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Physical studies of Centaurs and Trans-Neptunian Objects with the Atacama Large Millimeter Array

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ABSTRACT

Once completed, the Atacama Large Millimeter Array (ALMA) will be the most powerful (sub)millimeter interferometer in terms of sensitivity, spatial resolution and imaging. This paper presents the capabilities of ALMA applied to the observation of Centaurs and Trans-Neptunian Objects, and their possible output in terms of physical properties. Realistic simulations were performed to explore the performances of the different frequency bands and array configurations, and several projects are detailed along with their feasibility, their limitations and their possible targets. Determination of diameters and albedos via the radiometric method appears to be possible on ~500 objects, while sampling of the thermal lightcurve to derive the bodies' ellipticity could be performed at least 30 bodies that display a significant optical lightcurve. On a limited number of objects, the spatial resolution allows for direct measurement of the size or even surface mapping with a resolution down to 13 milliarcsec. Finally, ALMA could separate members of multiple systems with a separation power comparable to that of the HST. The overall performance of ALMA will make it an invaluable instrument to explore the outer Solar System, complementary to space-based telescopes and spacecrafts.

1. Introduction

Almost 1400 small bodies orbiting beyond Jupiter have been discovered so far, classified as Centaurs (orbiting within Neptune's orbit) or as Trans-Neptunian Objects (TNOs, orbiting beyond Neptune). Due to their distance to the Sun and hence their low physical and chemical processing (McKinnon et al., 2008), their surfaces are expected to expose some of the most pristine material in the Solar System. To relate today's outer Solar System characteristics to those of the primordial disk, we need to better constrain physical properties and composition of these bodies, and understand the physical, chemical and dynamical processes that took place to shape this region.

Obtaining thermal emission measurements on these bodies is an essential tool for this purpose, since they can give access to properties such as geometric albedo, size, shape and surface properties (e.g. thermal inertia, emissivity). Building a large database of albedos and sizes is necessary to identify possible correlations with spectral properties (infrared and visible colors) or dynamical parameters, that would help to understand the roles of processes such as space weathering and collisions (Doressoundiram et al., 2008). This would also allow refinement of the taxonomy of this population, and to compare it to other populations (comets, asteroids) so as to identify similarities and to trace population histories. Constraints on the size distribution power law can give clues on the planetesimal growth and fragmentation processes (Kenyon and Luu, 1999), and the identification of breaks in the size distribution is a powerful diagnostic of the intrinsic strength of these bodies (Pan and Sari, 2005). Accurate determination of the shape and size of individual bodies, along with mass determination, is important to determine their formation and collisional history, as well as their bulk density and their ability to retain an atmosphere and/or surface ices (Lacerda and Jewitt, 2007; Levi and Podolak, 2009; Schaller and Brown, 2007). Knowledge of surface albedos is also necessary to correctly interpret the ice bands that can be detected in near-infrared and visible spectra, and thus to accurately establish surface composition (Barucci et al., 2008). Measuring the variation of spectral emissivity with wavelength, by combining *Herschel* and ALMA data, gives access to thermophysical and composition properties of the surface and subsurface. Finally, precise determination of the brightness temperature itself is a key indicator of the physical temperature of the surface and subsurface, establishing the possible presence and abundance of a stable atmosphere sustained by ice sublimation.

So far, only about 50 Centaurs and TNOs with diameters generally larger than 100 km have been detected at thermal wavelengths, mostly by space-based infrared telescopes ISO (Thomas et al., 2000) and especially *Spitzer* (Stansberry et al., 2008; Brucker et al., 2009). With disk-averaged surface temperatures below 130 K

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for Centaurs and 50 K for TNOs, their thermal emission peaks between 20 and 100 μm, where the Earth's atmosphere is opaque. At longer wavelengths, the thermal emission is considerably lower. Only 8 bodies have been detected in the (sub)mm wavelength range (Altenhoff and Stumpff, 1995; Altenhoff et al., 2001, 2004; Margot et al., 2002; Lellouch et al., 2002; Bertoldi et al., 2006; Gurwell et al., 2010), mostly around 250 GHz (1.2 mm) with the MAMBO bolometer on the IRAM-30 m antenna. Interferometric facilities, with smaller or comparable total collective area, could only detect the brightest bodies (Pluto and Charon) so far (Gurwell et al., 2010), but the recent correlator upgrades on the IRAM-Plateau de Bure array now allows for point-source sensitivities better than MAMBO at 250 GHz.

The number of thermal detections is expected to increase significantly in the coming years. At 70–160 μm, *Herschel*'s sensitivity may allow to detect up to 140 Centaurs and TNOs, that are the targets of a large photometric program (Müller et al., 2009); first results have just been presented (Müller et al., 2010; Lim et al., 2010; Lellouch et al., 2010). In the (sub)mm wavelength range, starting in 2012–2013, the Atacama Large Millimeter Array (ALMA) will provide unprecedented sensitivity, allowing in principle the detection of a dramatically larger number of targets. This interferometric facility, under construction in Chile, will offer at completion 50 antennas of 12 m diameter each, along with 12 additional 8-m antennas and four 12-m antennas forming the Atacama Compact Array (ACA). In addition, the array will offer very extended configurations with baselines up to 14 km, that will provide spatial resolution down to 5 milliarcseconds (mas) at 850 GHz (350 μm), corresponding to ~150 km at 40 AU, which as we will show is sufficient to resolve the largest Centaurs and TNOs.

This paper presents an analysis of the capabilities of ALMA for physical studies of Centaurs and TNOs, in terms of sensitivity, resolution and imaging performance. Detailed simulations were performed, which take into account the array characteristics, atmospheric quality, expected receiver performance and correlator capabilities. Imaging capabilities were simulated using a realistic simulator, developed by the GILDAS team (Pety et al., 2001), to calculate the expected Fourier-plane coverage. Feasibility and observing strategies for a number of detection and imaging projects are detailed, along with their expected products in terms of the bodies' properties and in general outer Solar System science. A short study on ALMA capabilities for asteroid science can be found in Busch (2009).

2. ALMA technical characteristics and expected performance

2.1. Point-source sensitivity

To characterize the expected noise for a given observation, the point-source sensitivity is commonly used in radio astronomy. In the case of continuum emission measurements, this corresponds to the rms noise expected on flux measurements on an unresolved source obtained using the whole bandwidth of the instrument $\Delta\nu$ in Δt seconds of time. This quantity depends on the instrumental performances (antennas, receivers, correlator) coupled with the atmospheric qualities of the site (sky opacity and phase stability), following the classical formula expressed in flux density units (Thompson et al., 1986):

$$\Delta(S)(\mathrm{Jy}) = \frac{KT_{sys}}{\eta_{atm}\eta_{cor}\sqrt{\Delta t \Delta\nu n_p N(N-1)}} \quad (1)$$

where η_{cor} is the correlator efficiency, T_{sys} the system temperature characterizing the receiver and sky noise, n_p the number of polarizations and N the number of antennas. The K term describes the gain of the antennas in Jy/K, and is defined as $\frac{2kF_{eff}}{A_{col}\eta_a}$ with k the Boltzmann constant, F_{eff} the forward efficiency, A_{col} the collecting area of a single antenna, and η_a the aperture efficiency (e.g. K = 40 Jy/K at 230 GHz at the IRAM-PdBI). Finally, η_{atm} is the phase decorrelation (equal to $e^{-\sigma^2/2}$, σ being the phase rms at the observing frequency), that measures the effective signal loss due to the atmospheric phase fluctuation.

To calculate the point-source sensitivity expected from the ALMA array for each observing frequency, we will use the following approximate equation from De Breuck (2005) for dual polarization observations (n_p = 2), where the correlator and forward efficiencies are considered independent from frequency:

$$\Delta(S)(\mathrm{mJy}) = \frac{2.6 \times 10^6 T_{sys}}{\eta_a \eta_{atm} N D^2 \sqrt{\Delta t \Delta\nu}} \quad (2)$$

We will consider the other parameters as following:

- N = 50, D = 12 m: we thus consider only the main array at completion, excluding the contribution of the adjacent ACA (Atacama Compact Array).
- $\Delta\nu$ = 8 GHz per polarization using the full correlator capacity.
- η_{atm} = 0.87, corresponding to a phase rms of 30°.
- η_a: this parameter depends mostly on the accuracy σ_a of the surface of the antennas. Following (Ruze, 1966), $\eta_{ant} = \eta_0 e^{-\left(\frac{4\pi\sigma_a}{\lambda}\right)^2}$, where λ is the observed wavelength, and η_0 is the efficiency of a perfectly smooth antenna. The latest measurements on the already available antennas show that σ_a is of the order of 20 μm although it could rise to 25 μm in bad conditions (cold weather) (Wooten, private communication). The value of η_0 is assumed to be 0.8 following the antenna requirements as defined in Butler and Wootten (1999).
- System temperature (T_{sys}, in K): this parameter includes the combined effects of the thermal noise from the receivers and the opacity of the atmosphere. The values assumed here are the estimates by Moreno and Guilloteau (2002), calculated for a source at 50° elevation, and assuming a water vapor content varying with the observing frequency (0.5 mm for frequencies above 370 GHz and either 2.3 mm or 1.2 mm below), which is realistic since high-frequency observations require better sky conditions. The T_{sys} were lowered for bands 8 and 9 by respectively 33% and 40%, to match the latest sensitivity expectations as specified by the ALMA sensitivity simulator (http://www.eso.org/sci/facilities/alma/observing/tools/etc/). In addition, for band 6, the estimates have been updated using the most recent performance measurements on the receivers (ALMA Newletter, September 2010, www.almaobservatory.org).

The values of antenna efficiency, system temperature and point-source sensitivity, derived from Eq. (2), are gathered in Table 1 for a set of characteristic frequencies. For comparison, the best continuum point-source sensitivities reached by available instruments are shown. ALMA should provide very significant gains in sensitivity (factors 10–100). However given the minimal characterization of the system so far, the ALMA sensitivity estimates may change as new performance measurements will become available. It is also probable that in average, 10% of the antennas may not be used during standard observations, due to maintenance and/or technical failures. This would degrade the sensitivity estimates by 10%.

Finally we note that the point-source sensitivity should not strongly depend on the array configuration. Indeed, although the atmospheric decorrelation typically increases as the distances between antennas increase (i.e. with baseline length), the ALMA antennas will be equipped with water vapor radiometers at 183 GHz, that will monitor variations of the atmospheric optical depth along the line-of-sight. Application of the derived phase