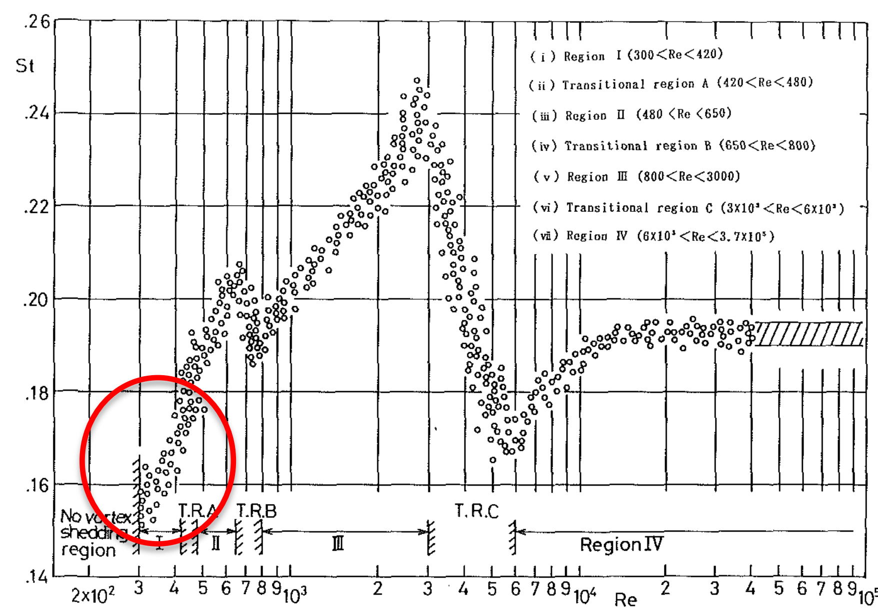




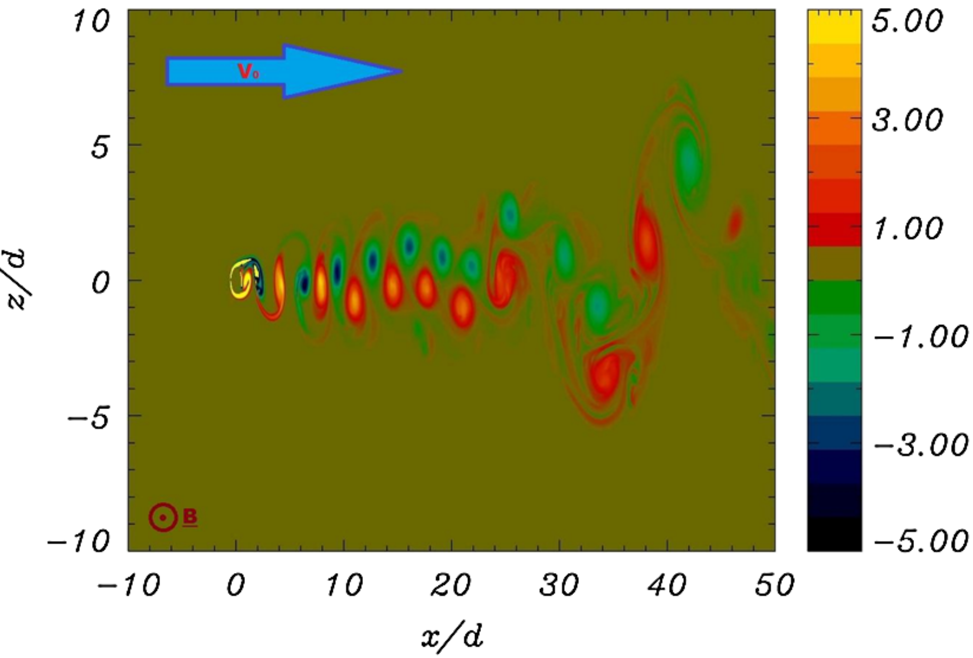
L is found to be > 10^6 km, in contraddiction to our estimates. However, values of $L \sim 10^6$-10^7 km for comet comas are reported in [8]. Measurements from Ulysses of the crossing of the tail of the comet Hyakutake in 1996 (~4 AU) provides a width of ~7×10^6 km [9].

Determination of the kinematic viscosity

Relationship between St and Re from laboratory experiments for a flow past a sphere [10]. For Re = 300-400, $L = 10^6$ km, V = 400 km s^{-1}, we obtain $\nu \sim 10^6$ km^2/s. Theoretical estimates: $\nu \approx 10^{9}$-10^{10} km^2/s [11].

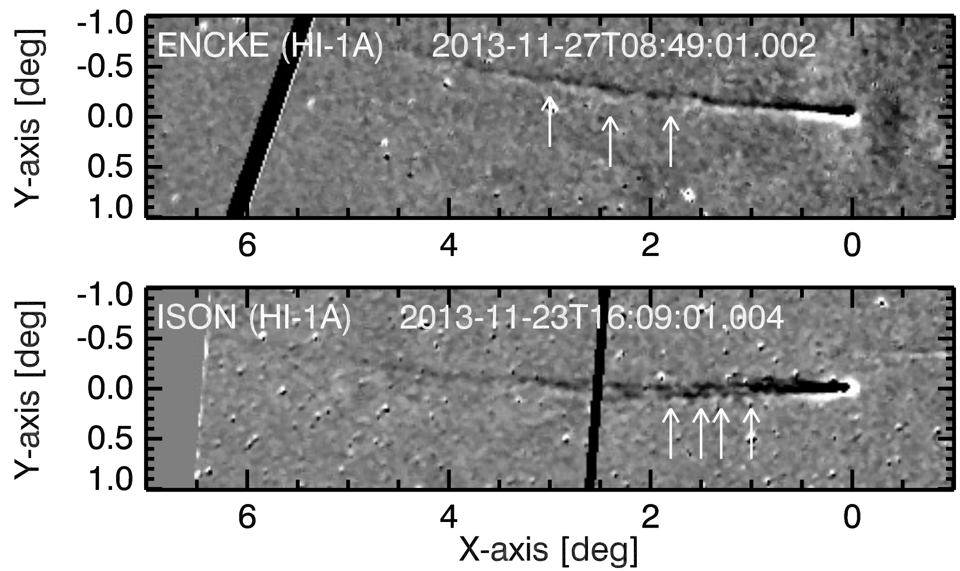


Is the vortex shedding scenario at work in comet tails?



Our estimates for *St* are < 0.05, too low to justify the vortex shedding scenario. However, MHD numerical simulations of vortex shedding in a cylinder [12] show that the wake structure gets unstable at some distance from the obstacle, exhibiting some large-scale oscillations. Our observations may be related to this dynamical regime.

A careful inspection of the images shows some ripples in the tails, which have not been studied because of the non-sufficient spatial resolution in the data. These small-scale perturbations may be a signature of a proper vortex shedding phenomenon. A thorough study will be achieved in the future.

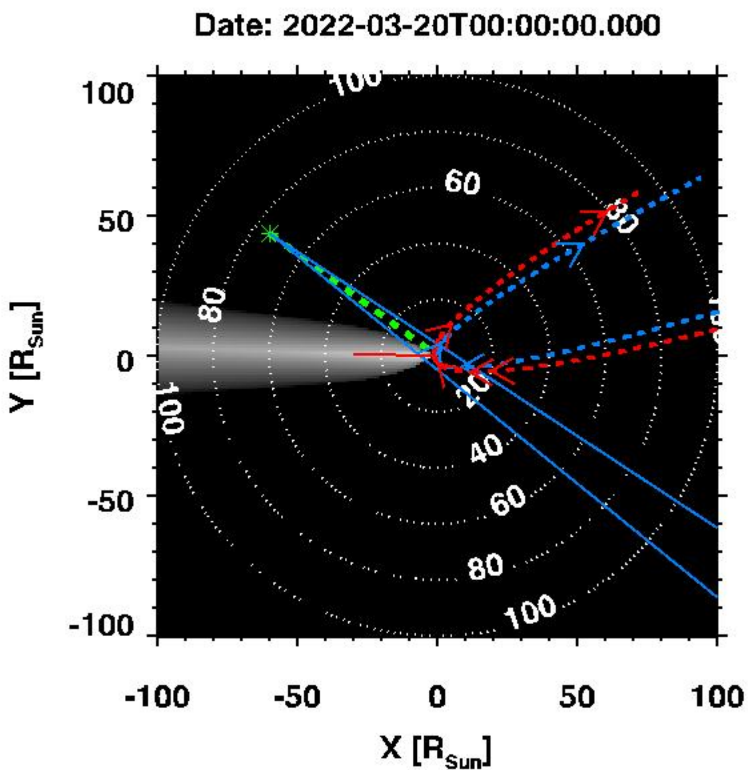


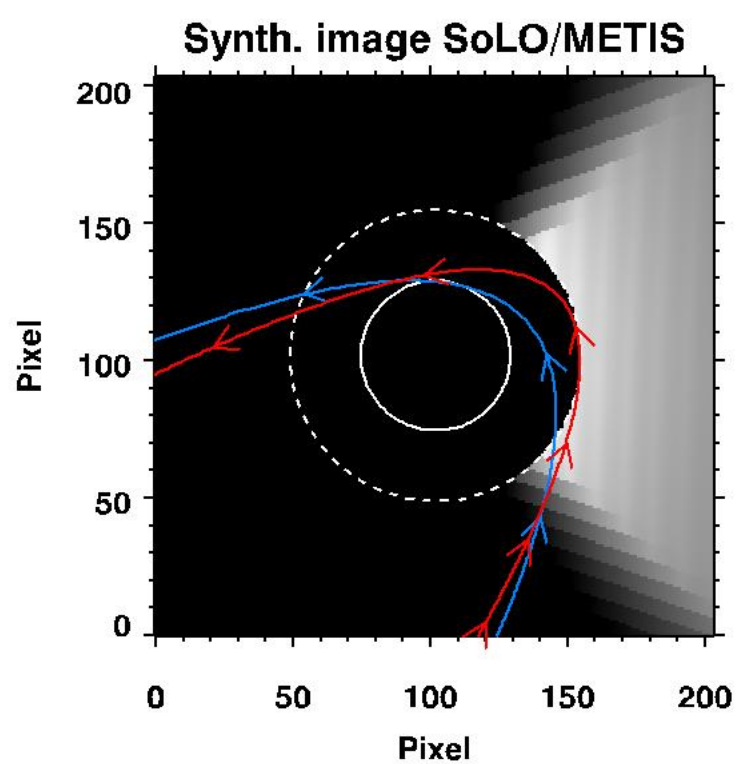
Observations of sungrazing comets with METIS

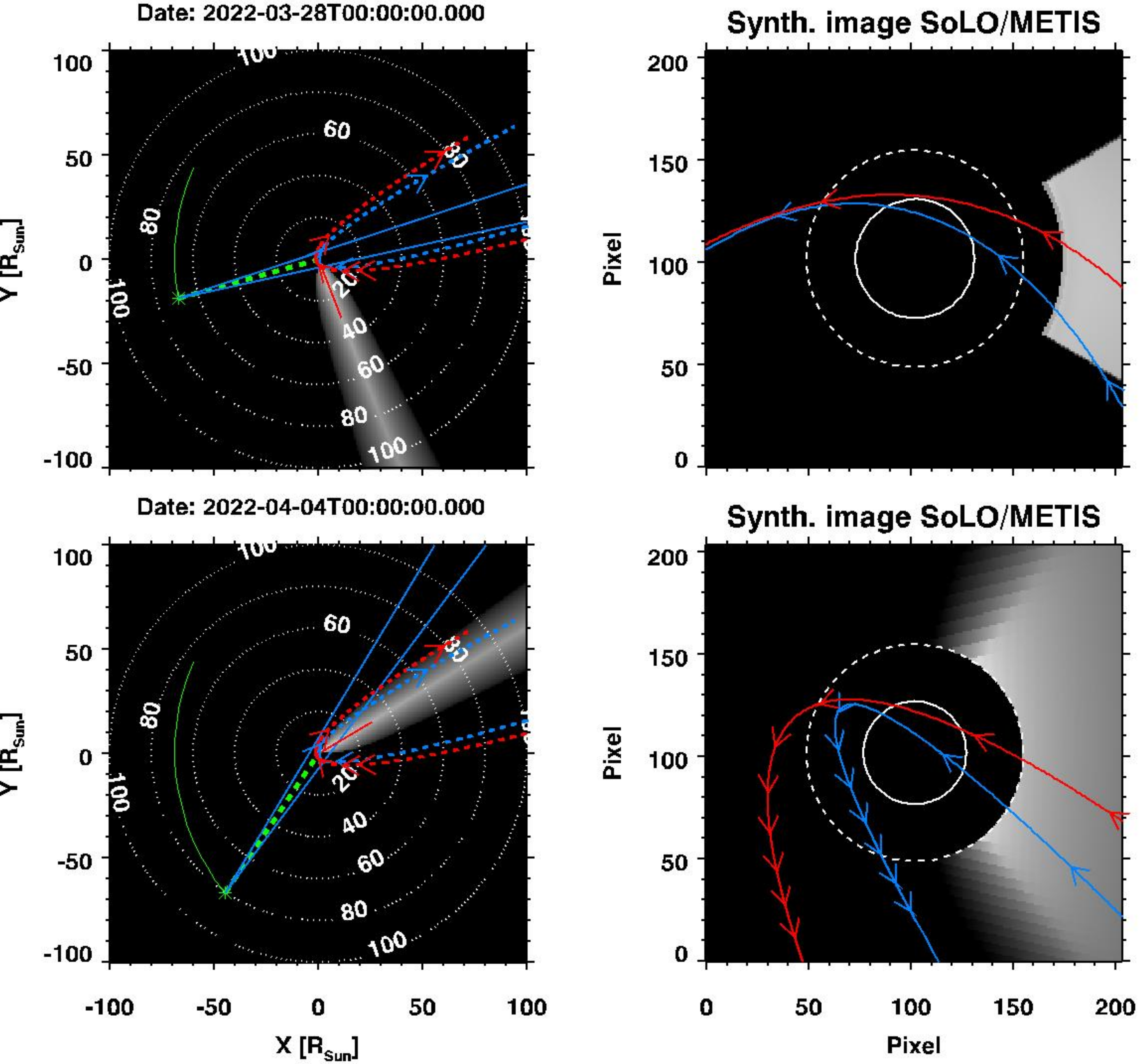
Examples of trajectories for comets belonging to some groups, which may contribute to the appearance of sungrazing comets in the FoV of Metis. Their transit is obviously affected by the orbit of Solar Orbiter, with strong changes in the projected locations during the perihelion phase of the spacecraft. The following images show: in the left panel the position of Solar Orbiter, the FoV of METIS (blue lines), the trajectories of comets and a model of streamer projected onto the solar equatorial (x-y) plane, in the right panel the associated synthetic image with the comet tracks.

a) Sungrazing comets of the Kreutz group

Representatives: comet Lovejoy (perihelion date: 15 Dec 2011, blue lines) and comet Ikeya-Seki (perihelion date: 21 Oct 1956, red lines)







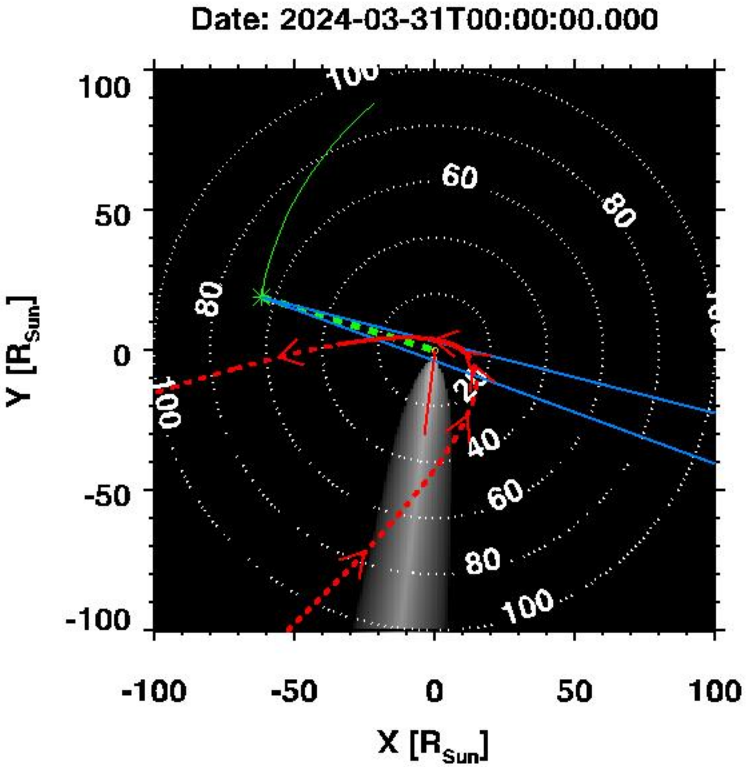
The dashed circle is the METIS occulter. The internal circle represents the solar disk, whose size changes during the orbit.

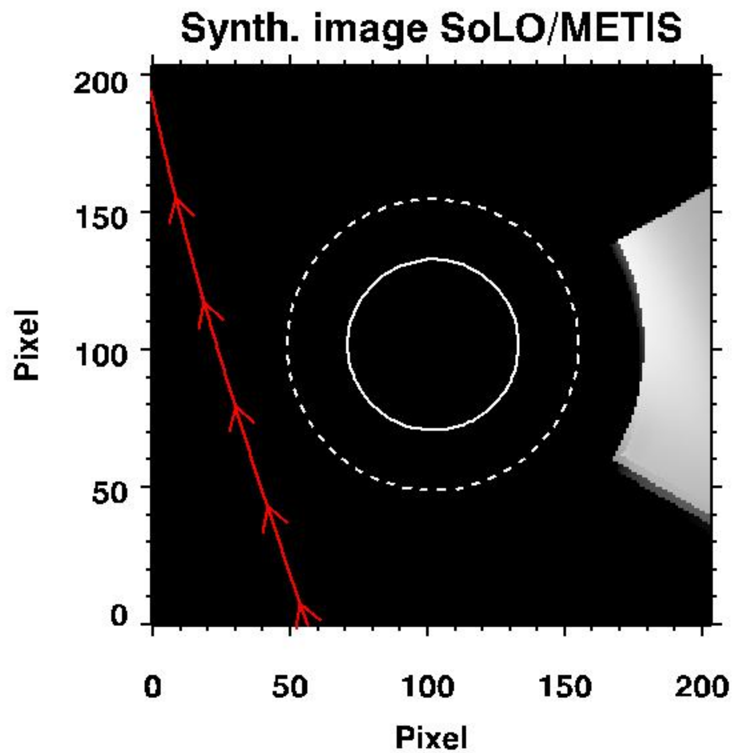
The perihelion of Kreutz-group comets is viewed by METIS in front of the solar disk. These comets may be detected with the EUV imager of Solar Orbiter.

(Online movie)

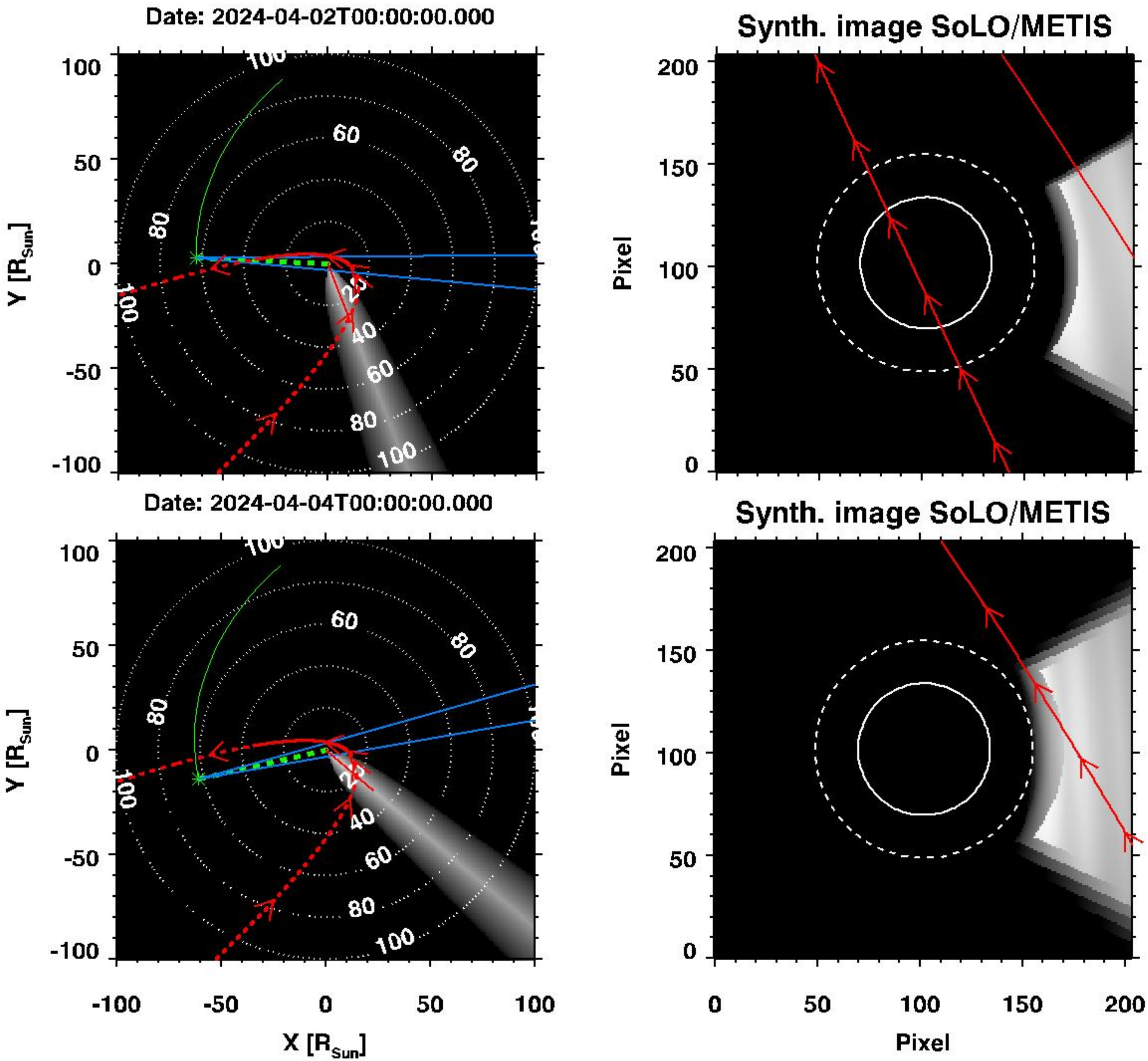
b) Sungrazing comets of the Meyer group

Representative: comet C/1997 L2 (SoHO-011). Perihelion date: 10 Jun 1997.



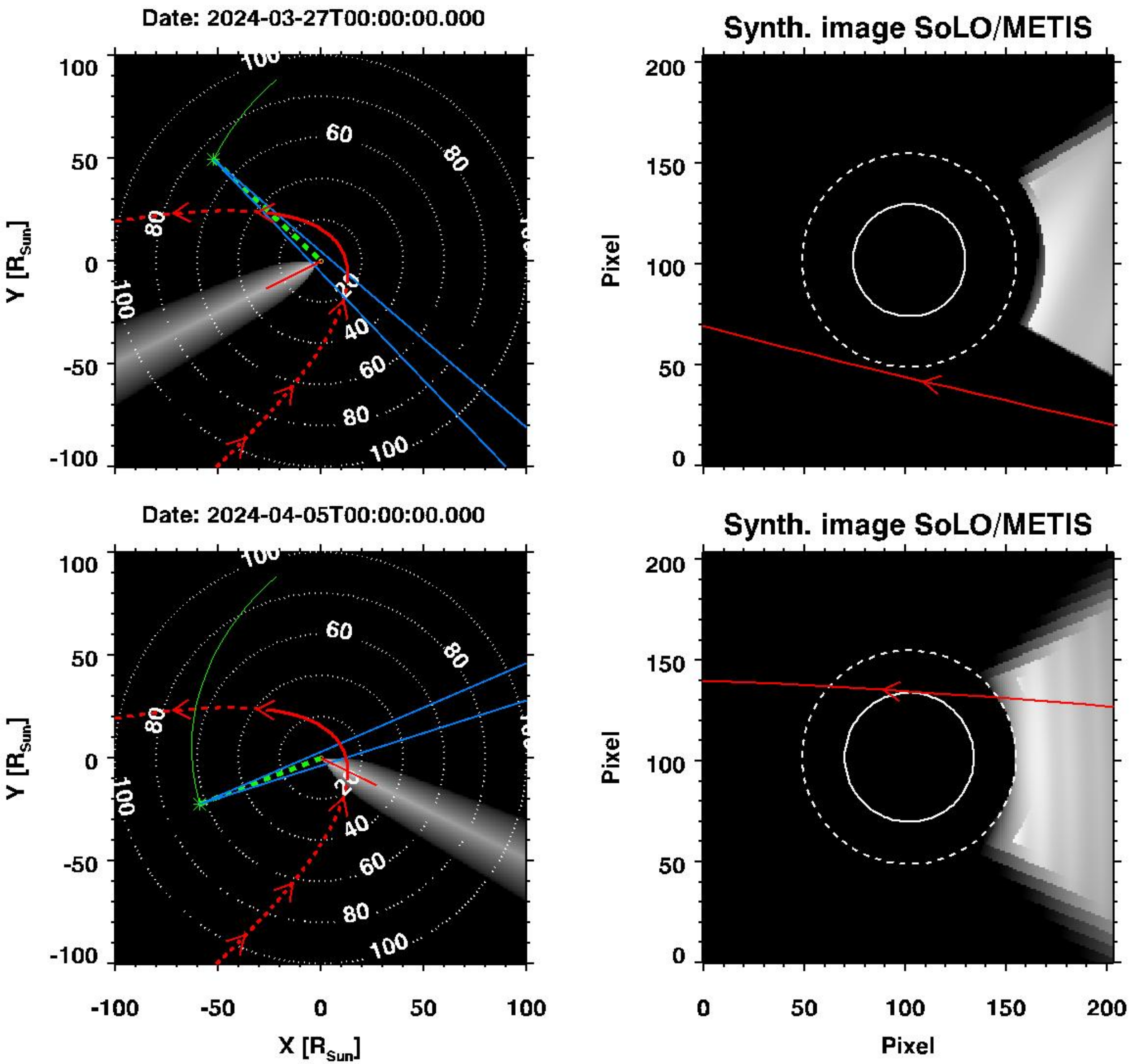


The perihelion for this group is viewed behind the solar disk from METIS.



(Online movie)

c) Sungrazing comets of the Kracht group



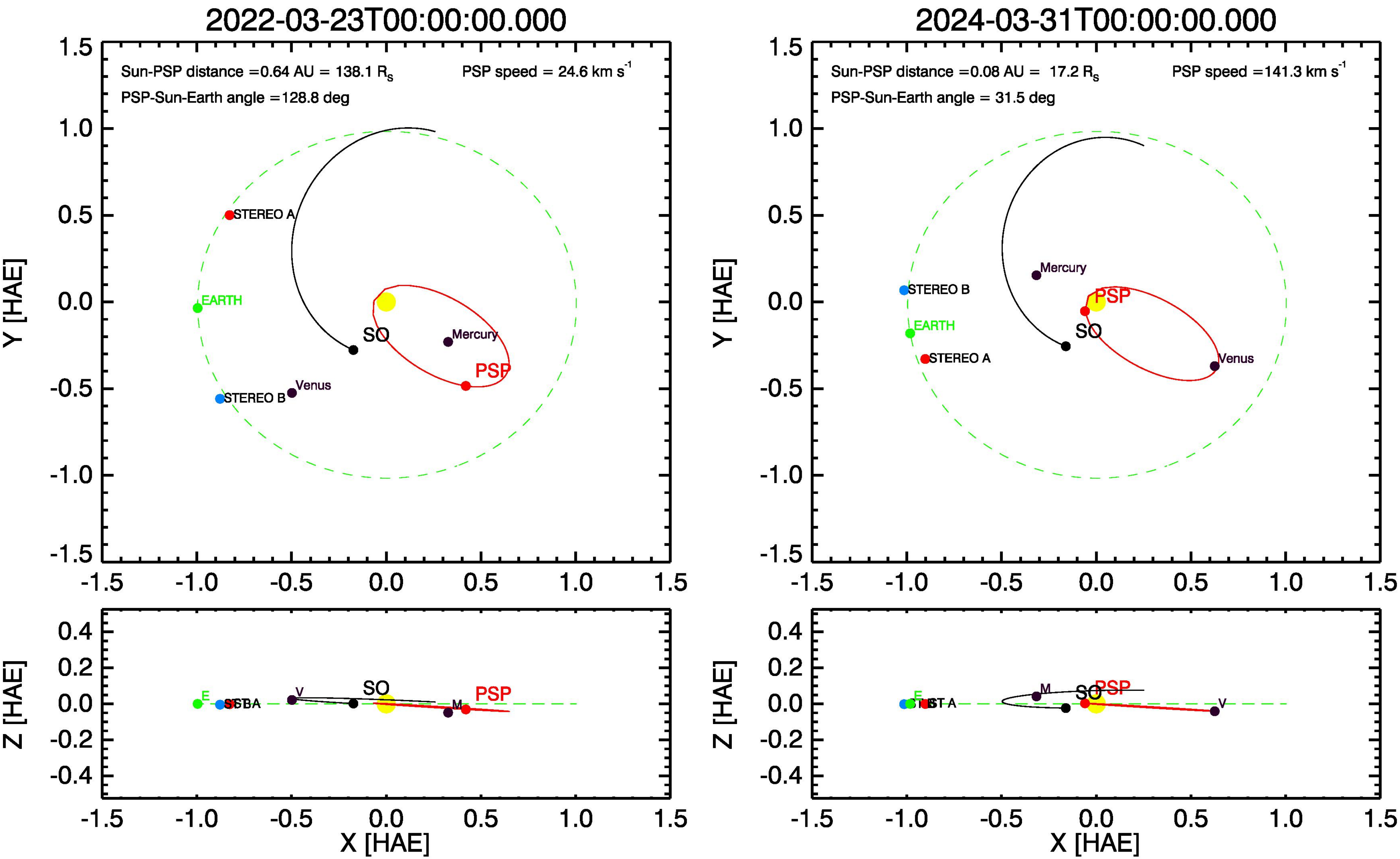
Representative:
comet C/2000 O3 SoHO-189.
Perihelion date: 30 Jul 2000.

The perihelion for this group of comets is viewed behind the solar disk from METIS.

(Online movie)

Orbital configuration of Solar Orbiter with Earth and other spacecraft for the simulated dates.

(Online movie)



Conclusions

- Sungrazing comets can be used as natural probes of the inner heliosphere and corona. We have analysed observations of comets Encke and ISON with STEREO/SECCHI/HI-A during the perihelion passage in Nov 2013.

- The comet tails respond to the physical conditions of the local medium and manifest unambiguous transverse oscillations on typical time-scales of 3-20 h.

- These oscillations are interpreted in terms of vortex shedding.

- Our analysis does not fully demonstrate the vortex shedding mechanism. However, uncertainties are still present in the determination of the Strouhal number, due to a lack of precise measurements for the relative speed and the comet size, and poor knowledge of the evolution of the wake structure past obstacles in MHD.

- We show how to determine the kinematic viscosity of the local medium from the observations of comets.

- The coronagraph METIS aboard Solar Orbiter may observe the transit of sungrazing comets in its FoV. To help plan future observations, we have plotted the trajectory of some sungrazing comets, members of the Kreutz, Meyer and Kracht groups.

References

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Acknowledgments

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Notes

The movies are available online at the following link
http://www.astro.physik.uni-goettingen.de/~nistico/metis/