Millimetre continuum observations of comet C/2009 P1 (Garradd)*


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ABSTRACT

Context. Little is known about the physical properties of the nuclei of Oort cloud comets. Measuring the thermal emission of a nucleus is one of the few means for deriving its size and constraining some of its thermal properties.

Aims. We attempted to measure the nucleus size of the Oort cloud comet C/2009 P1 (Garradd).

Methods. We used the Plateau de Bure Interferometer to measure the millimetric thermal emission of this comet at 157 GHz (1.9 mm) and 266 GHz (1.1 mm).

Results. Whereas the observations at 266 GHz were not usable due to bad atmospheric conditions, we derived a 3σ upper limit on the comet continuum emission of 0.41 mJy at 157 GHz. Using a thermal model for a spherical nucleus with standard thermal parameters, we found an upper limit of 5.6 km for the radius. The dust contribution to our signal is estimated to be negligible. Given the water production rates measured for this comet and our upper limit, we estimated that Garradd was very active, with an active fraction of its nucleus larger than 50%.

Key words. Comet: individual: C/2009 P1 (Garradd) – Radio continuum: solar system – Techniques: interferometric

1. Introduction

Cometary nuclei are among the most primitive objects in the Solar System, and their physical and chemical properties are thought to preserve a record of the conditions that existed in the early solar nebula. Dynamical arguments support the hypothesis that they originate from at least two different regions. Following the dynamics-based classification of Levison (1996), ecliptic comets (ECs) are thought to originate in the Kuiper belt (Fernandez, 1980), thus explaining their low inclinations and prograde orbits. In contrast, nearly isotropic comets (NICs) are thought to have formed in the giant planets’ region. They were members of a population of planetesimals that were scattered by planetary perturbations to the outskirts of the Solar System 3.5–4.5 Gyr ago, where their orbits were subsequently isotropized by gravitational perturbations from nearby stars and molecular clouds to form the roughly spheroidal Oort cloud. Some of the NICs were later perturbed again by passing stars, molecular clouds, or galactic tide, and their perihelia lowered to within ~3 AU, where they became active and could be detected. The detected NICs are either “returning” NICs on elliptical orbits, or “new” NICs, presumably on their first passage through the inner Solar System.

Lamy et al. (2004) completed a review of the properties of cometary nuclei and concluded that there are reliable size determinations for only 13 NICs. The range of radii is surprisingly broad, 0.4 to 37 km, much broader than that of the ECs (0.6 to 5 km for >98% of them). The NIC cumulative size distribution (CSD) substantially differs from that of a collisionally relaxed population (Dohnanyi, 1969; O’Brien & Greenberg, 2003), but with only 13 objects, a robust conclusion cannot be drawn.

Measuring the millimetric thermal emission of a nucleus is way to estimate its size which depends moderately on the assumption made on its albedo. However, due to the faintness of the signal, such observations are challenging. Up to now, this could only be achieved for C/1995 O1 (Hale-Bopp) and 8P/Tuttle (Altenhoff et al., 1999; Boissier et al., 2011).

Comet C/2009 P1 (Garradd), referred to as Garradd hereafter, was discovered in 2009, when it was at 8.7 AU from the Sun (McNaught & Garradd, 2009). With an eccentricity of 1 and an inclination of 106°, Garradd undoubtedly belongs to the NIC class. It presented a high level of activity during its approach to the Sun (e.g., a water production rate of $1.2 \times 10^{29}$ s$^{-1}$ at 1.9 AU was measured with the Herschel telescope in 2011 by Bockelée-Morvan et al., 2012). IR and millimetric observations revealed that Garradd is CO-rich with a CO/H$_2$O abundance of the order of 10% (Paganini et al., 2012; Biver et al., 2012).

We attempted to measure the nucleus size of comet C/2009 P1 (Garradd). We present here the observations of its thermal emission carried out at millimetre wavelengths with the IRAM Plateau de Bure Interferometer (hereafter PdBI) in March 2012. The observations are described in Sect. 2, and analyzed in Sect. 3.

2. Observations

The IRAM interferometer is a six-antenna (15 m each) array located on the Plateau de Bure, in the French Alps, and equipped with heterodyne, dual polarization, receivers operating around

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* Based on observations carried out with the IRAM Plateau de Bure Interferometer. IRAM is supported by INSU/CNRS (France), MPG (Germany), and IGN (Spain).
2.2. Observations at 1.9 mm

These observations were carried out between 3 March 2012, 22 h UT, and 4 March 2012, 8 h UT. The atmospheric conditions were good, with a phase noise in the range 30–65° and a system temperature of ~150 K. The instrumental and atmospheric variations of the phase and amplitude were calibrated using regular observations of the quasars 1435+638 and 1642+690, every ~30 min. The absolute flux scale was determined observing MWC349, with a precision of 10%.

Given the geocentric distance of the comet (1.3 AU), the synthesized beam of ~0.9" corresponds to a projected distance of ~850 km at the comet. The nucleus thermal emission is thus expected to appear as a point source. We fitted the Fourier transform of a point source to the observed visibilities and found an emission peak 9.4" away from the tracked position with a flux of 0.62 ± 0.13 mJy. This corresponds to a signal-to-noise ratio (SNR) of 4.8, slightly below the usual limit for a robust detection (SNR = 5). This is the only peak with a SNR exceeding 4 in a 20" region around the expected comet position. The uncertainty on the absolute flux calibration is 10%. We estimated the overall uncertainty limits as $F + 1\sigma = 1.1 \times (F + 1\sigma) = 0.83$ mJy and $F - 1\sigma = 0.9 \times (F - 1\sigma) = 0.44$ mJy. From this, we deduced new uncertainties on the flux: $F = 0.62_{-0.18}^{+0.21}$ mJy. Since the emission peak is offset from the pointing centre, the measured flux has to be corrected from the primary beam attenuation (gaussian profile with HPBW of 30.5°). At a distance of 9.4" from the pointing direction, this attenuation reaches 23%. The corrected flux is then $F = 0.81_{-0.23}^{+0.27}$ mJy. The interferometric map is presented in Fig. 1. Table 1 summarizes the measurements.

This emission peak cannot be attributed to a galactic or extragalactic source since the tracked position moved by more than 15 arcmin in the equatorial frame during the 8-h observing period. Furthermore, we splitted our visibility set in four parts and fitted in each of them the Fourier transform of a point source fixed at the position found using the global dataset. The result is illustrated in Fig. 2. The point source flux found in all the subsets is consistent with the overall flux at the 2σ level. Similar consistency is obtained when dividing the data in three subsets instead of four. This confirms that the emission peak we measured is not due to a short-lived interference or noise peak during the observing period.
3. Results

3.1. Comet position

Given the distance between the 4.8σ brightness peak and the comet expected position, the question naturally arises as to whether or not this signal can be attributed to the comet. The JPL#75 solution, used for comet tracking, was based on astrometric measurements performed between August 2009 and January 2012, before perihelion. More recent solutions which include a much larger data set, especially after perihelion, should be more accurate for March 2012. We now introduce the solution JPL#77 including data up to October 2012 and the solution provided by the Institut de mécanique céleste et de calcul d’éphémérides (IMCCE) with data up to January 2013. The two ephemerides predict nearly identical positions (separated by less than ~0.1") slightly closer to the brightness peak detected in the interferometric map (see Fig. 1 and Table 1) than that given by the JPL#75 solution. However, the separation remains large, 5.5", corresponding to ~5000 km at the distance of the comet, exceeding by far the uncertainties related to the ephemeris and the peak position. Indeed, the (O-C) rms values of the JPL and the IMCCE solutions respectively amount to 0.5" and 0.4", and the precision on the position of a brightness peak measured in interferometric data is of the order of the synthesized beam size divided by the signal-to-noise ratio of the detected flux, yielding ~0.2" in our case. The distance between our brightness peak and the ephemeris position of the comet (5.5") is thus well above the separation of 2.1" (0.5"+0.2")×3 which would correspond to an agreement at the 3σ level. Moreover, from our 15–19 Feb. 2012 single dish observations with the IRAM-30m telescope, coarse maps of HCN(3-2) and other species suggested that the peak intensity was within uncertainty (~1") of the predicted position from the lastest orbital solution (JPL#77, Biver et al., 2012).

In summary, the 5.5" offset from our brightness peak and the predicted position of the comet seems to be too large to be interpreted in terms of ephemeris and pointing uncertainties or even coma morphology, as it was done in the case of comet C/1995 O1 (Hale-Bopp) for which offsets of the order of 1" (Boissier et al., 2007) were found.

The hypothesis of a technical, systematic problem at the observatory leading to wrong positions is extremely unlikely since previous cometary observations provided excellent agreement between the ephemeris position and the continuum emission detected with the PdBI (e.g., observations of 103P/Hartley 2, Boissier et al., in preparation).

Whereas we do not have an explanation for the brightness peak, we cannot reasonably associate it to comet Garradd. Considering that the nucleus should have been at the common IMCCE–JPL#77 position, we can only derive a 3σ upper limit on the comet flux of 0.41 mJy at this position.

3.2. Nucleus size

We used a standard thermal model described in previous works (Groussin et al., 2004; Lamy et al., 2010) to derive an upper limit for the size of the nucleus assuming a spherical shape. We adopted standard values for the model parameters: null thermal inertia (Groussin et al., 2009; Boissier et al., 2011), beaming factor \( q = 1 \) (Lebofsky & Spencer, 1989), and millimetric emissivity \( \epsilon = 0.9 \). The upper limit measured at the expected nucleus position of 0.41 mJy corresponds to a nucleus radius smaller than 5.6 km. As a side remark, a nucleus radius of 7.8 ± 1.2 km would be required to produce the 0.81 mJy brightness peak found in the data at 5.5" from the comet expected position. These size estimates do not take into account the dust contribution to the continuum emission as we found it to be negligible (see Sect. 3.3).

In order to check whether these sizes are reasonable, we considered the case of a spherical nucleus made of pure water ice and computed its radius required to release the observed amount of water (~2 × 10^{29} \text{s}^{-1}) measured at 1.9 AU with Herschel space telescope (Bockelée-Morvan et al., 2012) and with the Nançay radiotelescope (Colom et al., 2011, and in preparation). To do so, we used our standard thermal model to compute the surface temperature and the water sublimation rate integrated over the entire nucleus at this heliocentric distance and found a radius of 4.0 km. However, if the active areas are limited to only 30% of the nucleus surface, the derived nucleus radius increases to 7.3 km. Given our upper limit on the nucleus radius of 5.6 km, we estimated that the active areas on Garradd’s nucleus cover at least 50% of the surface, making this comet a very active one. Admittedly, we do not consider that a significant fraction of the outgassing could be from icy grains, as observed for instance for 103P/Hartley 2 (A’Hearn et al., 2011).

Table 1. Continuum point source detection properties

<table>
<thead>
<tr>
<th>Day in March UT</th>
<th>Frequency GHz</th>
<th>RA° h:min:s</th>
<th>Dec° :′′′</th>
<th>Obs-JPL#75a (″,″)</th>
<th>Obs-JPL#77a (″,″)</th>
<th>Obs-IMCCEa (″,″)</th>
<th>Fitted Fluxb mJy</th>
<th>Corrected Fluxb mJy</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.917 – 4.333</td>
<td>157.2</td>
<td>14:46:22.870</td>
<td>+68:16:22.38</td>
<td>(−9,−2.6)</td>
<td>(−4.4,−3.3)</td>
<td>(−4.4,−3.4)</td>
<td>0.62 ± 0.13</td>
<td>0.81^{+0.27}_{−0.23}</td>
</tr>
</tbody>
</table>

\( ^a \) Apparent EQ 2000 positions of the 4.8σ brightness peak at the reference time 7h00 UT on 4 March 2012.

\( ^b \) Offset (RA,Dec) in arcsecond between the observed continuum emission peak and the position derived from the JPL#75 solution for the comet’s orbital elements, which is based on astrometric measurements between August 2009 and January 2012. This is the solution which was used to track the comet.

\( ^c \) Offset (RA,Dec) in arcsecond between the observed continuum emission peak and the position derived from the JPL#77 solution for the comet’s orbital elements. This solution takes into account astrometric measurements between August 2009 and October 2012.

\( ^d \) Offset (RA,Dec) in arcsecond between the observed continuum emission peak and the position derived from the IMCCE solution for the comet’s orbital elements. This solution takes into account astrometric measurements between August 2009 and January 2013.

\( ^e \) Flux obtained by fitting the Fourier transform of a point source to the observed visibilities. The error bars do not take into account uncertainties in the absolute flux calibration.

\( ^f \) Continuum flux corrected for the primary beam attenuation (gaussian profile with HPBW of 30.5"). The error bars take into account a 10% uncertainty in the flux calibration.
The thermal emission of a comet is the sum of the contributions arising from the nucleus and the dust grains in the coma. Our upper limit on the nucleus size did not consider the contribution of dust thermal emission to the millimetric flux.

In a first approach, the contribution of the dust coma can be extrapolated from past measurements of the 2 mm continuum emission of comet C/1996 B (Hyakutake) performed at the James Clerk Maxwell Telescope (JCMT) on 23–24 March 1996 (Jewitt & Matthews, 1997). Correcting for the geocentric and heliocentric distances and beam size, the dust flux expected for comet Garradd in the synthesized PdBI beam would have amounted to 0.22 mJy. One must further consider differences in the activity of the two comets. At the time of the JCMT observations, comet Hyakutake displayed a water production rate of \( Q(H_2O) \approx 2 \times 10^{29} \text{ s}^{-1} \) and \( Afp \approx 7000 \text{ cm}^2 \) (Schleicher & Osip, 2002). The values for comet Garradd on 14 March 2012 are \( Q(H_2O) = 4.4 \times 10^{28} \text{ s}^{-1} \) and \( Afp = 3400 \text{ cm}^2 \) (Schleicher, personal communication). Farnham et al. (2012) reported very similar values with \( Q(OH) = 1.9 \times 10^{28} \text{ s}^{-1} \) and \( Afp = 3400 \text{ cm}^2 \) on 6 March 2012 measured with the Medium Resolution Instrument (MRI) onboard the Deep Impact spacecraft. We note that these \( Afp \) values were obtained in the same spectral domain (visible) and that the two comets were at comparable phase angles so that the comparison is not biased. The water production rate and \( Afp \) are thus respectively ~5 and ~2 times lower than for comet Hyakutake. Hence, the dust contribution in the PdBI beam is not expected to exceed 0.1 mJy, which is lower than the uncertainty of the PdBI measurements, unless comet Garradd’s nucleus was releasing comparatively bigger particles.

In a second approach, it is possible to assess how the dust emission may affect the signal by determining the dust production rate required to explain the observed flux. We used the model of dust thermal emission presented by Boissier et al. (2012). Absorption cross-sections were calculated with the Mie model of dust thermal emission presented by Boissier et al. (2012). As introduced by Newburn & Spinrad (1985) and Hanner et al. (1985a,b), and extensively used thereafter (e.g., Toth et al., 2005), we considered a differential dust production \( Q_{\text{dust}}(a) \) as a function of grain radius \( a \), described by the size index \( \alpha_d \), between ~4 and ~2.5. We assumed a minimum grain size of \( a_{\text{min}} \) = 0.1 \( \mu \)m. The maximum grain size \( a_{\text{max}} \), as well as size–dependent velocities \( v_d(a) \) were computed following Crifo & Rodionov (1997). We assumed the same bulk density of 500 kg m\(^{-3}\) for the nucleus and the dust grains and considered two cases for the size of the nucleus: a relatively small one with \( R_N = 2 \) km (model 1) and a larger one with \( R_N = 6 \) km, similar to the upper limit on the nucleus size estimated in Sect. 3.2 (model 2).

Table 2 presents the grain maximum sizes and velocity ranges, as well as the dust production rates required to produce a flux of 0.41 mJy, corresponding to our upper limit on the comet emission.

The derived dust production rates (ranging from 0.5 to \( 4 \times 10^4 \text{ kg s}^{-1} \)) widely exceed (by factors of 4 to 30) the gas production rates of 1300 kg s\(^{-1}\), considering only water production (Schleicher, 2012, personal communication). Since comets display dust-to-gas mass ratios lower than 5 (see e.g., Weiler et al., 2003, for measurements in the dusty C/1995 O1 Hale-Bopp), the actual dust production rate is likely to be much less than our estimates. As a consequence, we consider that the dust contribution to our signal is negligible, and that the upper limit of 5.6 km derived previously for the nucleus is robust.

This calculation further allows us to rule out the 4.8\( \sigma \) brightness peak as resulting from a hypothetical dust outburst at an earlier date. This peak of 0.8 mJy translates in a dust production rate of \( 1-9 \times 10^4 \text{ kg s}^{-1} \) well above what is reasonably conceivable unless a major event took place such as the fragmentation of the nucleus. Indeed fragmentation events in comets C/1996 B2 (Hyakutake) and 73P/Schwassmann-Wachmann 3 produced dust structures in the antisolar direction observed in optical images (e.g., Ishiguro et al., 2009; Vincent et al., 2010). However, the magnitude of the hypothetical dust outburst is such that it should have had an optical counterpart, for instance a strong increase of the comet visual brightness resulting from the associated production of small grains reflecting sunlight. No such outburst was reported (e.g., Nicolas, 2012a,b) casting very serious doubt on this scenario. Moreover, large grains prominently contributing to millimetre emission are weakly affected by solar pressure and would not spread in the antisolar direction – contrary to the 4.8\( \sigma \) peak – but rather be distributed along the projected comet trajectory (very much like a cometary dust trail) which happened to be almost orthogonal to the antisolar direction (see Fig. 1).

### Table 2. Dust coma model parameters and production rate upper limits.

<table>
<thead>
<tr>
<th>Model number</th>
<th>( r_N ) (Nucleus radius)</th>
<th>( a_{\text{min}} ) (Smallest grain size)</th>
<th>( a_{\text{max}} ) (Largest grain size)</th>
<th>( v_d ) (Velocity range)</th>
<th>( Q_d ) - Silicatic grains</th>
<th>( Q_d ) - Organic grains</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2 km</td>
<td>0.1 ( \mu )m</td>
<td>13 ( \mu )m</td>
<td>1.6–490 m s(^{-1})</td>
<td>1.6–2.4 ( 10^4 ) kg s(^{-1})</td>
<td>1.9–4.0 ( 10^4 ) kg s(^{-1})</td>
</tr>
<tr>
<td>2</td>
<td>6 km</td>
<td>0.1 ( \mu )m</td>
<td>13 ( \mu )m</td>
<td>4.8–406 m s(^{-1})</td>
<td>0.5–2.1 ( 10^4 ) kg s(^{-1})</td>
<td>1.1–4.3 ( 10^4 ) kg s(^{-1})</td>
</tr>
</tbody>
</table>

*Dust production rate for a flux of 0.41 mJy at 1.9 mm. The range corresponds to size indexes \( \alpha_d \) between ~4 and ~2.5.*

### 4. Summary

We observed the thermal emission of the comet C/2009 P1 (Garradd) at 157 GHz (1.9 mm) using the IRAM Plateau de Bure interferometer in March 2012. A brightness peak of \( 0.81^{+0.27}_{-0.23} \text{ mJy} \) was detected at a distance of 5.5” from the position provided by the solutions IMCCE–JPL#77 for the comet’s orbital elements. Such an offset (~5000 km at the comet) is too large to be interpreted in terms of coma morphology and it is thus unlikely that this emission is coming from the comet. We then derived an upper limit on the comet thermal emission of 0.41 mJy at the position of the comet provided by the ephemeris. Two different approaches were implemented to ascertain that the dust coma contribution to the millimetric emission in the PdBI synthesized beam is negligible. We therefore established a robust 3\( \sigma \) upper limit on the nucleus radius of 5.6 km. According to the compilation of Lamy et al. (2004), 8 out of 13 NICs for which we have reliable estimates have nucleus radius less than 5.6 km. Although the statistics is limited, it appears that the nucleus C/2009 P1 (Garradd) has a size typical of NICs. Provided the production rates of this comet measured independently from our study, we showed using a simple model of comet activity that Garradd is a very active comet, with an active fraction of the nucleus of at least 50%.
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