How comets reveal structu

Yudish Ramanjooloo, Rishbeth Prizewinner at the 2012 NAM, describes how the interaction between comets and the solar wind can help to understand the inner heliosphere structure.

Comets have been a subject of wonder and study for centuries. Observations of famous comets, such as Halley's Comet, have been depicted (e.g. in the Bayeux Tapestry) and well recorded throughout history. These primitive bodies, condensed remnants of the protoplanetary disc that formed our solar system, have survived virtually untouched since the conception of the solar system some 4.5 billion years ago, aside from surface alteration by ultraviolet radiation and cosmic rays. Comets have fundamentally enriched our understanding of planetary physics, from providing the definitive proof of Newton's law of universal gravitation with the successful recovery of comet Halley's orbit, to the discovery of solar wind outflow based on remote observations of the cometary ion tail. Comets are thus natural probes of the solar wind in the inner heliosphere as they loop around the Sun.

The existence of a solar wind was first conjectured in the latter half of the past century by Biermann (1951), based on observations of comets' ion tails. Biermann argued that solar radiation pressure was not enough to explain the acceleration of plasma structures within comet tails. We now know that the solar wind not only dictates the orientation of cometary ion tails, but also directly influences fast-evolving features of their complex structure.

Our resources to probe the solar wind are limited to spacecraft data and spacecraft generally stay close to the ecliptic. To date, NASA's Ulysses spacecraft is the only one to have obtained measurements of the solar wind up to high heliolatitudes. I intend to achieve the same goals in an extremely cost-effective way, by identifying features in remote images of a comet's ion tail and understanding the associations of these features with the solar wind. This is the founding motivation for developing a new technique, limited only by the frequency of comets with a bright ion tail and their orbits.

Solar wind–comet interaction

Cometary magnetospheres are induced by the interaction of the interplanetary magnetic field (IMF) wind with its ionosphere. Far from the Sun, solar radiation energy heats up comets' nuclei. As their orbit brings them closer to the Sun, the surface layers become sufficiently hot to trigger sublimation processes beneath the mantle. The frozen volatiles escape supersonically from the cometary surface and the nucleus. Dust grains are dragged along as gas jets leave the comet's surface, creating an atmosphere of neutral molecules and gas. Water is the principal constituent of the coma, followed by carbon monoxide and carbon dioxide, in terms of concentration.

The coma eventually becomes fully ionized during its encounter with the solar wind through a combination of photodissociation of molecules via solar extreme ultraviolet (EUV) radiation, charge exchange with energetic solar wind protons, and electron impacts. The ions are picked up by the IMF via the Lorentz force and gyrate around the frozen-in magnetic field lines. This culminates in a mass-loading of the solar wind field lines with heavy water and oxygen ions. For conservation of momentum to hold true, the velocity of the interplanetary magnetic field lines must decrease as the mass on the solar wind increases. Most of the mass is added nearer to the nucleus, causing a velocity shear along the field line. The frozen-in heliospheric magnetic field lines drape around the magnetotail structure, trapping plasma within, as proposed by Alfvén (1957). The ion tail acts like a transparent windsock, showing the direction of the solar wind.

> **"The ion tail acts like a transparent windsock, showing the direction of the solar wind"**

The motion of charged particles in a magnetic field induces a tail current sheet in the plane perpendicular to the IMF orientation upstream. Unlike most planetary magnetospheric tails, such as Saturn and Earth, the comet's current sheet orientation is highly variable, more like that of Venus or Titan, for example. The induced magnetotail of a comet can be easily observed remotely as the comet's ion tail. The ion tail responds dynamically to its environment and reflects changes, often as abrupt discontinuities, in the local IMF.

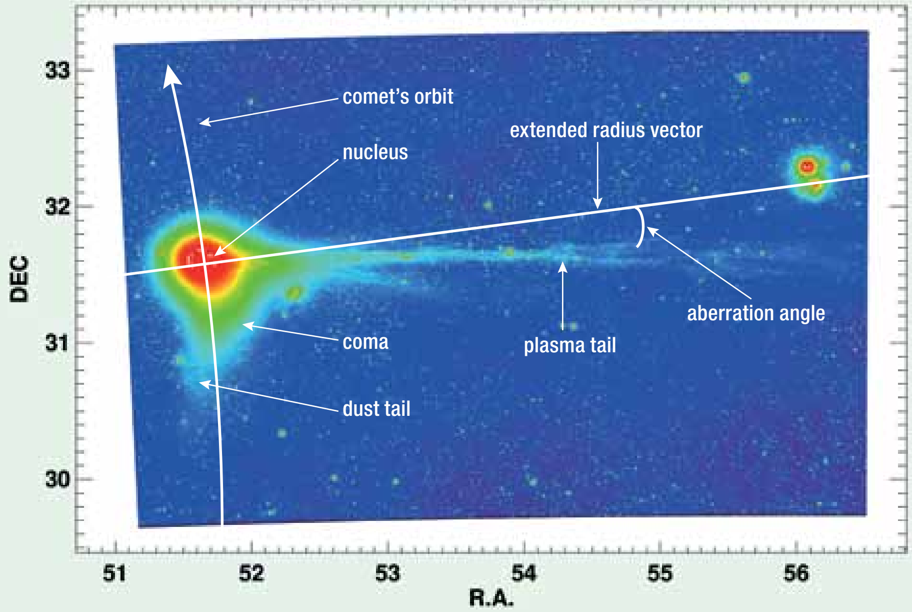
The morphology, structure and orientation of a comet's ion tail are primarily controlled by the local solar wind conditions. The cometary ion tail points along the anti-sunward direction, lagging the true anti-solar direction by a few degrees. The aberration angle arises from a combination of the comet's orbital velocity and local solar wind velocity (figure 1). When the observing geometry is ideal, remote observations of a comet's ion tail can yield extensive information on the variability of the solar wind velocity near the comet. Aside from velocity measurements, the continuously varying morphology and tail dynamics, including orientation, can be used to depict the fluctuations of both large-scale and small-scale structures in the solar wind. Ion tail disconnection events are considered to be key markers of solar wind phenomena interactions, such as coronal mass ejections and heliospheric current sheet crossings. Encounters with coronal mass ejections can also lead to rapid reconfigurations of tail features and orientations (Jones and Brandt 2004). Locations of co-rotating interacting regions, where fast and slow solar wind regions interact, and transitions between different solar wind regimes can be accurately identified from kinks in the ion tail, i.e. large and rapid changes in the aberration angle.

Technique

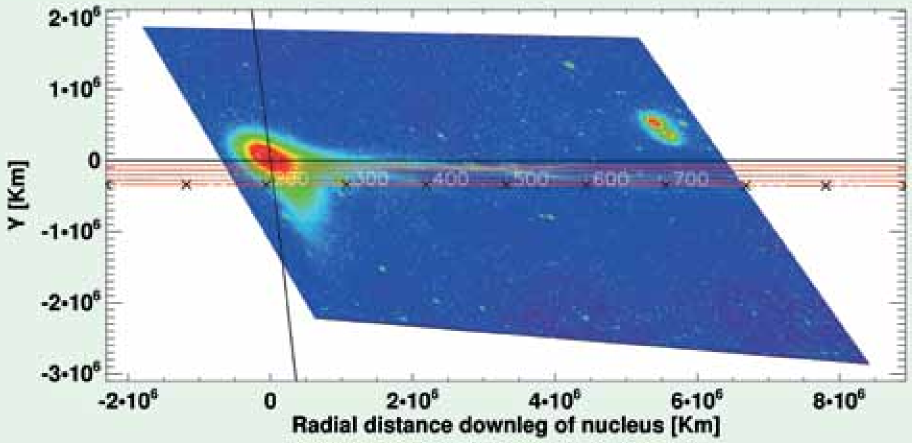
Most of the analysed images were gathered by a very active global community of astronomers, professional and amateurs alike, using advanced consumer technology such as the combination of medium to high end commercially available telescopes and digital cameras, allowing for near-continuous monitoring of the target. However, there are drawbacks associated with using images from multiple contributors and different observing instruments: there is no conformity or convention for the image formats, and the fields of view differ. Historically, the field of view (FOV), plate scale and orientation for each image would have to be resolved manually, but the use of http://www.Astrometry.net (Lang *et al.* 2010), a recent technological advance allowing the automatic recognition of any star field, has facilitated matters by returning the FOV, plate scale and orientation almost instantaneously.

Each image is extrapolated along its line of sight from Earth and mapped onto the comet's orbital plane. Multiple cross-sections of each image are taken and a brightness profile is extracted from each cut (figure 2). This technique assumes that the ion tail comprises multiple plasma bundles travelling at the solar wind velocity along the extended radial vector. Under ideal circumstances, it is feasible to use the brightness profile to pinpoint where the

re of the inner heliosphere



1: Image of comet Machholz, by Jhemann and Reiger, describing the main features. The hydrogen cloud is not represented on this image as it cannot be observed with the naked eye from Earth.



2: Mapped image of comet Machholz on 11 January 2005. Multiple cross-sections of the ion tail have been taken along the extended radial vector, in red. (Courtesy of Jhemann and Reiger)

radial vector, from the Sun, crosses the ion tail. Practically, the user's eye remains the best tool to determine this crossing point. Plasma bundle centres and their positional error can be derived from each image. From this, we simply compute an estimate of the solar wind velocity from each bundle centre and its respective time stamp.

This technique, which I pioneered at MSSL, could allow simultaneous monitoring of the heliosphere from several vantage points – something that has hitherto been impossible to achieve practically. Comparison of concomitant results from multiple observing locations and sources, professional and amateur astronomers and spacecraft, will allow us to assess whether my technique can be a valuable complement to the future of heliospheric research. Though studies of cometary ion tails are not new, my solar wind velocity catalogue highlights the solar wind's temporal and spatial variability.

Results

To validate the technique, I investigated amateur and spacecraft images of near-Earth bright comets with a good observing geometry (figure 3). For brevity, I will focus on two bright comets (C/2004 Q2 Machholz and C/2011 W3 Lovejoy), which yielded the most interesting milestone results.

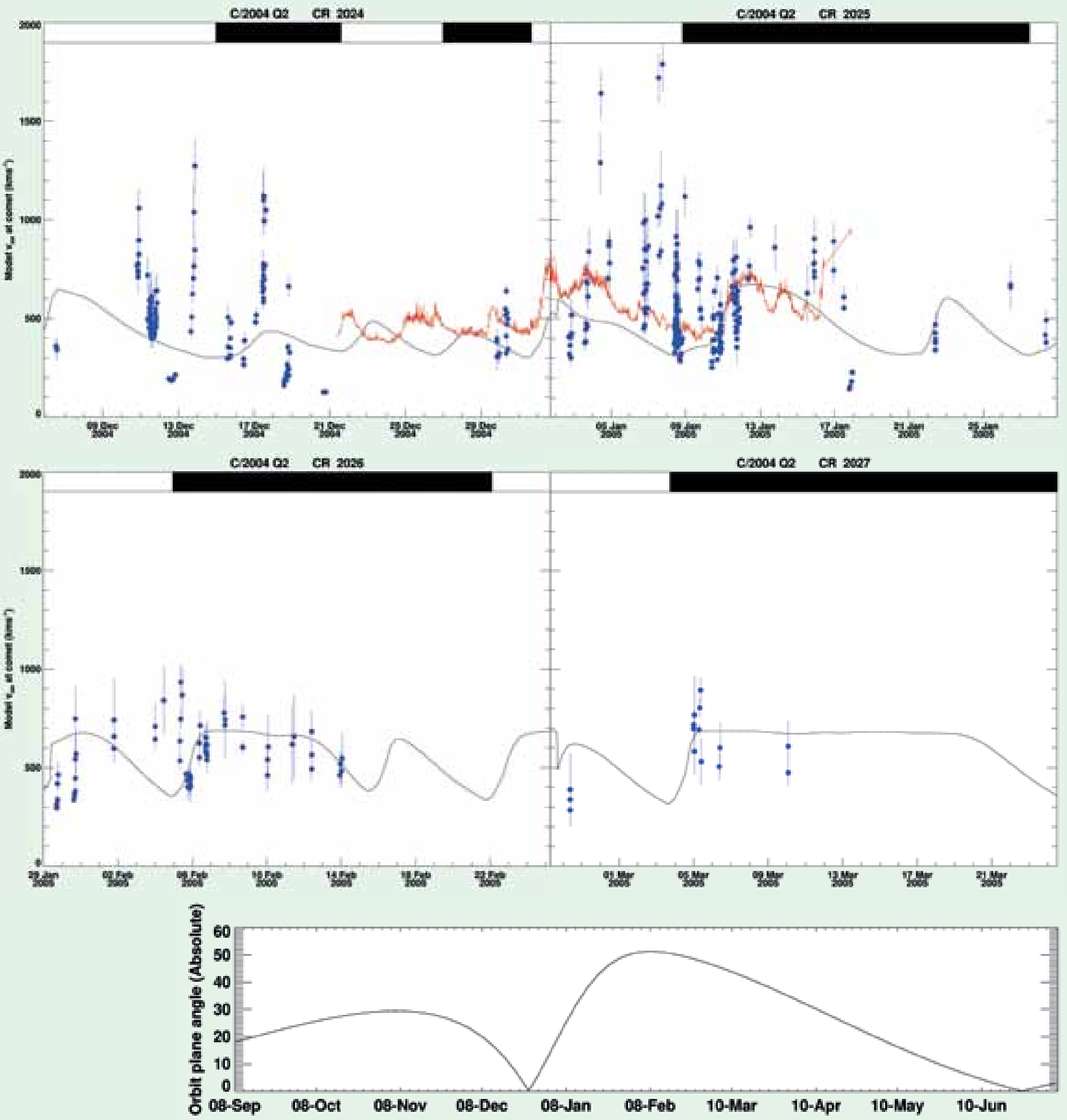
Comet Machholz (C/2004 Q2) was the first

Comets, their tails and the solar wind

A comet is best described as a loosely bonded, icy conglomerate of planetesimals composed mainly of frozen volatiles and meteoritic dust. With a solid nucleus at the centre, a luminous and spherical dust and gas envelope, also known as the coma, a comet also boasts two other easily recognizable features: the dust and ion tails extending across space (figure 1).

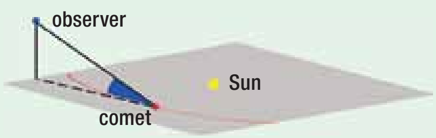
The white and diffuse dust tail consists of micrometre-sized dust grains pushed back from the nucleus and coma by solar radiation pressure. With a typical length of 10^7 km, it opposes the direction of motion of the comet and is slightly curved as it gravitationally orbits the Sun. The dust particles are in individual orbits about the Sun. The ion tail (also referred to as plasma tail or Type I tail) comprises mainly H_2O^+ and CO^+ ions. Fluorescing carbon monoxide (CO^+) ions give the tail its bluish tint. Ion tails tend to be oriented in the anti-sunward direction; however, it is always lagging the true anti-solar direction by a few degrees, opposing the direction of the comet's motion. Features such as curvature of the ion tail and rapid changes in the orientation are usually attributed to varying conditions in the solar wind. Ion tails can reach up to ~10^7–10^8 km (~1 au), with comet Hyakutake's ion tail reaching up to 3.8 au. More infrequently, some comets have been observed to be strong sources of sodium and have shown clear sodium tails (Knight *et al.* 2010), as observed at comet Hale-Bopp.

The solar wind is a continuous outflow of ionized solar plasma, carrying with it a remnant of the solar magnetic field that pervades interplanetary space. This fast-moving plasma flows radially outwards from the Sun at supersonic and super-Alfvenic velocities, with velocities ranging from 450 km s^{-1} in the equatorial region and 750 km s^{-1} in the polar region. Variations in the solar wind properties are large in the equatorial region compared to a steady flow with small variations in the polar region. A close correlation between the composition of the solar corona and the solar wind indicates that the corona is the source region for the solar wind.



4: Comet Machholz-derived solar wind velocities are in blue with two-dimensional error bars. Solid-line plot shows modelled values of the solar wind interpolated to the comet's vicinity. ACE data (red) was offset to account for angular separation between the comet and Earth. Black-and-white bars represent interplanetary magnetic field (IMF) reversals, an indication when cometary heliospheric current sheet (HCS) crossings are expected. The absolute value of the orbit plane angle is given below.

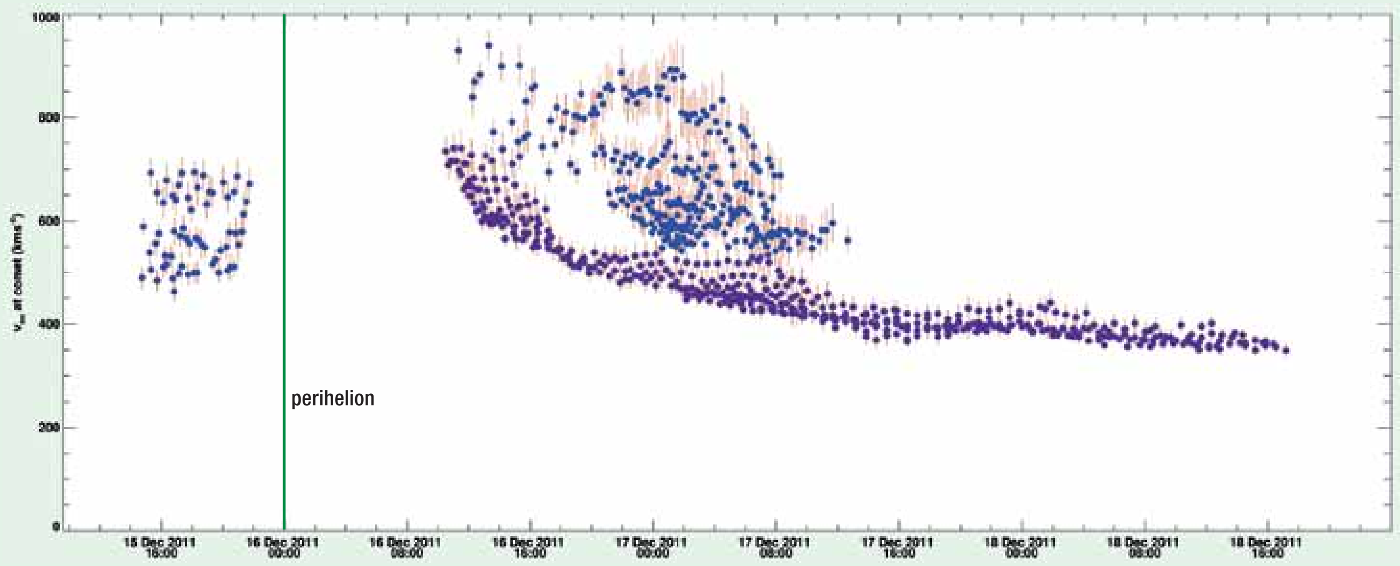
test candidate. Its fortuitous geometry brought it close to the ecliptic plane and within 0.3 au of Earth around its perihelion. During comet Machholz's period of maximum brightness and observability, the comet's orbit evolved almost in step with the Earth's motion in both solar ecliptic and heliographic longitudes. From this unique geometrical arrangement, we assume that (i) local Earth solar wind conditions, as registered by NASA's Advanced Composition Explorer spacecract (ACE), can be reliably extrapolated to the near-vicinity of the comet and (ii) any interplanetary coronal mass ejections would be experienced by both the Earth and the comet. Local solar wind velocity estimates, when comet Machholz crossed the ecliptic plane and was close to the Earth, can thus be compared to solar wind velocity measurements by the ACE/SWEPAM instrument. To account for the angular separation between the two bodies, ACE measurements needed to be offset by ~1.5 to 2 days to account for the time taken for the solar wind structures experienced by the comet to sweep the Earth. The SOHO/LASCO CME catalogue was used to narrow down potential CME candidates.



3: The orbit plane angle is a significant variable to consider when describing an ideal observing geometry. It is the angle formed (blue) between the observer–comet line and the comet's orbital plane (grey). When the orbit plane angle is at 90°, the observer has the perfect viewing geometry to measure the solar wind velocity. At 0°, the observer is lying in the same plane as the ion tail and cannot accurately measure the radial solar wind velocity. However, this scenario can offer the opportunity to measure non-radial flow components out of the comet's orbital plane.

My results were also compared to a coupled pair of corona–heliosphere models (CORHEL), in collaboration with M Owens of the University of Reading. Polarity reversals in the solar wind are also included in the modelled values of the solar wind and were compared to images displaying disconnection events. However, this model does not include other transient interplanetary events. Comparisons of my solar wind velocities to modelled values, the orbit plane angle and ACE *in situ* data near Earth suggest that the technique performs well for undisturbed solar wind conditions with the scatter lessening for high orbit plane angles.

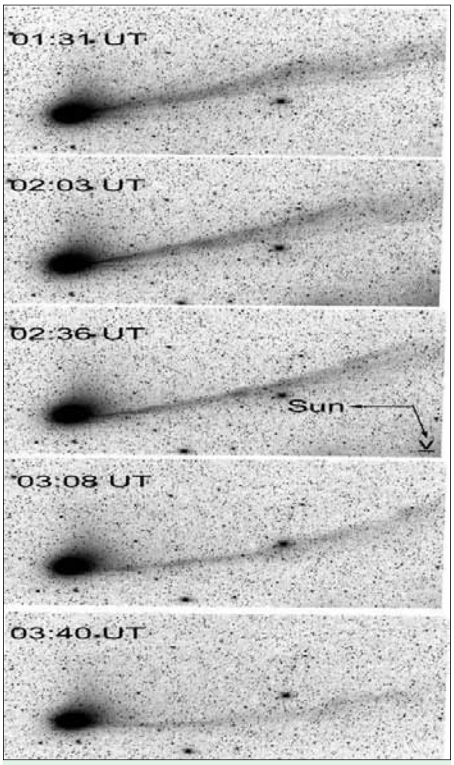
During Carrington rotations (CR) 2024 and 2025, the orbit plane angle ranges between 0 and 20°, improving up to 40° towards the latter half of January. The orbit plane angle peaks during February but remains high for CR 2026 and CR 2027. The large scatter during the first two Carrington rotations shown in figure 4 can be mostly attributed to ion tail disturbances evident in the image archive. These turbulent events can be linked to expected coronal mass ejection (CME) encounters and heliospheric current sheet crossings. An image sequence taken by W Koprolin on 17 January 2005 provides an excellent visual example of the



6: Solar wind velocities extracted from comet Lovejoy images (for Carrington rotation 2118). The blue dots represent solar wind velocities from the LASCO C3 (standard filter) images. The purple dots are solar wind velocities from STEREO A images. Images from STEREO B were ruled out for analysis due to the consistent low orbit plane angle through the observing period. X and Y error bars are in red. The *x*-axis represents the time at which the plasma bundle left the comet's orbit. The discrepancy between the solar wind velocities from two different vantage points indicates a non-radial ion tail.

influence of CMEs on cometary ion tails. In figure 5, the ion tail can be clearly seen to change, becoming thinner, curved and fainter as the CME flows past the comet. From such image sequences, we can build a velocity vector map, as a complementary method for calculating the solar wind velocity during transient events.

More recently, comet Lovejoy provided a unique opportunity: it was the perfect diagnostic tool to validate my processing pipeline as the comet was successfully observed remotely by an international fleet of spacecraft (Sekanina 2012). I updated my analysis methods to facilitate simultaneous monitoring of the heliosphere from several vantage points, something hitherto impossible to achieve practically. Through comparison of concomitant results from multiple observing locations, heliospheric white-light imagers (HI 1) from STEREO A and STEREO B (Howard *et al.* 2008) and the C2 and C3 coronagraphs from the SOHO spacecraft (Brueckner *et al.* 1995), my latest investigation demonstrated that comet Lovejoy's ion tail was non-radial, consistently curving towards its dust tail (figure 6). I am currently developing a new data analysis technique to resolve three-dimensional solar wind velocities from spacecraft images (Ramanjooloo, in prep).



5: Image sequence by W Koprolin showing the turbulent flow of comet Machholz's ion tail on 17 January 2005.

Comparison of the results to the orbit plane angle suggests that the observing geometries were good enough to produce valid estimates of the solar wind. Therefore, the discrepancy between the two solar wind velocity distributions cannot be attributed solely to geometrical effects, arising from the orientation between the comet and the imaging instruments. I conclude from this study that the observations are complicated by a combination of a non-radial solar wind flow and an ion tail whose curvature is influenced by ions emanating from the dust tail.

Summary

My overall goal is to produce a catalogue of the effects of solar wind conditions on comets, and solar wind velocities from historical comets. This catalogue will provide invaluable insight into the solar wind's variability, including a latitudinal map of ion tail disconnection events. The catalogue will infer solar-cycle-dependent latitudinal variations of the heliospheric current sheet locations and solar wind transition regions. We issue an open call for images of comets' ion tail, including, but not restricted to, C/2012 S1 (ISON) and C/2013 R1 (Lovejoy). More information and details of how to submit images are available at http://www.ucl.ac.uk/mssl/planetary-science/call-for-comet-tail-images.●

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Acknowledgments. Thanks to http://www.Astrometry.net for the initial image processing; Chris Arridge, Gethyn Lewis and Lin Gilbert for help with the programming; STFC for funding the studentship; Wilcox Solar Observatory (currently supported by NASA) data used in this study were obtained via http://wso.stanford.edu courtesy of J T Hoeksema. I extend my gratitude to the SOHO/LASCO and UK SECCHI science team at RAL for the data, advice and timely assistance, and final thanks to R Howard (NRL), PI of both the LASCO and SECCHI instruments.

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