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Observing Stars & Extrasolar Planetary Systems with ALMA

Bryan Butler, Alwyn Wootten, & Bob Brown [1]
National Radio Astronomy Observatory

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Abstract

We address in this memo the ability of ALMA to observe stars and extrasolar planetary systems (in various stages of formation). The observation of extrasolar planetary systems is thought to be one of the most important science drivers for ALMA. As such, we should have some idea of what the capabilities might be in this regard. In addition, ALMA will be the first instrument which will be able to detect, monitor, and even image (for the largest) a very large number of "regular" stars at wavelengths longer than the mid-IR. Again, we should have some idea of what our capabilities might be in this area. This was originally written up for a poster contributed to Symposium 202 at the IAU GA in 2000 in Manchester, and a shortened version was submitted to the proceedings of that symposium (Penny et al., unpublished to date).

1 Introduction

Recently, much emphasis has been placed on the optical and infrared wavelengths to observe extrasolar planets and planetary systems. We suggest here that the millimeter and submillimeter regions of the spectrum offer an attractive alternative to those shorter wavelengths. ALMA will be able to detect planetary systems at all evolutionary stages. In particular, ALMA will be able to observe planetary systems in four evolutionary stages:

1. Infancy - ALMA will all be able to image systems in the earliest stages of formation in the nearest star forming regions, in both dust and spectral lines.
2. Toddler - ALMA will be able to directly detect forming giant planets ("condensations") in protoplanetary disks, and the gaps created in these disks as the condensations grow.

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[1] now at National Astronomy and Ionosphere Center

3. Adolescent - ALMA will be able to directly detect very young giant planets in the nearest star forming regions.
4. Adult - ALMA will be able to indirectly detect the presence of giant planets around nearby stars through the use of astrometry. ALMA will also be able to detect and image dust/debris disks around nearby stars (zodiacal analogs).

2 The Instrument

The Atacama Large Millimeter Array (ALMA) is one of the largest ground based astronomy projects of this decade. The ALMA instrument is a merger of two major millimeter array projects - the U.S. Millimeter Array (MMA - see e.g., Brown 1998), and the European Large Southern Array (LSA - see e.g., Guilloteau 1998). There is also the possibility that Japan will soon join this collaboration, as an extension of their own millimeter array project - the Large Millimeter and Submillimeter Array (LMSA - see e.g., Ishiguro 1998).

ALMA will be comprised of 64 12-meter antennas. These antennas will have superb surface accuracy - better than 20μm, and extremely good pointing - better than 0.6 arcseconds. The frequency coverage of ALMA will include receivers in all of the atmospheric windows from 35 to 1000 GHz (7mm to 350μm). These receivers will be state of the art, with extremely good noise characteristics (as good as 3 times quantum limited). Total processed bandwidth will be 16 GHz per baseline in continuum mode. As many as 32000 spectral channels may be utilized to obtain unprecedented spectral resolution and coverage. Full polarization information will be available on all baselines. The antennas will be arranged in a number of different configurations, with the widest having maximum baselines of $\sim$ 15 km - providing for imaging with resolution as fine as 10 milliarcseconds.

The site for ALMA has been chosen, and lies in the high Andes of Northern Chile. This site is at $\sim$ 5050 m (16500 ft) altitude AMSL, in the Llano de Chajnantor. Testing of this site has been ongoing for 5 years now (see e.g., Radford & Holdaway 1998; Otárola et al.1998; Ishiguro 1998). The site is extremely good for millimeter and submillimeter astronomy, with excellent transparency and phase stability. The median precipitable water vapor is $\sim$ 1.3 mm, and the 25th percentile PWV is $\sim$ 0.7 mm.

The expected sensitivity for ALMA in both continuum and spectral line modes is shown in Tables 1 and 2. This is the sensitivity with only 1 minute of integration (Butler & Wootten 1999).

3 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

Table 1: Sensitivity for ALMA in 1 minute.

Frequency (GHz)	ΔS_{cont} (mJy)	ΔS_{line} (mJy)$^{\#}$
35^{+}	0.02	3.3
90^{+}	0.03	4.4
140^{+}	0.04	5.1
230^{+}	0.07	7.2
345^{+}	0.12	10
675^{*}	0.85	51
850^{*}	1.3	66

$^{+}$ PWV = 1.5 mm. * PWV = 0.35 mm. $^{\#}$ in a 1 km/s channel.

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.

As the youngest protostars begin to form, surrounding material hides them from view at all but the longest wavelengths. The reservoir of cold material, still to be accreted by the protostar, contributes appreciably to the total luminosity of the system. One of the most effective means of locating young protostars then is to detect that millimeter wavelength emission and to contrast millimeter luminosity to total luminosity. Since luminosity is measureable, and to first order proportional to mass, this ratio tracks the ratio of circumstellar to stellar mass, which decreases with age over the first few hundred thousand years of evolution. Finally, the leftover material swirling in a disk may become incorporated into planets, during the first several million years of a star's life.

ALMA will be an excellent instrument for the probing of circumstellar and protoplanetary disks. Some of the things which will be addressed by measurements with ALMA are:

- ALMA will be able to detect many more young low mass objects than can be currently detected. The spectral energy distribution (SED) of these objects can be examined to determine which of them might be expected to have disks. Much better statistics will thus be obtained for the fraction of these bodies which have disks, which will help constrain the theories of their formation. Distinctions between different types of low mass stars and their formation may be made possible (i.e., between embedded YSO's, cTTS's, wTTS's, Herbig Ae/Be's).

- The fantastic resolution of ALMA at the shorter wavelengths ($\lambda < 1$ mm) will enable images to be constructed 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 ~ 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. Images with such resolution could be used to perform a great deal of science:

- 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 1999 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 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? Chemical gradients of a great number of molecular species will be detectable, should they exist. In particular, images of disks in the water lines can be made from the Chilean site, something not possible at other wavelengths and from other sites.

4 Imaging Young Systems

As these systems age, condensations are expected to begin to form (see e.g., Boss 1999). 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 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 (see e.g., Lin & Papaloizou 1986), but inferred from the SED's of young systems (see e.g., Strom et al.1989; Beckwith et al.1990), and the inner holes have actually been observed in several systems (ϵ Eridani - see Greaves et al.1998; Fomalhaut and Vega - see Holland et al.1998; β Pic - see e.g., Lagage & Pantin 1994; and HR4796A - see Jayawardhana et al.1998; Koerner et al.1998). 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.

5 Direct Detection

The possibility of direct detection of planets around other stars is an exciting one, and we explore that possibility here. By direct detection, we mean the direct measurement of the emission (thermal or otherwise) from a "planet" and its central star, and hence the ability to produce an image of the star and the planet, albeit with only 1 pixel on each object. For the purposes of this section, "planet" means a distinct body orbiting a central star. The only such bodies luminous enough to detect are gaseous giant planets. However, they may be at any stage of their evolution, i.e., they may be very young, and hence very large and hot, or they may be quite mature (like Jupiter). The conditions necessary for such a detection are:

1. there must be sufficient flux density from the planet to obtain a "reasonable" signal to noise ratio (SNR), in a "reasonable" amount of time.
2. the emission from the planet must be distinguished from that from the star.
3. the detection must be obtained in a short enough time that the planet does not move too far in the plane of the sky.

5.1 Calculating Detectability

Here we consider the flux density from the planet compared to the expected noise characteristics of ALMA. The flux density from the planet is given by:

$$F_\nu = B_\nu \, \Omega \quad , \tag{1}$$

where B_ν is the *brightness* at frequency ν, and Ω is the angular size of the planet (as long as it is unresolved, which is the case here). The brightness is given by:

$$B_\nu = \frac{2\,h\,\nu^3}{c^2} \, \frac{1}{e^{h\,\nu/k\,T} - 1} \quad , \tag{2}$$

where h is the Planck constant, c is the speed of light in vacuum, k is the Boltzmann constant, and T is the equivalent temperature of the planet. Assuming a circularly symmetric planet, the angular size is given by:

$$\Omega = \frac{\pi\,R^2}{D^2} \quad , \tag{3}$$

where R is the radius of the effective emitting region of the planet, and D is the distance to the system. Assuming that we are in the Rayleigh-Jeans regime, and assuming that we do the observations at 345 GHz, this all reduces to:

$$F_{345} = \frac{2\,k\,T}{\lambda^2}\,\frac{\pi\,R^2}{D^2} \sim 6 \times 10^{-8}\,T\,\frac{R_j^2}{D_{pc}^2} \quad [\mathrm{Jy}] \quad , \tag{4}$$

where R_j is the radius in Jupiter radii, and D_{pc} is the distance in parsecs.

Why 345 GHz for these observations? For observations of any thermal blackbody (with emission which goes like λ^{-2}), the figure of merit that one wants to maximize is:

$$X_\nu = \frac{\nu^2}{\Delta S} \quad , \tag{5}$$

where ΔS is the noise at frequency ν. We want to maximize X_ν because it is proportional to the SNR obtainable. Table 3 shows this quantity for the ALMA frequency windows. So, even under the best atmospheric conditions, 675 GHz and 850 GHz is not as good as 345 GHz in median conditions. 345 GHz is the best frequency in median conditions, and hence the frequency of choice for the types of observations described in this document.

Table 2: Figure of Merit for ALMA observations of thermal sources.

Frequency (GHz)	ΔS_{cont} (mJy)	$X_\nu/10^4$
35^+	0.02	6
90^+	0.03	27
140^+	0.04	49
230^+	0.07	76
345^+	0.12	99
675^*	0.85	54
850^*	1.3	56

$^+$ PWV = 1.5 mm. * PWV = 0.35 mm.

As examples, we will consider 3 different types of giant planets, 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. Values of the flux density for these objects at 1, 5.7, 10 and 120 parsecs are shown in Table 4, for a frequency of 345 GHz.

Now, are these levels of flux density detectable with ALMA? We 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 flux density levels shown in Table 4 are shown in Table 5. It can be clearly seen

Table 3: Giant planet flux densities at 345 GHz (in μJy).

distance (pc)	Case 1 (Jupiter)	Case 2 (Gl229B)	Case 3 (protoJupiter)
1	12	130	59000
5.7	0.36	4.1	1820
10	0.12	1.3	590
120	0.0008	0.009	4.1

that the detection of any mature giant planet (like Jupiter) would only be feasible for the very nearest stars, but we know that these stars have no giant planets, from past observations. Even objects like Gl229B could only be observed out to $\sim$ 4 pc, and, again, we know such bodies are not present. However, the direct detection of the very young, hot, protoJupiters in the nearest star forming regions is very feasible, given the sensitivity of ALMA.

Table 4: Integration time (days) needed to 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

The separation of the protoJupiter from the central protostar must be sufficiently large to allow for discrimination between the two. For a face-on system, this separation is simply: $\theta_{sep} = a/D$. This may force us to carry out the observations in the largest possible configuration of ALMA, as for observations at 345 GHz with maximum baselines of 4 km, the resolution of ALMA will be $\sim$ 45 milliarcseconds. For a system at 120 pc with a protoJupiter at 5 AU orbital radius, $\theta_{sep} \sim 40$ milliarcseconds. So, we may have to utilize the 15 km configuration, where the resolution is $\sim$ 12 milliarcseconds.

The integration times shown in Table 5 should be short enough that the protoJupiter does not move in its orbit so much as to move through a significant portion of a resolution element. In the worst observable case, the system is face on to us (the absolute worst case is that the system is edge on, and the protoJupiter is within a resolution element of the central protostar). The face on geometry is worst because it yields the fastest plane-of-sky movement of the protoJupiter. In this case, the linear distance moved in the sky plane by a planet in a circular orbit is given by:

$$\Delta\, l = \frac{l}{D} = \frac{a\,\omega\,\Delta\, t}{D} \quad , \tag{6}$$

where l is the true physical distance moved by the planet, a is the radius of the orbit of the protoJupiter, and ω is the angular speed of the protoJupiter. This speed is given by:

$$\omega = \sqrt{\frac{G\,M_*}{a^3}} \quad ,$$

where G is the gravitational constant, and M_* is the mass of the central protostar. The resolution of an interferometer can be approximated by:

$$\theta_{HPBW} \sim \frac{\lambda}{B_{max}} \quad , \tag{7}$$

where λ is the wavelength of observation, and B_{max} is the maximum separation of the antennas of the interferometer. If we demand that the protoJupiter move less than 1/4 of a resolution element, then we have:

$$\Delta\, t_{max} \leq \frac{\lambda\, D}{4\, B_{max}} \sqrt{\frac{a}{G\, M_*}} \quad . \tag{8}$$

For observations at 345 GHz and maximum baselines of 15 km, this value is $\sim$ 8 days for a protoJupiter at 5 AU orbital radius around a solar mass central protostar, at 120 pc. So, this constraint should not be a problem. Even in the case where the motion begins to be an appreciable fraction of a resolution element, one can attempt to remove the motion (by searching the phase space of possible masses and orbits) in the interferometric visibilities, minimizing the effect.

The above treatment has ignored the flux density from the central protostar. At optical and infrared wavelengths, the confusion from the central protostar may be a problem, as it can be as much as 6 orders of magnitude brighter than the protoJupiter. Fortunately, this ratio is much less at submillimeter and millimeter wavelengths. Typical ratios at these wavelengths should be only on the order of 1000 or so, posing no dynamic range problem for ALMA. In fact, the flux density from the central protostar is an aid in imaging with ALMA, as it could be used to maintain the coherence of the instrument (provided its flux density is large enough).

6 Dust/Debris Disks (Zodiacal Analogs)

As systems mature, the gas is cleared out, leaving a dust/debris disk around the central star. Examples of systems with these dust disks are β Pictoris, Vega (α Lyra), Fomalhaut (α Piscis Austrinus) and ϵ Eridani. As the planetary system ages further, it may develop a zodiacal dust population similar to that in our own solar system. This section treats the detectability of such dust/debris disks. The problem of imaging them is more complicated, and we do not attempt to address that problem here.

The expected thermal emission from the central star is (again assuming Rayleigh-Jeans, and 345 GHz frequency):

$$F_{345} = \frac{2\,k\,T_{eff}}{\lambda^2}\,\frac{\pi\,R_*^2}{D_*^2} \sim 6 \times 10^{-6}\, T_{eff}\, \frac{R_s^2}{D_{pc}^2} \quad \text{[Jy]} \quad , \tag{9}$$

where T_{eff} is the brightness temperature of the star at 345 GHz, and R_s is the radius of the star in solar radii.

We assume that the dust is distributed in a cylindrical disk around the central star with disk diameter L, and disk width d. If the physical characteristics of the disk are constant throughout its extent (surface density, physical temperature, size distribution, etc…), and that the emission from the dust in the disk is optically thin, then the flux density from the dust disk is:

$$F_\nu^d = \tau^d \, \epsilon_\nu^d \, B_\nu^d \, \Omega^d \quad , \tag{10}$$

where τ^d is the total geometric opacity of the dust in the disk, ϵ_ν^d is the average emissivity of the dust grains at frequency ν, B_ν^d is the *brightness* of the disk at that frequency, and Ω^d is the angular size of the disk. The average emissivity of the grains in the disk varies like $\epsilon_\nu^d \propto \lambda^{-\beta}$, where β is typically in the range 1–2. τ^d is a function of the angle of the system to us, ϕ (0° for face–on, 90° for edge–on disks), since as the disk is tipped over from face–on to edge–on, the geometric opacity increases. For angles which are not near edge–on (the cutoff angle is $\tan\phi = d/L$), the opacity is: $\tau^d = \tau_o^d / \cos\phi$, where τ_o^d is the opacity when $\phi = 0^\circ$ (face–on). For near edge–on systems, $\tau^d \sim \tau_o^d \, L/d$. The angular size of the dust disk is:

$$\Omega^d = \frac{\pi \, (L/2) \, R_p}{D_*^2} \cos\phi \quad , \tag{11}$$

where R_p is the apparent polar radius of the dust disk:

$$R_p = \sqrt{(L/2)^2 \, \cos^2\phi + (d/2)^2 \, \sin^2\phi} \quad . \tag{12}$$

The brightness is given by:

$$B_\nu^d = \frac{2 \, h \, \nu^3}{c^2} \, \frac{1}{e^{h\,\nu/k\,T_\nu^d} - 1} \quad , \tag{13}$$

where T_ν^d is the physical temperature of the dust grains.

Three Examples:

Take three dusty disks which are face–on ($\phi = 0^\circ$) with solar type central stars, with the following properties:

system 1; very dusty and large, analagous to β Pic:
$L = 500$ AU, $\tau_o^d = 10^{-3}$, $\epsilon_{230}^d = 10^{-2}$, $\beta = 1$, $T_\nu^d = 100$ K

system 2; dusty and large:
$L = 500$ AU, $\tau_o^d = 10^{-5}$, $\epsilon_{230}^d = 10^{-2}$, $\beta = 1$, $T_\nu^d = 100$ K

system 3; much smaller and less dusty, similar to our solar system:
$L = 10$ AU, $\tau_o^d = 10^{-7}$, $\epsilon_{230}^d = 10^{-2}$, $\beta = 1$, $T_\nu^d = 200$ K

The flux densities of these three systems are shown in Table 5. Given the estimated noise flux densities for ALMA, it is clear that dusty systems should be quite easy to detect, even beyond 20 pc. However, systems like our own solar system basically cannot be detected by ALMA.

Table 5: Flux densities for dusty systems (in mJy, except as noted).

	$D = 5$ pc		$D = 10$ pc		$D = 20$ pc	
system	F^*_{345}	F^d_{345}	F^*_{345}	F^d_{345}	F^*_{345}	F^d_{345}
1	1.401	930.9	0.350	232.7	0.088	58.2
2	1.401	9.31	0.350	2.33	0.088	0.58
3	1.401	0.078*	0.350	0.019*	0.088	0.005*

* values in μJy.

7 Number of Stars Detectable by ALMA

How many stars can be observed with ALMA? We address that question in this section. If we take Gliese's 3rd Catalog of Nearby Stars (Gliese & Jahreiss 1988 - available on the web from the CDS at http://cdsweb.u-strasbg.fr/htbin/Cat?V/70A) for all stars within 25 parsecs, and the Hipparcos catalog (Perryman et al.1997 - available on the web from the CDS at http://cdsweb.u-strasbg.fr/htbin/Cat?I/239) for stars further from us, then we can calculate the expected flux density for these stars and check for detection possibility. Since we know the planned location for ALMA is near -23° latitude, we reject all stars in the catalogs with declination $> +40°$. Again, the expected thermal emission from a star is (assuming Rayleigh-Jeans, and 345 GHz frequency):

$$F_{345} = 6 \times 10^{-6}\, T_{eff}\, \frac{R_s^2}{D_{pc}^2} \quad [\mathrm{Jy}] \quad , \tag{14}$$

where T_{eff} is the brightness temperature of the star at 345 GHz (we take this to be equivalent to the effective temperature of the star), and R_s is the radius of the star in solar radii. The distance is calculated from the measured parallax listed for each star in the catalogs. We determine the radius and temperature of the star from spectral class, subclass, and luminosity class information listed in the catalog. We reject stars that have completely unknown spectral class. If the spectral subclass is not listed, we take it to be 5. If the luminosity class is not listed, we take it to be V. So, given the spectral class, subclass, and the luminosity class, we look up the effective temperature in a table (taken from de Jager & Nieuwenhuijzen 1987) and the radius (and mass, for later purposes) from another table (taken from Allen's Astrophysical Quantities, 4th Ed., Table 15.8). We then calculate the expected flux density, and compare it to the noise (for a given integration time), and declare that a star is detectable if the SNR > 5.

Given an integration time of 1 minute, there are $\sim$ 200 total stars (of which 40 are variables and 50 are members of multiple systems) from Gliese's catalog which are detectable. Of these, about 50 are solar-type stars. From the Hipparcos catalog, again with 1 minute integration time, there are $\sim$ 2800 detectable stars (800 variables and 400 multiples), of which virtually none are solar-type. Increasing the integration time to 10 minutes increases the number of detectable stars to $\sim$ 400 from Gliese's catalog (90 variables, 130 multiples, and 200 solar-type) and $\sim$ 7600 from Hipparcos (1700 variables, 900 multiples, and again virtually no solar-type).

7.1 Number of Stars Resolved by ALMA

Not only will ALMA be able to simply detect stars, it will be able to resolve (and hence image) most stars with diameters $\gtrsim$ 10 masec. Such stars include some which are very large indeed (e.g., carbon stars, Mira stars, etc…), along with M and K giants and supergiants. From the stellar diameter catalog (Fracassini et al.1988 - avaliable on the web from the CDS at: http://cdsweb.u-strasbg.fr/cgi-bin/Cat?II/155), there are $>$ 200 stars with apparent diameter $>$ 10 masec. ALMA should be able to image virtually all of these stars, given that the expected brightness temperature sensitivity of ALMA at 345 GHz in a 15 km configuration is less than 10 K in only 1 minute (Butler & Wootten 1999). In fact, given this fantastic sensitivity, snapshots of the stellar surface might be made, allowing for "features" (starspots, e.g.) to be tracked as they rotate.

8 Indirect Detection (Astrometry)

The orbit of any planet around its central star causes that star to undergo a reflexive circular motion around the star-planet barycenter. By taking advantage of the incredibly high resolution of ALMA in its widest configuration, we may be able to detect this motion. Making the usual approximation that the planet mass is small compared to the stellar mass, the stellar orbit projected on the sky is an ellipse with angular semi-major axis θ_r (in arcsec) given by:

$$\theta_r = \frac{m_p}{M_*} \frac{a_{AU}}{D_{pc}} \quad , \tag{15}$$

where m_p is the mass of the planet, M_* is the mass of the star, a_{AU} is the orbital distance of the planet (in AU), and D_{pc} is the distance to the system (in parsecs).

The astrometric resolution of ALMA, or the angular scale over which changes can be discriminated (Φ), is proportional to the intrinsic resolution of ALMA, and inversely proportional to the signal to noise with which the stellar flux density is detected (SNR_*):

$$\Phi = \frac{\theta_{HPBW}}{2 \cdot \mathrm{SNR}_*} \quad . \tag{16}$$

This relationship provides the key to high precision astrometry: the astrometric accuracy increases both as the intrinsic resolution improves and also as the signal to noise ratio is increased. Astrometry at radio wavelengths routinely achieves absolute astrometric resolutions 100 times finer than the intrinsic resolution, and can achieve up to 1000 times the intrinsic resolution with special care. The phase stability specifications for ALMA will allow such astrometric accuracy to be achieved for wide angle astrometry.

When the astrometric resolution is less than the reflexive orbital motion, that is, when $\Phi \lesssim \theta_r$, ALMA will detect that motion. As above, we use the approximation that $\theta_{HPBW} \sim \lambda / B_{max}$, so that detection will occur when:

$$\mathrm{SNR}_* \gtrsim 10^5 \, \frac{\lambda}{B_{max}} \left(\frac{m_p}{M_*} \frac{a_{AU}}{D_{pc}} \right)^{-1} \quad . \tag{17}$$

The factor of 2×10^5 enters in to convert from radians to arcseconds.

Plugging numbers into the above equation for the giant planets in our own solar system shows that ALMA will detect the reflex motion of systems with such planets as far away as SNR_* parsecs distant (i.e., the ratio of SNR_* to D_{pc} is roughly 1 for our own giant planets). So, e.g., if we can reach an SNR of 10 on the central star, we can detect companions around such stars to 10 parsecs. If we use the expected thermal flux density of the Sun at 345 GHz as a guide, the received flux density from other similar stars would be:

$$F_* \sim \frac{30}{D_{pc}^2} \ \mathrm{mJy} \quad . \tag{18}$$

Given that the noise of ALMA at 345 GHz will be about 0.1 mJy/min, an SNR_* of 10 should be achieved in about 10 min for a star at 10 parsecs distance. Note, however, that astrometric detection of a planet requires that curvature in the apparent stellar motion be measured, since linear terms in the reflex motion are indistinguishable from ordinary stellar proper motion. This implies that at the very minimum, one needs three observations spaced in time over roughly half of the orbital period of the observed system. A detection of a planetary system with astrometry would thus require some type of periodic monitoring.

8.1 Number of Stars with Detectable Wobble

If all of the detectable stars (see the stellar detection section above) had planetary companions, how many of them could be detected (via astrometry) with ALMA? We address that question in this section. We use the same catalogs as in the stellar detection section, but for this exercise, we reject all variable and multiple star systems from consideration. This is rather strict, but we prefer to avoid the complications of these systems for astrometry and planet detection.

We assume that the planets are in orbits with semimajor axis of 5 AU. We consider 3 masses of planetary companions: 5 times Jovian, Jovian, and Neptunian. We assume integration times of 10 minutes, again at 345 GHz. From the Hipparcos catalog, there are $\sim$ 800 stars around which a 5*Jovian companion could be detected, $\sim$ 180 stars around which a Jovian companion could be detected, and no stars around which a Neptunian companion could be detected. Again, virtually none of these stars are solar-type. From the Gliese catalog, there are $\sim$ 200 stars around which a

5*Jovian companion could be detected, $\sim$ 120 stars around which a Jovian companion could be detected, and $\sim$ 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.

8.2 Comparisons with Other Techniques

Ground based efforts to find extra solar planets have focused in recent years in several areas, including differential astrometry, radial velocity measurements, and gravitational lensing. There are also proposals for methods which could directly image Jovian-class planets near a small number of stars. Planet detection using astrometry with ALMA will both complement these efforts, and have several important advantages:

- Astrometric searches for planets with ALMA will use absolute (wide-angle) astrometry, avoiding the problem of solving for motions in both a target star and a background reference star. ALMA will be able to tie stellar positions directly to the quasar reference frame, since both stars and quasars will be bright enough for high precision astrometry with ALMA.
- Systematic errors will be lower with ALMA than with techniques at optical or IR wavelengths because ALMA can observe stars 24 hours a day, providing various types of closure constraints on ALMA astrometry. This will reduce the kinds of seasonal systematic errors that plague optical astrometry.
- Astrometry measures the position of the star, so that the mass of the unseen planet can be easily determined. Direct detection techniques, either ground or space-based, cannot determine planetary masses, but will provide constraints on the parameters of a particular planetary system that complement those provided by astrometry.
- Astrometric results from ALMA will directly complement the results expected from differential astrometry with proposed ground-based IR interferometers. ALMA will not face the constraints on finding suitable background reference stars that are required by differential IR astrometry, so some additional stellar systems may be accessible to ALMA.
- As with other astrometric techniques, the detectability of a planet does not depend on the inclination of the planet's orbital plane around its primary star. In fact, astrometry could resolve inclination ambiguities for planets discovered using radial velocity techniques, if the amplitude of the astrometric signal is large enough.
- Astrometric searches are complementary to radial velocity searches in that the former are more sensitive to planets with larger semimajor axes, and the latter are more sensitive to ones with smaller semimajor axes.

9 Summary

ALMA will make substantial contributions to the observations of extrasolar planetary systems at all evolutionary stages. In particular, there are four areas in which ALMA will be able to aid in the investigation of extrasolar planets and planetary systems:

1. ALMA will all be able to image systems in the earliest stages of formation in the nearest star forming regions, in both dust and spectral lines.
2. ALMA will be able to directly detect forming giant planets ("condensations") in protoplanetary disks, and the gaps created in these disks as the condensations grow.
3. ALMA will be able to directly detect very young giant planets in the nearest star forming regions.
4. ALMA will be able to indirectly detect the presence of giant planets around nearby stars through the use of astrometry. ALMA will also be able to detect and image dust/debris disks around nearby stars (zodiacal analogs).

These observations are absolutely crucial to our understanding of how our own solar system formed, and may help in answering the question of whether we are alone in the universe.

ALMA will also be a fantastic instrument for observations of stars. Many thousands of stars can be detected with ALMA in a reasonable amount of time, and roughly 3000 of them could be detected with only 1 minute of integration. ALMA will be able to image more than 200 of the largest (in angular diameter) nearby stars.

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