

Astro2020 Science White Paper

Ground-based Observations of Small Solar System Bodies: Probing Our Local Debris Disk

Thematic Areas:

- 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

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Abstract:

Small bodies (comets and asteroids) are a window into the formation, evolution, and dynamic environment of our solar system, an end-state of debris disks that we can only study from afar. Observations of these objects constrain the dynamical, collisional, thermal, and compositional evolution and mixing in our solar system, providing a much-needed comparison point for extra-solar planetary systems. Long-wavelength ground-based observations of asteroids and comets provide an excellent complement to shorter-wavelength observations both from the ground and from space. In addition to the high spectral resolution characteristics of modern radio astronomy instrumentation, single-dish mapping observations with focal-plane or phased arrays provide instantaneous sensitivity for investigation of faint, extended, and time-variable sources such as cometary comae. A single-dish beam with large-footprint mapping instruments can capture the big picture to allow a scientific spectroscopic or continuum overview which can also serve to complement higher resolution observations with interferometry. For asteroids, the flexibility and sensitivity of single-dish radio and millimeter-wave continuum observations are ideal for surveys to characterize different populations (NEOs, main-belt, centaurs/TNOs) or to enable more intensive time-resolved follow-up for unresolved bodies.

New Opportunities with Small Solar System Objects

In observations of small bodies (comets, asteroids) in our solar system, we have the opportunity for close-up study of the objects of interest in debris disks and planetary formation, in an environment that we know formed at least one habitable planet. Recent and anticipated high-yield discovery programs and campaigns will continue to provide a wealth of such objects for investigation, both from the ground and from space. Larger volumes of known objects will lead to better statistics, more robust groupings, and better scientific categories of small bodies, and thus will better enable connections between these categories and the protoplanetary disk in which they formed and the thermal, collisional, chemical, and dynamical environment in which they evolved.

Connections to protoplanetary conditions may be developed in a few lines of investigation: 1) investigations of volatile matter and types of ices, either through surface imaging by spacecraft or spectroscopy from the ground or orbit, to inform the thermal evolution during and after accretion; 2) chemical characterization of the relative abundances of atoms, molecules, and isotopes, for comparison with such ratios in the interstellar medium and in protoplanetary disks; 3) spectroscopy of cometary comae, in different solar activity environments and solar wind speeds, to constrain the stellar-wind-planetary interactions in a system known to be habitable; and 4) long-wavelength thermal investigations, probing the sub-surfaces of asteroids and comets to constrain density and composition, which relate to accretion and collisional history.

As the sizes and relative brightness of newly discovered or returning asteroids and comets decreases, small body investigations will require increased sensitivity of telescopes and flexibility of instrumentation. Continuum observations will require precision calibration over longer integration times, with reliable flux calibration across multiple wavelength bands. Optimal cometary spectroscopy requires flexible spectrometers with wide bandwidths to detect multiple lines simultaneously, with high spectral resolution for optimal dynamical constraints, observable across a wide swath of the sky to probe the entire visible coma simultaneously.

In recent years, there has been tremendous progress in discovery and characterization of comets and asteroids in our solar system, with over 1,000 comets and nearly 800,000 asteroids catalogued (<https://www.minorplanetcenter.net/iau/lists/ArchiveStatistics.html>). Recent near-Earth object surveys have been particularly effective in increasing the numbers of known small bodies throughout the solar system, approaching completeness at lower and lower diameters. In near-Earth space, where both ground-based and space-based investigations are highly effective, over 20,000 asteroids and over 100 comets are known (<https://cneos.jpl.nasa.gov/stats/totals.html>). This rapid increase in discovery, which promises to increase even more rapidly with the availability of new survey assets such as LSST, provides a wealth of opportunities for characterization of existing and new categories of small bodies in our solar system, at size scales of interest for comparison to extra-solar debris disks. As we push the completeness of size-frequency distributions for small solar system objects, we will gain greater insights into the collisional and fragmentation processes at work in forming solar systems.

Spectroscopic investigations of comets

Radio spectroscopy is well-suited to investigation of cometary atmospheres (comae) because many of ice-derived molecules have rotational transitions observable in the radio and millimeter-wave bands at typical cometary temperatures (Crovisier et al. 2002, 2004; Crovisier 2006a,b; and references therein). Large, efficient single-dish radio telescopes are critical in the study of cometary atmospheres because of the long photo-destruction lifetime of the molecules, yielding a large coma -- tens of thousands of kilometers, up to tens of arcminutes on the sky. Gas production from volatiles, as well as photo-dissociation and other solar wind interactions, may vary rapidly, while the spatial distribution of observable emissions may change due to evolving source regions on the comet, changing insolation, or rotation of a complex-shaped nucleus. Tenuous but highly extended atmospheres that vary both temporally and spatially require the instantaneous sensitivity of a large radio dish as well as the high spectral resolution of modern high-quality radio astronomy spectrometers.

Volatile chemical species and the persistent presence of ice on cometary and asteroidal surfaces are important diagnostics of (a lack of) thermal processing and the composition of the natal cloud (Mumma & Charnley, 2011). While suggestions of the presence of ice on and beneath the surface can be accomplished with ground-based radar for a limited number of objects, direct imaging of ices on the surface requires in-situ spacecraft imaging. From the ground, the spectroscopic techniques for detecting volatiles (1), for determining other chemical and isotopic abundances (2), and for high-cadence monitoring for solar-environment influences (3) are similar, so we treat them here together.

Comets with favorable apparitions, with gas production rates $\geq 10^{28}$ molecules per second are observable at integrated spectral line intensities of 10 mJy km/s or stronger for OH at 18 cm (Λ -doublet at 1667 MHz). Higher sensitivity or closer apparitions permit detection of lower-production comets, or tracking of a single comet over a longer orbital arc. At higher radio frequencies, rotational transitions for molecules with significant dipole moments (such as CO, HCN, CH₃OH, H₂CO) are detectable in the millimeter-wave (and submm) for comets with gas production $\geq 10^{29}$ molecules per second, depending on the telescope and instrumentation. Lower frequency observations permit detection of ground-state molecular transitions appropriate to the low-energy excitation environment for comets, as well as detection of heavier, larger organic molecules (A'Hearn, 2006; A'Hearn et al., 2012; Albertsson et al., 2014; Marboeuf & Schmitt, 2014; Starkey & Franchi, 2013; Wooden, 2008; Wozniakiewicz et al., 2012).

In a typical year, 2-3 cometary apparitions will permit observations at useful signal-to-noise ratios for single-dish radio telescopes such as Arecibo, GBT, and LMT, but with greater sensitivity (and the discovery of fainter comets), this will increase in the coming decade.

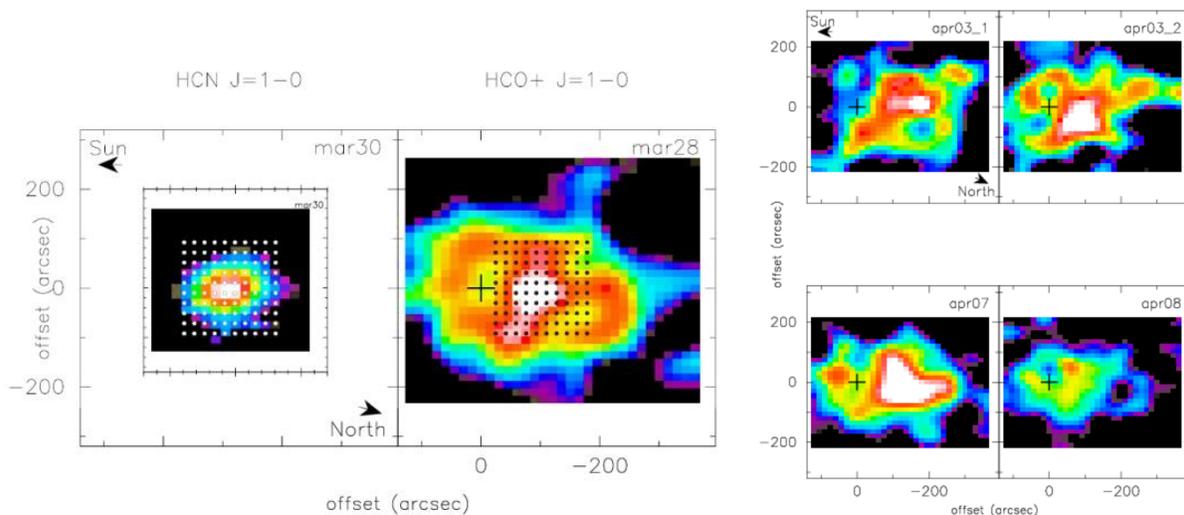


Figure 1: Spectral line integrated intensity maps of molecular emission from comet C/1995 O1 Hale-Bopp (Lovell, 1999), with the QUARRY array receiver on the 14m telescope of the Five College Radio Astronomy Observatory. The images were made with approximately 50 arcsecond resolution, and overlaid on them for illustration is the footprint of a 10x10 array at the 7-8 arcsecond resolution of the 100m Green Bank Telescope (GBT) at 90 GHz (3mm). Neutral HCN (left) has a much smaller footprint and less variability than HCO+ (left center and right). HCO+ is seen to vary dramatically in a few hours (top right), and from day to day (bottom right), presumably due to influences of the solar environment.

Chemical mixing ratios vary strongly from comet to comet, indicating heterogeneity in formation locations and circumstances; however, it is important to track comets over a range of heliocentric distances and viewing angles to disentangle the effects of individual jets of volatiles and differing sublimation energies (e.g. Gicquel et al. 2015). A mapping spectrometer with a sky footprint of ≥ 2 arcminutes, whether a focal-plane or phased array, permits a snapshot of the gases across the coma, and such spectrometers with flexible, multi-wavelength backends can permit simultaneous snapshots of the gas coma in multiple gas species. Simultaneous assessment of mixing ratios for nuclear (“parent”) species and the photodissociation product (“daughter”) species, particularly when the daughter products may also have a nuclear source, is an important piece of the connection between comets and their formation environments (Villanueva et al, 2011). In addition, some comets may produce additional volatiles from dust grains or other extended sources within the coma, so observations of the dust coma (in scattered light, thermal emission or with radar) and the gas coma at similar timescales are also important for the assessment of volatile sources. High sensitivity for rapid mapping is also critical for the assessment of ionized species that may be influenced on short time scales by the solar environment.

Different cometary source populations (short-period evolved comets that have continually been exposed to heating, and dynamically new long-period comets that are preserved at low temperatures from the era of giant planet formation) can be compared in gas production, activity levels, chemical makeup, and thermal history. Such comparisons are very important constraints on the models, which derive the distribution of different populations of comets in the evolution of the early solar system. Furthermore, in the investigation of volatile delivery and the chemical and thermal history of the early solar

system, it is of interest to observe nuclear breakup events and comets with extended dust comas. With large single-dish radio continuum receivers (as well as planetary radar) it is possible to detect the otherwise invisible large dust grains that typically form as cometary nuclei disrupt.

Thermal Investigations of Asteroid Sub-surfaces

Thermal emission from solid surfaces can be observed into the subsurface at depths of 6-10 times the observation wavelength, depending on the characteristics of the materials. From such observations, we infer the density, composition, porosity, and heterogeneity of the object. Observations at more than one depth enable investigation of dust/regolith depth, near-surface density, or even the nature of the object as a rubble-pile. Thermal observations, in combination with other techniques are a power diagnostic (c.f. Mueller, et al 2018). Continuum observations spanning into the radio regime will become possible with higher sensitivity continuum instruments.

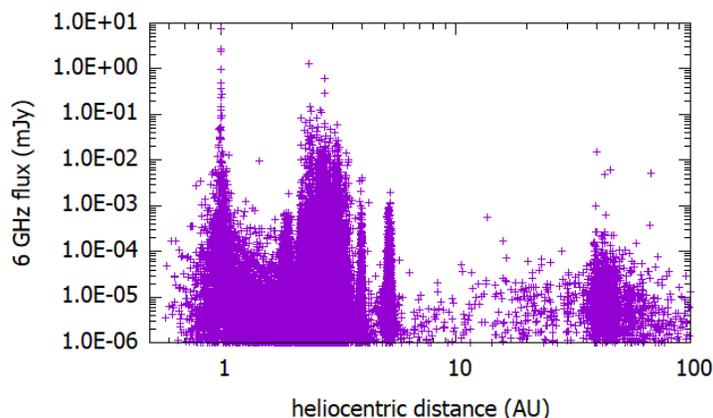


Figure 2: 6 GHz (5-7cm, C-band) predicted fluxes for known asteroids, assuming observation at opposition in thermal equilibrium with sunlight. Clearly, sensitivities at the sub-mJy level will permit characterization of numerous asteroids, and can complement IR and submm fluxes observed with other techniques. Thermal emission at these wavelengths would originate in the top half-meter of the surface, and likely be in annual equilibrium for most materials.

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