Cometary observations and derivation of Solar Wind properties

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• Evidence of varying solar wind flows recorded in comets since the 19th century

• Early, blue-sensitive photographic plates excellent at recording CO$^+$ ions
Comets provided first evidence for solar wind’s existence

• Evidence of a solar “corpuscular radiation” first hypothesised by Chapman & Bartels (1940)

• In 1943, Hoffmeister noted the difference of a few degrees in direction between cometary plasma tails and the anti-sunward direction, i.e. these ions carried in a medium moving at a finite speed

• 1951: Biermann published statistical study of this anomaly; average tail direction ~3° from radial direction
• Biermann suggested that cometary ions were being swept away by Chapman & Bartels’s corpuscular radiation, with a speed of a few 100 km/s.

• For momentum coupling between solar plasma and cometary ions by Coulomb collisions, Biermann invoked too high a plasma density.

• Alfven (1957) solved this by proposing that solar wind had frozen-in magnetic field.

• Also that comet tail ray features were tracing solar wind flow through cometary coma & tail.

• Comets have induced magnetotails; comet-solar wind interaction region of very different scale to planetary magnetospheres due to freely-expanding atmosphere (Biermann et al. 1967)

*Brandt & Chapman (1992), after Alfven (1957)*
ISEE-3/International Cometary Explorer at 21P/Giacobini-Zinner
Induced magnetotail confirmed by in situ magnetic field observations

Slavin et al. (1986)
Comets trace the solar wind – what do they show us?

**Disconnection Events**

• Comet’s ion tail detaches completely and regrows
• Usually crossings of the Heliospheric Current Sheet, some appear correlated with fast ICMEs

Comet Morehouse (1908)
Comet C/2002 X5 (Kudo-Fujikawa)

Observation of $\text{C}^{2+}$ ion tail by UVCS on SOHO (Povich et al. 2003)

Comet 2P/Encke

STEREO SECCHI observation of tail disconnection associated with ICME (Vourlidas et al. 2007)
Primary cause of disconnection events: reconnection when crossing the HCS.

Niedner & Brandt (1978)
Abrupt Tail Disruptions

- Rapid change in ion tail appearance
- Jockers (1986) proposed term “cometary substorms”
- Jones & Brandt (2004) associated events in Comet 153P with fast ICME, plane-of-sky velocity $\sim1200$ km$^{-1}$
- ICME overtakes ion tail, forming scalloped features
• Another example from Comet 153P/Ikeya-Zhang

• Images gathered from amateur astronomers in several countries

• Arrival of two ICMEs seen: second one overtakes the first, resulting in abrupt tail disruption. Plane-of-sky velocities ~600 and 1093 kms$^{-1}$
• Many complex tail features not yet understood, presumably associated with solar wind features.

• Example: Comet C/1957 P1 (Mrkos) (Miller, 1988)
Exploitation of archival data

INTERPLANETARY GAS. XII. A CATALOGUE OF COMET-TAIL ORIENTATIONS*

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ABSTRACT

Some 1600 observations of the position angle of comet tails, including both original and published measurements, are reduced to orientations in the plane of the orbit of the comet. Measured and computed quantities are given together in the tabulation. Also given are the vectors which describe the geometrical circumstances at the time of observation.

These observations are of value not only from the standpoint of the physics of comet tails but also in computing the velocity of the solar wind and/or for testing models of the interplanetary plasma.

- 1600 observations analyzed
- Solar wind speed estimated from orientation of tail
- Removing dust tails, “impossible” directions, reduces number to 1038
• Dataset is relatively sparse

• Despite this, Pflug (1965) reported that lowest solar wind speeds are observed when comets are at lowest latitudes, consistent with known solar wind structure at solar minimum (McComas et al.)
New Analysis Techniques

Comet 1P/Halley
April 21, 1910
Arequipa, Peru

(Digital Access to a Sky Century @ Harvard)
Figure 5. Image sequence from 02/01/2005. The image time for image on the left should be considered unreliable due to cut off optocentre. Only the first and third Nakamura images were successfully solved. The knot within was identified to be travelling at 72.9 ± 212.6 kms along the Sun-Earth vector, whilst the comet is at a low orbit plane angle. The plausibility that the massive ion cloud in the 21:25 UT JR images is the expanded Nakamura knot is moderately high due to its low velocity. This sets the feature's velocity at 115.8 ± 14.3 kms in the JR images. The extremely small velocity uncertainty for this feature is due to the low pixel projection uncertainty and small FOV for this image.

- Technique found to be very sensitive to orbit plane angle: if Earth close to comet’s orbital plane, technique is not reliable
• From each image, several solar wind speed estimates can be obtained

• Image field of view recognized with astrometry.net

• Image mapped onto comet’s orbital plane

• Sun-comet line horizontal

• User identifies several points along the tail.

• Distance from orbit of each section of tail, and time elapsed since nucleus at that position gives a solar wind speed estimate.
For best results:

- Comet orbit plane angle has to be large (observer not near orbital plane of the comet)

- Phase angle not too large or too small (not observing “along” tail; linked to orbit plane angle)

- Time of observation very important! Centroiding technique can provide good estimates of observation time.

- Yudish’s code being adapted for use via a web interface as part of PSWS activities. IDL source code will be made available in any case.
Final Caveat:

- This technique relies on solar wind flow being radial
- This is untrue for much of the time; mean non-radial components at ACE: 30 km/s
C/2011 W3 (Lovejoy)

Figure 6.1: Images of comet Lovejoy from C3, C2, C3 and STEREO A, pre- and post-perihelion. Image courtesy of SOHO and STEREO team. The coma and dust tail can be seen growing shortly after perihelion in a composite of SOHO C2 images (panel 2). Observations with the C3 coronagraph and STEREO HI 1A yielded an extensive data set of the evolution of comet Lovejoy's ion tail [Figure 6.1 and Table 6.1]. During this period, C/2011 W3 moved from 11.59 R☉ down to 1.19 R☉ at perihelion and back outwards to 54.49 R☉ [Figure 6.2]. There is no photographic evidence of the period when comet Lovejoy was within 2.5 R☉, the theoretical boundary within which the comet would have experienced purely non-radial magnetic field lines. The comet's ion tail remained distinctly smooth and featureless, as C/2011 W3 (Lovejoy)
C/2011 W3 (Lovejoy) – evidence of non-radial solar wind
Near-Sun comets: Pan-STARRS (C/2011 L4)

This comet was an ideal target for the velocity vector map. The ion tail was very dynamic, leading just ahead of a wide and very bright, well-structured dust tail and lagging behind what may be a neutral iron (Fe) tail (Fulle et al. 2007). The difference images revealed an aberrant, sinuous tail over a large extent of the observations with multiple trackable plasma blobs and disconnection events as the comet left the STEREO HI-1B FOV. The results oscillated about conventional slow solar wind velocities. The variations seen in the later measurements corresponded to large orientation changes and increase in turbulent dynamicity in the ion tail.

On March 13, 2013, the comet appeared to have two ion tails, one stemming from the expected location, the other jutting out from one of the top dust striae. This is likely a matter of perspective with a turbulent ion tail masked by the saturated, curved dust tail.

Figure 6.31: STEREO B FOV of a CME and the multiple tails of C/2011 L4 on 13/03/2013 12:49 UT. Note that it is not necessary that the CME will have interacted with the comet. The CCD blooming has been masked by the white columns.
My period of analysis started shortly after perihelion, and extended from March 10.673 UT to 16.478 UT, when the comet was moving from southward (blue) to northward of the ecliptic plane (red) [RHS of Figure 6.32]. Although this geometry was disadvantageous for ground-based ion tail observations, STEREO B was well positioned on the far side of the Sun. Figure 6.31 shows that the orbit plane angle for STEREO B remains stable and large enough to produce reliable solar wind estimates; that of Earth clearly shows the deteriorating observing geometry, albeit over a longer period of time.
Solar wind–comet interaction

crossing. The ion tail was analysed, though no data was saved during this period to prevent unreliable estimates of the solar wind velocity. The measured values hovered at ~ 300 km s\(^{-1}\), in line with the other measured velocities.

Figure 6.35: Post-perihelion solar wind velocities for C/2011 L4, based on observations with STEREO HI-1B.

Table 6.2: Observed time for CME eruptions, speed, central position angle (CPA) and angular width from the CDAW CME catalog.

- The comet is between position angles 95\(^{\circ}\) to 55\(^{\circ}\) and the solar axial tilt is \(-23\)^{\circ}.

<table>
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<th>Date</th>
<th>Time (UT)</th>
<th>Linear Speed (km s(^{-1}))</th>
<th>CPA ((^{\circ}))</th>
<th>Angular Width ((^{\circ}))</th>
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</table>

Pan-STARRS (C/2011 L4) using STEREO-B SECCHI HI data
Comet Tail Crossings
Ulysses’s First Cometary Encounter
C/1996 B2 (Hyakutake)
- Riley et al. (1998) reported a proton “hole” in Ulysses SWOOPS data
- Unprecedented drop in proton number density
• Coincident with the proton “hole” were magnetic field signatures reminiscent of draping patterns expected at a cometary ion tail

• Search was conducted for possible source comets
• C/1996 B2 (Hyakutake) alignment found (Jones et al. 2000)
Draping observed at 1P/Halley

Observations of the magnetic field directions along the trajectory of Giotto from 23:45 on March 13 to 00:15 on March 14.

The parabolae show the possible shapes of the draped Tangential Discontinuities (Raeder et al 1987).
Draped discontinuities: Magnetic field structure in an ion tail
Alignment with Hyakutake

- On May 1, 1996, Ulysses, at 3.73 AU from the Sun, was aligned with position of Hyakutake around 8 days earlier, at 0.35 AU.

- Distance and relative timing consistent with ions being carried at around the solar wind velocity (~740 kms$^{-1}$)

- Proton hole consistent with charge-exchange processes at the comet’s head

SOHO LASCO observation on same day as Ulysses tail crossing
• SWICS data revealed presence of pick-up ions (Gloeckler et al. 2000)

• Atomic:molecular ion ratio higher than at Halley, indicating a source closer to the Sun, consistent with Hyakutake.
Ulysses’s Second Cometary Encounter
C/1999 T1 (McNaught-Hartley)

Image: Sárneczky, Konkoly Observatory
Ulysses’s Third Cometary Encounter
C/2006 P1 (McNaught)
For a tail crossing (b) to be possible, several conditions have to be met:

- The spacecraft has to be close to a comet’s orbital plane.
- This plane crossing has to be anti-sunward (downstream) of the orbital path.
- The nucleus (c) has to have passed upstream of the spacecraft position (a) shortly before the spacecraft was in that position (hours to weeks, depending on the relative geometry).
- The solar wind speed has to be of the correct magnitude to “carry” the comet pickup ions past the spacecraft at the right time.
- Software being made available to search for comet tail crossings, as part of PSWS activities.
- Can provide list of times when tail crossings possible.
- If solar wind speed data available, accuracy much higher.
Summary (1)

• Active comets provide tracers of solar wind at remote locations

• From archive comet images, we can study solar wind speeds and transient events from >100 years ago!

• Ion tails indicate solar wind speed at comet under favourable viewing geometries, routine links with fast solar wind streams, etc. (Ramanjooloo et al., in prep.)

• Disconnection events can reveal location of heliospheric current sheet

• Abrupt tail disruptions usually reveal arrival of fast ICMEs at comets

• Tails orientation analysis routines to be provided to wider community via Europlanet-funded project (2018)

• Code will be available to all to derive solar wind speeds from comet images
Summary (2)

• Comets’ ion tails can persist as coherent magnetic field structures for at least several AU, even when disrupted by transient solar wind structures

• Code will be made available to search for possible comet tail crossings, with and without in situ solar wind speed data

Future Work

• A search for all possible comet tail crossings:
  • comprehensive survey of comets’ trajectories and all spacecraft in solar wind
  • follow-up to search for magnetic field signatures, proton dropouts, and compositional information, when available