Asteroids and Comets: the Prospect for Observations with a Large Millimetre Array

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Abstract. Radio continuum observations of asteroids provides an appreciable complement to the radiometric observations at other wavelengths, contributing to the determinations of their size and albedo. In addition, it offers the unique possibility to sample their subsurface temperature and to study their thermal properties. Radio continuum observations of comets reveal the large-size particles of their dust coma rather than their nucleus. Radio spectroscopic observations allow us to determine the molecular composition of the nucleus ices sublimating into the coma, to study the kinematics of the cometary atmosphere and to investigate its physical conditions. In addition to an increased sensitivity, a large millimetre array would permit, by imaging comets, to study the structure and evolution of the gas and dust jets, in connection with the outgassing processes of the cometary nuclei.

1 Introduction

The study of small Solar System bodies with radio astronomical techniques is relatively recent, due to the weakness of the signals emitted by these objects and the demand for highly sensitive instruments. We will review here the current status and future prospect of radio astronomical observations of asteroids and comets at millimetre and submillimetre wavelengths with a special emphasis on imaging observations with a large millimetre array.

2 Asteroids

Imaging asteroids — if one excepts the beautiful pictures taken by *Galileo* during the Gaspra and Ida flybies — is still very difficult at distance, because of their small sizes. Even the largest ones are barely resolved: Ceres has at most 0.85" angular diameter (for a 930 km diameter and a closest approach of 1.50 AU). Attempts have been made to image such objects with adaptative optics (Saint-Pé *et al.* 1993) or with the *Hubble Space Telescope*. However, one may have the luck to observe a *Near Earth Asteroid*, like recently Toutatis ($\simeq$ 4.6 km size and a closest approach of 0.024 AU, making an angular diameter of 0.26") with more conventional instrumentation.

Reviews on radio astronomical observations of asteroids were given by Altenhoff (1985) and Webster & Johnston (1989). See also Ostro (1989, 1993) for reviews on radar observations, to be complemented by recent observations of Toutatis (Ostro *et al.* 1995; Hudson & Ostro 1995; Zaytsev *et al.* 1993). Tens of

Fig. 1. The radio spectrum of Ceres (from Webster *et al.* 1988).

Fig. 2. The map of Vesta obtained at the VLA (from Johnston *et al.* 1989).

asteroids are accessible to existing large millimetre telescopes equipped with bolometers (Altenhoff *et al.* 1994; Altenhoff & Stumpff 1995; Jewitt & Luu 1992b; Redman et al. 1995). It should be noted that the largest asteroids are commonly used as calibrators for millimetre telescopes (c.f. Webster *et al.* 1988; Altenhoff *et al.* 1996; Fig. 1).

Asteroids (and cometary nuclei when they can can be separated from the contamination of emission by the dust coma — see next section) are thermal emitters at radio and infrared wavelengths. This emission is expected to come from material at a depth of several wavelengths below the surface. Therefore, comparative mid-infrared, submillimetric, millimetric, and centimetric observations probe the temperature at various depths and provide us with a very important clue to the outer structure of these bodies.

Radio observations of asteroids allow a reliable determination of their diameter with minimal model assumption. Combined with observations in the visible, they also provide a determination of their albedo. It was thus possible to determine the diameter (168 ± 20 km) and albedo (0.13) of Chiron with the 30-m IRAM telescope (Altenhoff & Stumpff 1995); these determinations were in close agreement with those from independent measurements in the thermal infrared (Campins *et al.* 1994).

Up to now, the VLA has the unique ability to image the surfaces of the largest asteroids; images of Ceres and Vesta observed at 2 cm with a resolution of 0.1" are reproduced in Webster & Johnston (1989) (see also Fig. 2. A large millimetre array would have the necessary sensitivity and spatial resolution for extending such studies to millimetre wavelengths.

3 Comets

Comets are among the most popular objects in the sky and their imaging has been practised for a long time. Besides naked eye observations of the large scale structure of spectacular comets at historical times, the short-scale structure of the inner coma has been imaged using telescopes and was recorded first by hand drawing, then by photography and now with the CCD technique. Imaging comets at radio wavelengths, however, is still very poorly developed because of the weakness of the signal, either continuum or spectroscopic.

3.1 Continuum Observations

After a succession of pioneering observations with doubtful results (see the review by Crovisier & Schloerb 1991), positive results were obtained at millimetre and submillimetre wavelengths on a handful of comets. This was mainly due to the efforts of two teams. W. Altenhoff and his collaborators at the IRAM 30-m detected continuum emission at 1.2 mm wavelength in comets P/Halley (Altenhoff *et al.* 1989), P/Brorsen-Metcalf and Austin 1990 V. Jewitt and Luu reported observations of P/Brorsen-Metcalf and several other comets at the JCMT at 0.8 mm wavelengths (Jewitt & Luu 1990, 1992a; Jewitt 1996).

The continuum signal detected from these observations appears to be too strong to be due to the cometary nucleus alone. It is rather interpreted as the emission of large-size dust particles. Since photometry in the visible or near and mid-infrared is rather sensitive to micrometre- or submicrometre-size particles, radiometry at millimetre wavelengths provides unique complementary information on the dust content of the coma. A theoretical basis for such an interpretation has been provided by Jewitt & Luu (1992a) (see also Walmsley 1985). Continuum emission can also be related to the hypothetical *icy grain halo* which is likely to have a transient existence at a specific heliocentric distance.

A tightly related topic is that of the radar observations of comets at centimetric wavelengths. An early review of the subject is given by Kamoun *et al.*

Table 1. A list of the molecular radio lines observed in comets (adapted from Crovisier, 1995, where references can be found).

	frequency MHz	species	transition	comet a)	comments
decimetric	1612	OH	ground F1-2	M, L	
	1665	OH	ground F1-1	K...	more than 40 comets
	1667	OH	ground F2-2	K...	"
	1721	OH	ground F2-1	M, L	
	3335	CH	ground F1-1	K	not confirmed
centimetric	4830	H_2CO	1_{10}-1_{11}	P/H	marginal
	8188	?		K	marginal, unidentified
	22 235	H_2O	6_{16}-5_{23}	B, IAA	not confirmed
	23 870	NH_3	(3,3)-(3,3)	IAA	not confirmed
millimetric	89 088	HCN	1-0	K, P/H...	
	96 7xx	CH_3OH	(2,K)-(1,K) s)	A, L	
	110 700	CH_3CN	6-5 $\nu_8 = 1$	K	not confirmed
	115 271	CO	1-0	P/SW1, H-B	
	145 1xx	CH_3OH	(3,K)-(2,K) s)	A, L...	
	165 xxx	CH_3OH	(J,K)-(J,K-1) s	L, P/ST	
	168 763	H_2S	1_{10}-1_{01}	A...	
	216 710	H_2S	2_{20}-2_{11}	L	
	218 440	CH_3OH	(4,2)-(3,1)E	L	
	225 698	H_2CO	3_{12}-2_{11}	P/BM...	
	230 538	CO	2-1	P/SW1, H-B	
	265 886	HCN	3-2	P/BM, A...	
submillimetric	338 xxx	CH_3OH	(7,K)-(6,K) s)	P/ST	
	341 416	CH_3OH	(7,1)-(6,1)A-	P/ST	
	345 796	CO	3-2	P/SW1, H-B	
	351 767	H_2CO	5_{15}-4_{14}	L, P/ST	
	354 505	HCN	4-3	L, P/ST	
	2 509 949	OH	5/2-3/2	P/H	*KAO* with Fabry-Pérot

a) Full designation of comets: A: Austin 1990 V; B: Bradfield 1974 III; P/BM: P/Brorsen-Metcalf 1986 IX; P/H: P/Halley 1986 III; H-B: C/1995 O1 Hale-Bopp; IAA: IRAS-Araki-Alcock 1983 VII; K: Kohoutek 1973 XII; L: Levy 1990 XX; M: Meier 1978 XXI; P/SW1: P/Schwassmann-Wachmann 1 1989 XV; P/ST: P/Swift-Tuttle 1990 XXVIII.

s) Several lines of methanol are observed around the same frequency.

(1982), which has to be updated by the more recent observations of IRAS-Araki-Alcock at its close approach to the Earth (Goldstein *et al.* 1984; Harmon *et al.* 1989) and of P/Halley (Campbell *et al.* 1989). These observations demonstrate that, in addition to the signal of the nucleus, an echo is coming from large-size particles.

3.2 Spectroscopic Observations

The goals of spectroscopic observations of comets are the following:

– *Investigating the composition of comets.* Spectroscopy at radio wavelengths is peculiarly adequate for identifying the *parent molecules* directly sublimed from the nucleus ices (e.g. Crovisier 1994). This technique was thus able to identify without ambiguity, and for the first time, HCN, H_2CO, CH_3OH and H_2S. It is especially sensitive, since it is able to observe molecules such as

Fig. 3. Millimetre lines observed in comets with the IRAM 30-m telescope. Top: the formaldehyde line at 227 GHz observed in comet P/Swift-Tuttle 1992 XXVIII (Despois *et al.* 1996). Bottom: the CO line at 230 GHz observed in comet C/1995 O1 (Hale-Bopp) in Sept.–Oct. 1995, when it was at 6.5 AU from the Sun (Biver *et al.* 1996).

HCN and H_2S which have abundances of only 10^{-3} relative to water, the major gaseous output of comets. It was also able to observe the CO production of comets far from the Sun, where spectroscopy at other wavelengths (infrared, visible, ultraviolet), which observes *fluorescence* emission excited by the solar radiation, is inefficient: comet P/Schwassmann-Wachmann 1 at 6 AU from the Sun (Senay & Jewitt 1994; Crovisier *et al.* 1995) and quite recently comet C/1995 O1 (Hale-Bopp) at nearly 7 AU (Matthews *et al.* 1995; Rauer *et al.* 1995; Biver *et al.* 1996; Fig. 3).

– *Probing the kinematics of cometary atmospheres by observing molecular line shapes.* The unique spectral resolution at radio wavelengths allows to resolve the molecular lines, which have Doppler profiles (Fig. 3). From the line widths, one can thus determine the expansion velocity of the cometary atmospheres (Bockelée-Morvan *et al.* 1990). From the line centre, one can evaluate the bulk motion of the atmosphere with respect to the cometary rest of frame, which is due to the anisotropic sublimation of cometary ices, preferentially occurring from the nucleus hemisphere heated by the Sun, and which is related to the non-gravitational forces which affect cometary orbits (Colom *et al.* 1996).

– *Probing the excitation conditions within cometary atmospheres.* This can be done by observing the relative intensities of molecular rotational lines and retrieving the rotational distribution and the coma temperature. This possibility was especially applied to the methanol lines (Bockelée-Morvan *et al.* 1994).

Fig. 4. Imaging of the 18-cm OH lines in P/Halley with the Very Large Array. The maps are averages of 13–16 November 1985, convolved to two different spatial resolutions. The highest contour levels are 19 and 10 mJy/beam for maps a) and b), respectively (from de Pater *et al.* 1991).

Observations with an Interferometer. Imaging observations of comets with radio interferometers are reviewed in detail by de Pater *et al.* (1991). Positive results were obtained at the VLA on the 18-cm OH lines of comets P/Halley and Liller 1988 V (Fig. 4). The maps are hampered by the limited signal-to-noise ratio in a synthesized beam and the lack of zero-spacing observations. The maps show the presence of small OH *clumps* (Fig. 4) which are difficult to understand in the context of the smooth spatial distribution expected for the cometary OH radical. It would be desirable to repeat such observations on future bright comets. De Pater *et al.* also claimed, from their VLA observations of comet Liller 1988 V, the existence of short-term variations of the OH line profiles, but it seems difficult to follow their conclusions due to the limited signal-to-noise ratio and spectral resolution of their data.

Fig. 5. Visible images of P/Swift-Tuttle obtained at the Pic-du-Midi Observatory showing the time evolution of the dust jets (from Jorda *et al.* 1994).

Prospects for a Large Millimetre Array. Using such an instrument as a phased array, we benefit from the increase in sensitivity due to the large collecting area. Tracking a comet with a radio telescope is often a problem, since one has to rely on ephemeris extrapolated from past astrometric positions. The advantage of the phased array versus a single dish with the same collecting area is that the tracking accuracy has to be of the order of the primary antenna beam only (on the other hand, its disadvantage is the difficulty to obtain accurate phase corrections). One should note the idiosyncrasy of the brightness distribution of a comet which is neither that of a point source nor that of a uniform extended source: the column density of cometary dust or of a parent molecule scales as $1/\rho$, ρ being the distance to the nucleus centre (in a spherical symmetry approximation). So, the average brightness in a beam of radius ρ scales as $1/\rho$. The *size* of a cometary coma has thus no meaning. In order to retrieve correctly such a brightness distribution, zero-spacing observations are a requisite (this could be done either with the same instrument in the phased-array mode or independently with a larger single-dish).

Comets are variable objects. They present long-term variations due to the varying distance to the Sun. There are also important short-term variations due to nucleus rotation and to outburst processes (Fig. 5). The time scales are of the order of a fraction of day. Therefore, it is not possible to synthesize images by grouping observations made on different periods, e.g. for different positions of movable antennas. It is even not desirable to use the Earth rotation to cover the *uv* plane. Images of comets will have to be obtained as *snapshots* of at most a few hours.

Mapping the space distribution of cometary molecules with a large millimetre array permits to investigate which part of these molecules are directly sublimed from the nucleus, or coming from distributed sources: icy grains, CHON grains, or decaying complex molecules. Molecules such as H_2CO and CO are known to come — at least partly — from yet unidentified distributed sources. This may be the case of several other *parent* molecules.

Mapping the space distribution and the velocity field of parent molecules (such as HCN, CH_3OH or CO) in the inner coma gives also the possibility to investigate the relations between dust jets (as imaged in the visible; Fig. 5) and the outgassing from sublimation of the nucleus ices and the icy grains of the dust coma.

In order to investigate the small features of the velocity field (anisotropic outgassing yields velocity offsets that may be as small as 0.1–0.2 km s^{-1}) and the profiles of the cometary lines, which may vary from lines as narrow as 0.15 km s^{-1} to structured lines about 2 km s^{-1} wide (see Fig. 3), a very good velocity resolution is required — of the order of 0.1 km s^{-1}.

4 Conclusion

Radio astronomical observations, and especially imaging with a large millimetre array, of the small bodies of the Solar System — asteroids and comets — are not only a useful and necessary complement to the observations at other wavelengths. They provide unique data on the thermal properties of the nucleus of these small bodies, on the large-size particles of cometary dust, on the composition, distribution and kinematics of the cometary atmospheres. Informations of paramount importance will also be provided from the space exploration of these objects. It can be noted that a microwave experiment has been proposed for the orbiter of the *Rosetta International Mission*, in order to map the nucleus of comet Wirtanen and rotational lines of selected molecular species in its coma at a very short distance (Gulkis *et al.* 1995). However, space explorations will be limited to a very small number of objects, whereas there is a large diversity in the Solar System objects to be studied. This could only be achieved from a long-term Earth-based investigation.

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Note added in proof. Quite recently, comet C/1996 B2 (Hyakutake) was an outstanding opportunity for observations when it passed at only 0.10 AU from the Earth at the end of March 1996. Several new cometary molecules were detected at radio wavelengths (NH_3, OCS, HNC, CS, CH_3CN, HDO) through efforts at various telescopes. Successful observations were conducted with the IRAM interferometer at the Plateau-de-Bure where the emissions of the lines of CO $J(2-1)$ and HCN $J(1-0)$ were mapped with resolutions of 1.5 and 3 arcsec, respectively.

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