Planetary Systems in the Universe - Observation, Formation and Evolution
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Observing Extrasolar Planetary Systems with ALMA

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Abstract. The next generation millimeter to submillimeter wavelength synthesis telescope, the Atacama Large Millimeter Array (ALMA), is an excellent instrument for direct and indirect detection of extrasolar giant planets and imaging of extrasolar planetary systems at all evolutionary stages. We examine some possibilities of ALMA in this respect here.

1. Imaging Very Young Systems

Recent observations indicate that a large fraction (as much as 50%) of young low mass stars in galactic molecular clouds are surrounded by disks of molecular gas and dust (see e.g., Sargent & Beckwith 1994). Such disks appear to be a natural feature of the process of star and solar system formation. The observations show that the properties of the disks are similar to those predicted to have existed in the nebula from which our solar system is presumed to have formed. These disks may therefore provide tests of the theories of how our solar system formed, and how other systems may form in general.

ALMA will be an excellent instrument for the probing of circumstellar and protoplanetary disks. The fantastic resolution of ALMA at the shorter wavelengths ($\lambda < 1$ mm) will enable the construction of images of these disks which may be used to determine the properties of a large number of objects with associated disks. These disks are currently thought to be about 100 AU in radius. Given 15 km baselines for ALMA at 345 GHz, its resolution will be $\sim$ 12 milliarcseconds. This would provide roughly 60 "pixels" across such a disk in the Taurus molecular cloud (at 140 parsecs distance). Even at the distance of the Orion cloud (at 500 pc), almost 20 pixels would be obtained. Continuum images could be used to ascertain disk properties as a function of distance from the star, e.g., size, physical temperature and dust density. Observations at many frequencies could be used to constrain the value of β (the dust grain opacity exponent) quite accurately. Variation of these parameters from system to system may give insight into the formation process. By observing many systems of different age, evolution of these properties could be investigated. Images of molecular line emission would be a valuable tool in determining the dynamics of these disks. Particularly, it could be diagnosed whether these disks are currently in keplerian rotation, or are undergoing gravitational infall, or both, and whether this changes as a function of age in these systems. Images of molecular line emission could also be used to answer many questions about the chemistry in these disks (see van Dishoeck & Blake 2001 for an overview of some of these questions), including: is there is a change from kinetically controlled "interstellar" chemistry in the outer part of the disk, to equilibrium dominated "nebular" chemistry in

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the inner part? Why are molecular species in these disks depleted relative to their usual interstellar abundances? How does grain boundary chemistry affect the overall chemical structure of the disk?

2. Imaging Young Systems

As these systems age, condensations are expected to begin to form (see e.g., Boss 2001). These condensations are the cores of what will later become giant planets. The process of formation of these cores is not well understood, and observations of protoplanetary disks in various stages of early formation may allow investigators to distinguish between proposed models of their formation (e.g., via core accretion or disk instability).

As gas and dust from the surrounding disk is accreted onto these cores, they may become luminous enough to be detected with ALMA. As these condensations continue to grow, they are expected to clear gaps or inner holes in the protoplanetary disks. These gaps and holes are not only predicted theoretically (e.g., Lin & Papaloizou 1986), but inferred from the SED's of young systems (e.g., Beckwith et al. 1990), and the inner holes have actually been observed in several systems (e.g., ϵ Eridani, Fomalhaut, β Pic, and HR4796A). Warping in protoplanetary disks may also be induced by planets, as has been proposed as the cause of the warp in the inner part of the β Pic disk (see e.g., Mouillet et al. 1997). Examining these various indicators of forming planetary systems (and their variations with time/age) will yield important clues as to the progression of planet formation in other systems.

3. Direct Detection

The possibility of direct detection of giant planets around other stars is a very exciting one. We will consider the possibility of directly detecting 3 different types of giant planets with ALMA, corresponding to different evolutionary ages. First, a mature giant planet similar to our own Jupiter: $R \sim 7.0 \times 10^7$m $\sim 1R_j$; $T \sim 200$ K. Second, a mature, but hotter planet (which might be considered a brown dwarf, e.g., Gl229B): $R \sim 1.0 \times 10^8$m $\sim 1.5R_j$; $T \sim 1000$ K. And lastly, a very young "protoJupiter": $R \sim 2.1 \times 10^9$m $\sim 30R_j$; $T \sim 2500$ K. We consider observations with ALMA at 345 GHz (the most sensitive for thermal emission), and take the noise flux density at 345 GHz as 0.11 mJy in 1 minute (Butler & Wootten 1999). Given this, and presuming that we want to make these detections with a reasonable SNR (we choose 5), the times required for detections of the expected flux density from the 3 different classes of "planets" are shown in Table 1. Mature giant planets (like Jupiter) can be detected out to only a few pc. Objects like Gl229B could be detected out to 5-10 pc. The very young, hot, protoJupiters can be detected out to the nearest star forming regions.

4. Indirect Detection (Astrometry)

The orbit of a companion around its primary causes that primary to undergo a reflexive circular motion around the system barycenter. By taking advantage of the incredibly high resolution of ALMA in its widest configuration, we may

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Table 1. Time (days) needed to directly detect extrasolar planets.

distance (pc)	Case 1 (Jupiter)	Case 2 (Gl229B)	Case 3 (protoJupiter)
1	1.5	0.01	+
5.7	*	12.5	+
10	*	120	+
120	*	*	12.5

* $\Delta t_{min} > 1$ year + $\Delta t_{min} < 1$ hour

be able to detect this motion. If all of the stars detectable by ALMA (many thousands) had companions, how many of these companions could be detected (via astrometry) with ALMA? We assume that the companions are in orbits with semimajor axis of 5 AU. We consider 3 companion masses: 5 times Jovian, Jovian, and Neptunian. We assume integration times of 10 minutes, at 345 GHz. From the Hipparcos catalog, there are ~ 800 stars around which a 5*Jovian companion could be detected, ~ 180 stars around which a Jovian companion could be detected, and no stars around which a Neptunian companion could be detected. Virtually none of these stars are solar-type. From the Gliese catalog, there are ~ 200 stars around which a 5*Jovian companion could be detected, ~ 120 stars around which a Jovian companion could be detected, and ~ 30 stars around which a Neptunian companion could be detected. Of these, close to 100 of the 5*Jovians are solar-type, close to 30 of the Jovians are solar-type, and none of the Neptunians are solar-type.

We note here that, as with other astrometric techniques, the detectability of a companion does not depend on the inclination of its orbital plane around the primary. In fact, astrometry could resolve inclination ambiguities for companions discovered using radial velocity techniques, if the amplitude of the astrometric signal is large enough. We also note that astrometric searches are complementary to radial velocity searches in that the former are more sensitive to companions with larger semimajor axes, and the latter are more sensitive to ones with smaller semimajor axes.

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