Astro2020 Science White Paper

Radio Scintillation Studies of Comet Ion Tails

Thematic Areas: **X** Planetary Systems ☐ Star and Planet Formation
☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments
☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

Principal Author:
Name: Christopher J. Salter
Institution: Green Bank Observatory, WV & Arecibo Observatory, PR
Email: csalter@nrao.edu
Phone: 304-456-2143

Co-authors: (names and institutions)
P.K. Manoharan, Arecibo Observatory, PR & RAC, NCRA, TIFR, Ooty, India

Abstract (optional):
The nuclei and comae of comets are frequent targets for radio/radar astronomical investigations. However, the ion/plasma tails of these objects are more "elusive" observational targets. Nevertheless, the electron density fluctuations in these tails allow their study via the scintillations that they impress on the radio emission from a sub-arcsecond sized radio source as a comet's ion tail passes across the line-of-sight from Earth to the radio source. This phenomenon offers a simple way of investigating the plasma in a comet's ion tail. It is also extremely cheap compared to the cost of any "in-situ" measurementvia a space mission. The present document reviews the technique and the results obtained from existing studies. It also highlights the potential for expansion of our understanding of ion tails from such observations given actual and expected instrumental and programmatic advances over the coming decade at the major US single-dish radio observatories.

Radio Scintillation Studies of Comet Ion Tails

1. Introduction

Cometary nuclei are made up of rock, dust, and frozen gas. When heated as they approach the Sun, dust and gas are released from the nucleus producing a gravitationally unbound atmosphere surrounding the nucleus known as the coma. The coma generally consists of H_2O and dust, water making up to 90% of the volatiles that outflow from the nucleus when the comet is within 3–4 AU of the Sun. The H_2O parent molecule is destroyed primarily through photodissociation and to a lesser extent photoionization by the solar wind. The force exerted on the coma by solar radiation pressure and the solar wind causes an enormous tail to form, which points away from the Sun. Cometary tails can have sizes of at least an AU, and subtend many degrees on the sky. Both the coma and tail are illuminated by the Sun and may become visible when a comet passes through the inner Solar System, the dust reflecting sunlight directly while the gases glow from ionization.

The dust and gas streaming from the coma form their own individual tails, each pointing in somewhat different directions (Fig. 1). The *dust tail* (often called the type-II tail) is left behind towards the comet's orbit such that it frequently forms a curved tail. Meanwhile, the *ion* or *plasma tail* (often called the type-I tail) consisting of gases, always points directly away from the Sun as this ionized gas is more strongly affected by the solar wind than is the dust, following magnetic field lines rather than any orbital trajectory. On occasion, the magnetic field lines in the ion tail are squeezed together to the point where, at some distance along the tail, magnetic reconnection occurs, leading to a "tail disconnection event". One such event was seen in April 2007, when the ion tail of Comet Encke was completely severed as the comet passed through a coronal mass ejection. On occasions, such as when the Earth passes through a comet's orbital plane, a tail pointing in the opposite direction to the ion and dust tails (called the *antitail)* may be seen.

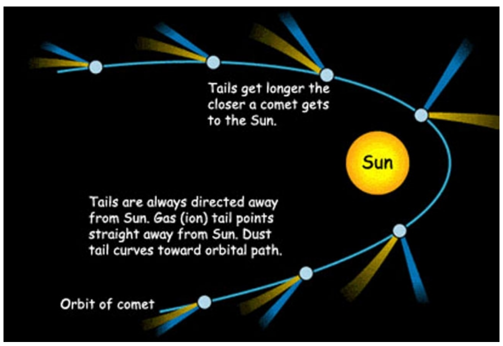

Figure 1:(Left) A schematic illustration of the very different paths that dust and ion comet tails trace on the sky as a comet passes its perihelion. The dust tail is sketched as light brown curving towards the comet orbit, while the ion tail is shown as light blue and is strictly radial to the Sun. **(Right)** A particularly good example of both a dust (white/red brown) and an ion tail (blue) was seen for Comet Hale-Bopp (1997).

Radio/radar astronomy is able to study the nuclei, comae and dust tails of comets, as detailed in other white papers in this series. The ion tails of comets are in many ways more “elusive” observational targets. However, radio astronomy has a role to play here too, and this will be elaborated on in the remainder of this document.

2. Observational Potential

Scintillation of the continuum emission from compact radio sources caused by inhomogeneities in the the electron density of a foreground plasma provides a well understood method for studying conditions in an intervening medium such as the solar wind. Such *interplanetary scintillations* (IPS) have been employed to study Coronal Mass Ejections as they convect outwards from the Sun. Electron density fluctuations also exist in the ion tails of comets, and offer the potential to study the electron density spectrum within a tail as it occults a compact radio source. In particular, information can be obtained on the magnitude of density fluctuations, and their scale sizes, which otherwise would only be available via occasional, highly expensive, space probes.

3. Technical Details

Studies of the turbulent nature of the plasma distribution in a comet's ion tail via its effects in the form of scintillations impressed on the radio emission from compact (sub-arcsecond sized) radio sources as the plasma tail occults the source have been made by a number of observers with varying success. However, observations of such scintillations induced by cometary ion tails offer a relatively simple and extremely cheap way of investigating the plasma within these tails compared with the cost of "in situ" measurements from space missions.

The scintillation index of the signal from a radio source, m, is defined as the rms fluctuation of the recorded source intensity divided by its mean intensity. For a Gaussian electron density correlation function of irregularities in the plasma, and for weak scattering;

$$m^2 = 2\pi^{1/2}\, r_e^2\, \lambda^2 \langle \Delta N^2 \rangle\, a\, L \qquad (1)$$

where, L = the thickness of a cylindrical ion tail, λ = wavelength, r_e = the classical electron radius, a = the scale size of the density irregularities, and $\langle \Delta N^2 \rangle^{1/2}$ = the rms electron density variations.

Further,

$$m = \sqrt{2}\, \varphi_0 \qquad (2)$$

where, $\varphi_0 = (2\pi)^{1/4}\, r_e\, \lambda\, (a\, L)^{1/2} \langle \Delta N \rangle$ is the rms phase deviation introduced into the incoming wavefront by the irregularities in the plasma "screen".

Additionally,

$$a = v / (2\pi\, f_2) \qquad (3)$$

where v = the velocity of the diffraction pattern across the observer (the relative component of the plasma velocity), and f_2 = the width of of the scintillation power spectrum at the $e^{-0.5}$ point.

Given (1)–(3) it is possible to study the turbulence in the plasma tail. For example, L, v and N can be obtained from H_2O and emission imaging (e.g. Debi Prasad, 1994, BASI, 22, 67) allowing ΔN to be derived. Debi Prasad 1994 derived $\Delta N/N \sim 40\%$ for Comet Austin 1990.

In addition, in the weak scattering regime, the power spectrum of the scintillations of the recorded radio source emission, after correction for system noise, provides the scintillation index from the area under the spectrum, while the shape of the spectrum contains information on the power spectrum of the plasma turbulence.

4. Existing Studies

Previous studies of radio source scintillations caused by the occultation of a target source by the ion tail of a comet have produced a mix of results ranging from failure to detect the hoped-for scintillations to clear positive results. For example, Hajivassiliou & Duffett-Smith (MNRAS, 1987, 229, 485) noted that it is often hard to discriminate between true scintillations impressed on radio source signals , and interplanetary and ionospheric scintillations. These authors used existing data from the Cambridge 81.5 MHz IPS Survey of Purvis et al. (1987) to look for scintillations impressed on source signals for a number of compact targets via predicted occultations by the ion tails of several comets. For 12 bright comets they examined some 45 potential occultations of bright radio sources that were observed at appropriate times in the IPS survey. However, they found no unequivocal evidence of additional scintillations compared with nearby control sources, and reserved judgement concerning the effect.

Likewise, no convincing enhanced scintilations over and above ambient IPS were found by Ananthakrishnan, Manoharan & Venugopal (Nature, 1987, 329, 698) using the Ooty Radio Telescope (ORT) at 326.5 MHz for four compact sources occulted by the plasma tail of Comet Halley. These authors stressed the importance of the quasi-simultaneous observations of nearby, but non-occulted, compact sources. It should be noted that these observations were made along lines of sight where the solar wind was in strong scattering regions, a point that will be elaborated on in Section 5 below.

In contrast, Alurkar, Bhonsle & Sharma (1986, Nature, 322, 439) claimed to detect strong scintillations of the 103 MHz emission from 3C459 when it was occulted by Comet Halley. Similarly, Slee, McConnell, Lim & Bobra (1987, Nature, 325, 699) observed the passage of the ion tail of Comet Halley over PKS 1827-360. They detected weak intensity scintillations which they attribute to the effects of electron fluctuations in the plasma tail of the comet, deriving an electron density 5.4×10^6 km downstream from the cometary nucleus some 14 times the density of the undisturbed solar wind.

Iju et al. (Icarus, 2015, 252, 301) studied scintillations caused by the ion tail of Comet ISON (C/2012 S1) shortly before its nucleus “collapsed” on 28 November 2014. This comet had a well developed plasma tail. These authors used the STEL Nagoya telescope to study radio source scintillations at 327 MHz, together with imaging from the STEREO spacecraft to estimate electron densities. They produced g-maps of the scintillations, finding significantly increased g values when PKS 1148-00 was occulted by the comet tail, and concluded that the plasma tail was seen beyond the visible length of the ionized tail. They also concluded that the power law spectral index ($P(f) \propto f^{-\beta}$) had a steeper value when the source was occulted by the comet ion tail than for standard IPS.

Roy, Manoharan & Chakraborty (2007, ApJ, 668, L67) observed the occultation by Comet Schwassmann-Wachmann 3-B (73P/Schwassmann-Wachmann) of the highly compact radio source B0019-000 with the Ooty Radio Telescope at 326.5 MHz in May 2006. At that epoch the comet was in the process of disintegrating. From the power spectra derived from the signal scintillations, they obtained the scintillation indices from the area under the spectra, while the detailed shape of the power spectra provided detailed information on the plasma turbulence. As the plasma tail approached the radio source, a change in the shape of the source's scintillation power spectrum occurred (Fig. 2), with steepening being seen at low temporal frequencies. This effect was interpreted as being due to large scale irregularities of size >500 km, assuming a typical solar wind speed of 400 km/sec. Close to the actual time of maximum occultation, excess power was also seen attributable to small scale structure of size <50 km . The scintillation index of the source also increased for about an hour during the occultation. None of these effects were seen at the time for nearby, non-occulted control sources, or for B0019-000 away from the time of occultation. The authors suggest that that their observations may indicate two main turbulence regions within comet plasma tails, as previously suggested by Slee et al. (1987, 1990) from observations of Comets Halley and Wilson.

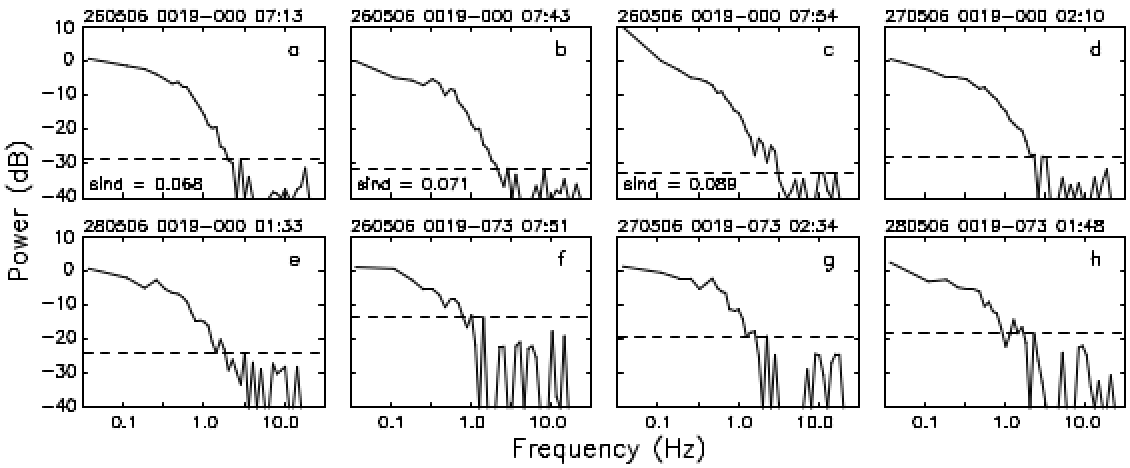

Figure 2: Power spectra of the intensity fluctuations of radio sources near the time of occultation of B0019-000 by the ion tail of Comet Schwassmann-Wachmann 3-B. The horizontal axis is the temporal frequency (Hz) and the vertical axis is power (dB). Date, source name, and the time of observation (UT) are given at the top of each panel. The dashed lines indicate the noise power level. Note the steepening of the spectrum at high spatial scales (low temporal frequencies) in Panels b and c, and significant excess power at low spatial scales (high temporal frequencies) in Panel c compared to the rest of the spectra from follow-up and control observations.

Similarly, Fig. 3 shows power spectra of the occultation of compact radio source 3C48 by the ion tail of Comet Austin in April 1990 (Manoharan, unpublished).

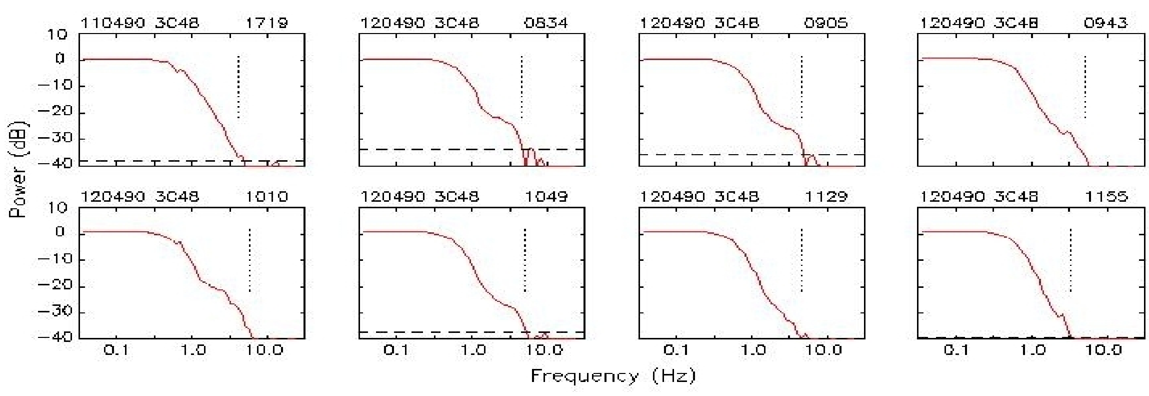

Figure 3: The power spectra of intensity scintillations for 3C48 on 12 April 1990, during its occultation by the tail of Comet Austin. In each plot, the vertical axis is power (dB) and the horizontal axis is temporal frequency (Hz). The first plot at the top shows the spectrum of 3C48 on the day previous to the occultation, while the last plot at the bottom corresponds to a spectrum when the source came out of the occultation. These spectra are of good signal-to-noise ratio (dashed lines indicate the noise level). It is evident from these spectra that during the time of occultation, the level of turbulence increased at high-frequencies (i.e., at small-spatial scales, <50 km) when the line of sight to the quasar probed varying turbulence levels in different parts of the tail.

5. Looking to the Future

Most existing studies of radio source scintillations due to their occultation by cometary plasma tails have been carried out at low frequencies (≤ 408 MHz) with relatively narrow receiver bandwidths. However, scintilations are a broadband phenomenon. In general, maximizing sensitivity is an essential for moving such studies into a new era. This would enable the study of far more occultations by ion tails, many with very high signal-to-noise ratios, permitting a major leap forward in interpretation and understanding. For example, with observations of a number of occulations by the same comet ion tail, the turbulence properties as a function of distance along the tail can be determined. In addition, an increase in the number of potential target occultations would allow considerable insight into such phenomena as "tail disconnection" events.

It was noted in Section 4 that the inconclusive observations of the occulations of 4 compact radio at 326.5 MHz by the ion tail of Comet Halley (Ananthakrishnan, Manoharan & Venugopal 1987) were made when the lines of sight passed through regions where the solar wind was in the strong scattering regime at that frequency. This was a case where multi-frequency observations could have been crucial towards revealing the physical properties of Comet Halley at its closest solar approach. In similar future situations, multi-frequency observations by such instruments as the Green Bank GBT and the Arecibo 305-m telescope offer huge potential for obtaining vastly richer information to that yet existing.

Already, broadband observations with excellent sensitivity could be undertaken with both the Arecibo 305-m telescope for the declination range $-01^{o} < \delta < +38^{o}$, and the Green Bank GBT for all declinations north of $\delta = -46^{o}$. Arecibo can cover all frequencies between 1.1 and 10 GHz, with additional bands at 327 ± 15 MHz and 430 ± 10 MHz, while the GBT has receivers covering all radio frequencies above 290 MHz. Particularly relevant is the planned introduction on the GBT in 2022, and subsequently at Arecibo, of a very wide-band feed system covering the frequency range of 0.7 to 4.0 GHz. Further, the forthcoming availability of phased-array feeds on both Arecibo (40 beams) and the GBT (19 beams) offers the possibility of sometimes being able to observe a control source simultaneously with the continuous monitoring of an occulted target.

Preliminary IPS measurements have recently been made at 327 MHz, L-, S- and C-band in preparation for commencing a major IPS program with the Arecibo telescope (see http://www.naic.edu/~phil/usrproj/ips/ips.html). Data analysis programs for reducing and displaying data taken for this study are now available in the Arecibo IDL analysis package written by Phil Perrilat (see http://www.naic.edu/~phil/ipsdoc.html), and could easily be replicated for GBT data.