Science with the Atacama Large Millimeter Array
ASP Conference Series, Vol. 3×10^8, *1999*
A. Wootten, ed.

Solar System Science with ALMA

Bryan J. Butler

NRAO, P.O. Box O, Socorro, NM 87801

Mark A. Gurwell

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

Abstract. Observations of solar system bodies with the ALMA array will undoubtedly allow significant progress to be made on our understanding of the individual bodies therein, their interactions, and possibly their formation. With its fantastic resolution, sensitivity, and speed, ALMA will be one of the most important ground based observatories for planetary science in the coming decades. While it is nearly impossible to predict what will be learned about the solar system and its bodies, we can predict some general areas where we expect that ALMA will make significant contributions. We will concentrate here on 2 such areas: observations of small bodies, and observations of the solid surfaces of the larger bodies. For a discussion of observations of planetary atmospheres, see Gurwell et al. (1999).

1. Introduction

Millimeter and submillimeter wavelength observations of the solid surfaces of solar system bodies are important for several reasons, including:

- they probe the subsurface (down to about 10 λ) of these bodies, yielding information on the bulk physical properties of the upper few cm's (or possibly more for icy bodies) of the surface
- sizes of small bodies can be determined fairly accurately, and combined with optical observations albedo may be determined
- observations are not constrained to nighttime, implying full rotational phase coverage, and good orbital coverage for astrometric studies

The ALMA array, with its fantastic resolution and sensitivity, will make it possible to observe some of the smallest solar system bodies, as well as make very detailed maps of the larger bodies. We focus on these two capabilities in this paper.

2. Small Bodies

This class of bodies includes comets, asteroids (including Near Earth Asteroids or NEAs), smaller satellites of the giant planets, and Kuiper Belt Objects (KBOs).

2.1. Comets

Millimeter wavelength observations of comets will help disentangle the story of their formation and history, and shed light on the physical processes occuring in their atmospheres. Current observations of this kind have already begun to contribute in this respect and we expect that ALMA will continue this work.

Given no obscuration, the nuclei of many short and long period comets could be detected relatively easily with ALMA (a 1 km nucleus at 1 AU distance has 0.1 mJy flux density at 1mm). The problem is that the nuclei are obscured by the dust (and possibly ice) grains ejected from the nucleus as it approaches the Sun. Therefore, only at the longer wavelengths will ALMA be able to detect the nuclei of comets. This is an argument for the 35 GHz frequency band on ALMA.

Observations of the dust (and possibly ice) grains themselves over the full range of frequencies of ALMA will yield very important results on the distribution of this dust, its properties, its total mass and mass ejection rate, and the variation of these properties with heliocentric distance (e.g., Altenhoff et al. 1999).

The more important contribution of ALMA to cometary studies will likely come in the area of spectral line observations of the gaseous component of cometary comae. Millimeter and submillimeter wavelength observations of comets with existing telescopes have discovered and yielded maps of a number of molecular species, including HCN, HNC, CH_3OH, H_2CO, HCOOH, HNCO, NH_2CHO, $HCOOCH_3$, CH_3CN, H_2CS, OCS, SO, SO_2, H_2S, and HCO^+ (e.g., Biver et al. 1999; Biver et al. 1997; Lis et al. 1997). ALMA will be a very important instrument for the study of these and other molecules and their implications on comet composition and kinematics and their evolution as the comet approaches the Sun.

2.2. Asteroids

Observations of asteroids by ALMA will contribute to knowledge of their properties and orbits (ALMA can observe in daytime). At 3 AU distance, a 10 kilometer sized main belt asteroid has a flux density of:

$$S_{MBA} \sim \frac{1}{\lambda_{mm}^2} \quad \mathrm{mJy} \quad ,$$

at wavelength λ_{mm} millimeters. This flux density is detectable by ALMA in all wavelength bands in less than 1 minute! It is therefore safe to say that most main belt asteroids of this size will be easily observable by ALMA. ALMA will also be able to make images all of the main belt asteroids with diameters $\gtrsim 200$ km (some 40 of them).

ALMA will also be a superb instrument for probing Near Earth Asteroids (NEAs). At .3 AU distance, a 1 kilometer sized NEA has the same flux density as shown above ($S_{NEA} \sim 1/\lambda_{mm}^2$ mJy), meaning that all of the NEAs with sizes at least this large will be probed with ALMA. As with the main belt asteroids, it will also be possible to image the larger of the NEAs at the higher frequencies of ALMA.

2.3. KBOs

ALMA will be a premier instrument for probing Kuiper Belt Objects (KBOs) and Centaurs. Figure 1 shows the predicted flux density from all of the known (as of October 1999) KBOs (192) and Centaurs (15) as the hatched area, and the sensitivity of ALMA in a single 6 hour observing session as the connected stars. At all wavelengths but the longest, each currently known KBO and Centaur can be detected by ALMA in a single 6 hour session.

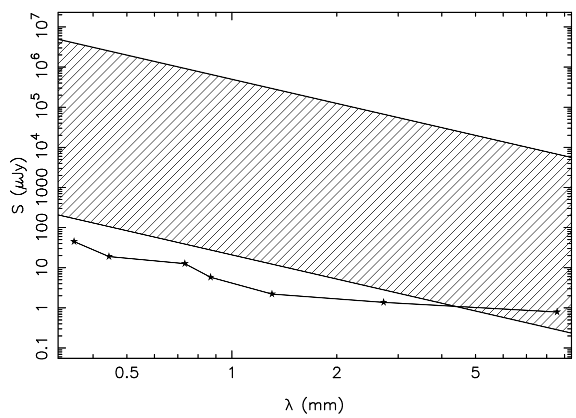

Figure 1. Detectability of KBOs and Centaurs with ALMA. Hatched area is predicted flux density from all of the known (as of October 1999) KBOs (192) and Centaurs (15). Connected stars are sensitivity of ALMA in a single 6 hour observing session.

3. Larger Bodies

3.1. Icy Satellites

Figure 2 shows the synthesized beam size for ALMA in the 10 km array. Even at the longer wavelengths, well-resolved images of the larger icy satellites of Jupiter, Saturn, Uranus, and Neptune can be made. In addition, Pluto and Charon will also be well-resolved. Given the superb brightness sensitivity, rotationally resolved images may also be made, allowing for important studies of surface and subsurface properties to be made. ALMA is unique in its ability to do this kind of imaging.

3.2. Mercury and Mars

The surfaces of Mercury and Mars will most certainly be imaged by ALMA. We illustrate some of the possibilities of such observations by outlining two problems related to Mercury which could be addressed by ALMA observations.

There is indication from cm-wavelength radar that permanently shaded regions in the polar regions of Mercury may contain water ice (Butler et al. 1993). An important requirement for the stability of these putative ice deposits is that the temperature be $\lesssim$ 110 K. Images of the polar regions of Mercury made

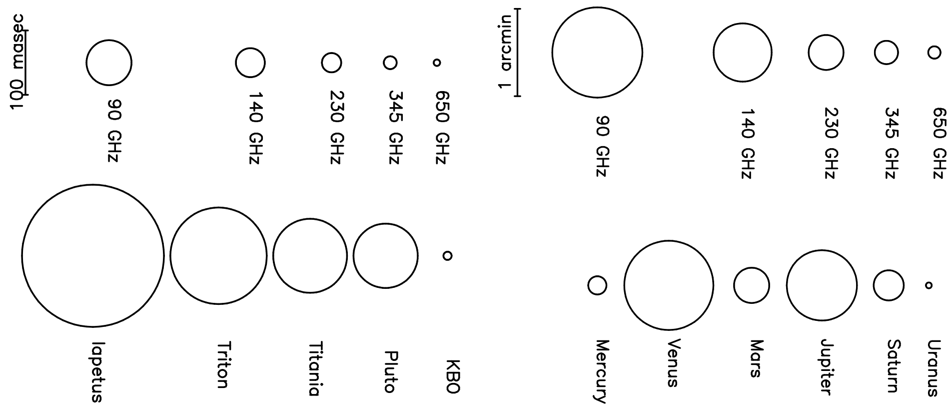

Figure 2. Alma beams. Comparison of synthesized beam size (10 km array) to some smaller solar system bodies on the left, and primary beam size (12 m antennas) to some larger solar system bodies on the right.

with ALMA at the highest resolution would be able to resolve these regions and accurately determine the physical temperature, which would in turn constrain whether water ice (or other kinds of ices) could be stable there.

The question of whether Mercury has a molten core or not is currently open (e.g. Stevenson 1987). The relatively strong magnetic field would seem to argue that it does. The ancient surface would seem to argue otherwise. Very accurate measurements of the brightness temperature as a function of wavelength and position on the surface would allow for a strong constraint to be placed on the heat flow from the interior. This could then be used to help determine whether a molten core is consistent with this heat flow value.

3.3. Large Bodies - Primary Beam Resolution

Because of the size of the larger solar system bodies, and the fact that we have migrated to 12m antennas, the larger of these bodies are now resolved by the primary beams of ALMA at the higher frequencies. In fact, Jupiter and Venus are at least partially resolved by the primary beams at all $\nu > 100$ GHz. Figure 3 compares the primary beam sizes to the larger planets, illustrating this fact. Because of this, most observations of the larger planets will necessarily be mosaiced.

References

Altenhoff, W.J., & 20 others 1999, A&A, 348, 1020

Biver, N., & 11 others 1997, Science, 275, 1915

Biver, N., & 13 others 1999, AJ, 118, 1850

Butler, B.J., D.O. Muhleman, & M.A. Slade 1993, JGR, 98, 15003

Gurwell, M.A., Muhleman, D.O., & Butler, B.J. 1999, this book

Lis, D.C., & 8 others 1997, Icarus, 130, 355

Stevenson, D.J. 1987, E&PSL, 82, 114