Cradle of Life Breakout Group Summary
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1 Image Disks where Earth-like Planets Form

1.1 Terrestrial Planet-Forming Regions around Sun-like Stars

The advent of high-spatial resolution, high-sensitivity millimeter wave interferometry with ALMA has led to the recognition that so-called *protoplanetary* disks are often highly structured, with gaps, holes, and spiral dust arms, in many cases the likely product of perturbations by forming planets. Probing the innermost regions of these dusty disks where terrestrial planets form– planets that ultimately could reside in habitable zones– is difficult at millimeter wavelengths because these regions are likely optically thick in many disks. Penetrating through the dusty disk layers to the midplane will require observations at longer wavelengths (10-50 GHz) with very high angular resolution, about 5 mas at the 140 pc distance of the large population of targets in nearby dark clouds.

ALMA and optical scattered light observations already show the presence of non-axisymmetric disk structures in dust, presumably due to the presence of a perturbing planetary body. Spiral wakes and other structures tend to orbit with the same period as the planet rather than the local Keplerian velocity. High-resolution centimeter observations will detect the motions of such non-axisymmetric structures over a few years, pointing to the presence of protoplanets.

1.2 Grain Growth to Centimeter Sizes

The new paradigm for the formation of large solid bodies in protoplanetary disks is that of "pebble accretion", in which solids of centimeter to meter sizes are accreted by planetesimals- self-gravitating bodies which may themselves have been formed by condensation of pebbles in "streaming instabilities". Current observations demonstrate the presence of mm-sized grains in the outer regions of protoplanetary disks, with weak constraints on larger particles. Probing the populations of grains in the centimeter (and beyond) range throughout disks as a function of the central star properties and ages will provide crucial tests of these theories of planet formation. Again, centimeter wavelength observations are needed to combine with millimeter data to constrain the spectral index of dust opacities and thus infer changes in the dust population.

1.3 The Water Snow Line

The inner bodies of our Solar System tend to be "dry", suggesting that they formed inside the water "snow line". Many models require snow lines at 3 to 4 AU, yet there are theoretical difficulties in providing a high enough temperature at such radii in an optically-thick disks. Direct observational detection of midplane water sublimation would provide crucial tests of our understanding of protoplanetary temperature structures and water delivery (as needed) to terrestrial planets in habitable zones. A possible way of finding snow lines would be to detect NH_3 emission released from solids, which is expected to occur when water ice sublimates. Observations at short centimeter wavelengths (10-50 GHz) with the high spatial resolution required above would be needed, and may also provide detections of complex organic molecules. The required sensitivity is uncertain, and the observations are likely to be challenging, but the payoff would be great.

1.4 Issues/requirements/goals

- centimeter wavelengths (10-50 GHz) needed to overcome opacity in inner disks
- 5 mas resolution (1 AU at 140 pc) needed to resolve structures
- follow evolution to pebbles at centimeter wavelengths
- measure snow lines and possibly organics using molecular lines
- use time domain to observe evolution directly over months to years

2 Star Formation: Near, Far, and Extreme environments

While our understanding of star formation in nearby environments is far from complete, observational constraints on the production and characterization of young stars in extremely dense, often highly irradiated, environments are rare; yet the bulk of star formation over cosmic times arguably occurred in such regions. To make progress, it will be necessary to probe regions that are opaque at millimeter wavelengths, pushing observations to the centimeter regime; and, as the typical massive star-forming regions are beyond 1 kpc, high angular resolution will be essential.

2.1 Massive Star Formation

Massive stars are important for their impact on the interstellar medium, with recent simulations suggesting that stellar winds and particularly supernova explosions are critical in regulating star formation. Key unresolved questions in massive star formation are (1) how can accretion rates be high enough to form high-mass stars in the required short periods of time? and (2) is high-mass star formation mediated by accretion through disks, as suggested by models to circumvent the radiation pressure problem? Observations at centimeter wavelengths can penetrate the large dust column densities implied by high infall rates, and also detect free-free emission from ionizing stellar radiation. Resolutions of 5 to 10 mas are needed to resolve these systems out to 10 kpc. Such observations also may detect the photoionized surfaces of accretion disks (e.g., Source I in BN/KL).

2.2 Stellar Multiplicity

Characterizing proto-binary systems is important for understanding the fundamental processes of fragmentation, especially as there is some evidence that orbital properties evolve during formation. Observations at centimeter wavelengths are needed to penetrate the dense dusty envelopes and disks in which fragmentation can occur, with resolutions of 10 mas to probe separations from 4 to 15 AU at 140 (nearby dark clouds) and 500 pc (Orion), respectively, spanning the peak of the G star binary orbit distribution. Related, massive star multiplicity is very high and must be probed in the formation stage.

2.3 Extreme Environments: the Galactic Center

Clues to the mechanisms of star formation can be found in understanding the effects of varying environment (metallicity, etc.) The most extreme environment in our Galaxy is that of the Galactic Center circum-nuclear disk. While apparently young, massive young stars are found there, detection of any low-mass stellar population would help resolve whether ongoing star formation is really occurring and whether the properties of the population are affected by the extreme environment. Short centimeter observations (20-50 GHz) are needed to penetrate the large obscurations toward the Galactic Center; this wavelength range limits the signal from ambient dust and ionized mini-spiral emission, and a wide bandpass could be used to search for various signals of the low-mass population (synchrotron, free-free jet, and dust disk emission). Angular resolution of 10 to 20 mas would resolve typical protoplanetary disks, and would help for observing proper motions, to be compared with near-infrared studies with VLT, Keck, and the next generation of large optical telescopes.

2.4 Issues/requirements/goals

- centimeter wavelengths (10-50 GHz) needed to see into massive star forming regions
- centimeter wavelengths (10-50 GHz) needed to probe stellar multiplicity in the formation stage
- 5 mas resolution needed to resolve disks in star forming environments to 10 kpc (< 50 AU)

3 Exoplanets and our Solar System

3.1 Stellar activity and Habitability

The habitability of exoplanets can be affected by stellar magnetic activity, in particular stellar coronal winds and other mass ejection, including high-energy particles. The long-known observational evidence that solar mass stars exhibit a very wide range of X-ray luminosities at ages of 100-500 Myr (related to differences in rotation) has now been recognized as a potential issue in habitability, with the most active stars potentially able to remove terrestrial planet atmospheres efficiently. Stellar activity is also a major issue for M dwarfs, the most common stars, which can remain magnetically active for long periods of time, and for which habitable zones lie close to the star. Sensitive observations at 100 GHz can enable the measurement of stellar wind mass loss rates for these main sequence stars for the first time. Stellar Coronal Mass Ejections (CMEs) are known to cause radio bursts at 10s of MHz when interacting with planetary magnetospheres; detection of such bursts for systems with hot Jupiters could provide essential constraints on their magnetic fields.

3.2 Solar System Bodies: Atmospheres, Surfaces, Compositions

Understanding the atmospheres of planets requires mapping at a range of wavelengths to probe different layers. Sensitive observations at 10 GHz and below would complement current results from optical, infrared, and VLA studies. Because of the rapid rotation of the giant planets and the time-variability of atmospheric structures, good simultaneous uv coverage is needed along with sensitivity.

Studying deeper layers in solid bodies also would be made possible by observations at centimeter wavelengths, which would be of interest to probe levels that are not greatly affected by diurnal heating, thereby helping to infer thermal inertia and porosity. Other applications include probing lake formation on Titan. Resolution to < 50 mas would enable imaging of the largest asteroids and Kuiper Belt Objects.

Deeper centimeter wavelength observations of comets than currently feasible with the VLA could enable the detection of many heavier molecules. In particular, the important water to ammonia ratio might be measured by simultaneous observations of the 22 and 24 GHz lines of water and ammonia, respectively, helping to understand how comet chemistry relates to conditions in the Solar Nebula.

3.3 Issues/requirements/goals

- long wavelengths (10's of MHz) needed to detect exoplanet B-fields via "CME" interactions that could be crucial for habitability
- < 50 mas resolution at 10-100 GHz to image sub-surfaces of planets, their satellites, and the largest asteroids and Kuiper Belt Objects
- high spectral resolution (< 1 km s^{-1}) needed for cometary molecules