Imaging a Central Ionized Component, a Narrow Ring, and the CO Snowline in the Multigapped Disk of HD 169142

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Abstract

We report Very Large Array observations at 7 mm, 9 mm, and 3 cm toward the pre-transitional disk of the Herbig Ae star HD 169142. These observations have allowed us to study the millimeter emission of this disk with the highest angular resolution so far (0′′.12 × 0′′.09, or 14 au × 11 au, at 7 mm). Our 7 and 9 mm images show a narrow ring of emission at a radius of ~25 au tracing the outer edge of the inner gap. This ring presents an asymmetric morphology that could be produced by dynamical interactions between the disk and forming planets. Additionally, the azimuthally averaged radial intensity profiles of the 7 and 9 mm images confirm the presence of the previously reported gap at ~45 au and reveal a new gap at ~85 au. We analyzed archival DCO+ (3–2) and C18O (2–1) ALMA observations, showing that the CO snowline is located very close to this third outer gap. This suggests that growth and accumulation of large dust grains close to the CO snowline could be the mechanism responsible for this proposed outer gap. Finally, a compact source of emission is detected at 7 mm, 9 mm, and 3 cm toward the center of the disk. Its flux density and spectral index indicate that it is dominated by free–free emission from ionized gas, which could be associated with the photoionization of the inner disk, an independent object, or an ionized jet.

Key words: ISM: jets and outflows – planet–disk interactions – protoplanetary disks – stars: individual (HD 169142) – stars: pre-main sequence

1. Introduction

Planetary systems are formed in circumstellar disks around pre-main sequence stars. Tidal interactions between the forming planets and the disk can result in complex substructures such as cavities, gaps, spirals, or lopsided rings (Baruteau et al. 2014). Studying disks showing these features could provide us with critical information about the planetary formation process itself. In particular, transitional disks, which are protoplanetary disks with central dust gaps or cavities typically of tens of au in size (Strom et al. 1989), appear as excellent candidates to study the first stages of planetary formation.

Cavities in transitional disks were first identified through modeling of their spectral energy distributions (SEDs; Calvet et al. 2005). This modeling also led to the discovery of a subfamily of transitional disks, the so-called pre-transitional disks, which are thought to present a residual inner disk inside the cavity that can still emit significantly at near-IR wavelengths (Espaillat et al. 2007). Submillimeter and polarimetric IR observations have been able to image several of these disks and confirm the presence of the central cavities or gaps (e.g., Andrews et al. 2011; Quanz et al. 2011). Since their discovery, a number of mechanisms have been proposed to explain these inner clearings of dust (Espaillat et al. 2014 and references therein). Nevertheless, observations seem to indicate that most cavities in transitional disks are created by dynamical interactions with orbiting substellar or planetary companions (Andrews et al. 2011; Espaillat et al. 2014).

Until recent years, (sub)millimeter observations lacked the sensitivity and angular resolution necessary to reach distances very close to the central star. With the outstanding angular resolution provided by the most extended baselines of the Atacama Large Millimeter/Submillimeter Array (ALMA), as well as with the new capabilities of the Karl G. Jansky Very Large Array (VLA), it is now possible to attempt this type of study. In particular, recent ALMA observations have revealed the presence of very small central cavities, a few au in size, in some transitional disks (e.g., TW Hya, Andrews et al. 2016; XZ Tau B, Osorio et al. 2016). On the other hand, in a few cases it has been possible to detect compact central emission inside the cavity of transitional disks (Isella et al. 2014; Rodríguez et al. 2014; Andrews et al. 2016). This central emission has been associated with an inner disk (emission either from dust or from photoionized gas) or with an ionized jet. Additionally, (sub)millimeter ALMA observations have also revealed the presence of several gaps and rings up to distances of ~90 au from the star in the protoplanetary disk around HL Tau (ALMA Partnership et al. 2015). These gaps, however, might have a different origin from those observed at the inner regions of transitional disks. The young age of HL Tau, as well as the fact that some gaps are very narrow and appear at very long distances from the star, has led us to question whether a planet could produce this type of gap. This has resulted in a number of studies proposing new physical processes that could create similar gap structures—e.g., zonal flows in magnetized disks (Bai & Stone 2014), magnetorotational instability (MRI) at the dead-zone outer edge (Flock et al. 2015), sintering-induced gaps and rings (Okuzumi et al. 2016), or grain growth close to snowlines in the disk (Ros & Johansen 2013; Zhang et al. 2015).

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Gaps produced by these mechanisms could also be present in older protoplanetary and transitional disks, but they would have remained unnoticed in previous (sub)millimeter observations, due to a lack of sensitivity and angular resolution. In fact, recent ALMA observations, with a similar angular resolution to the HL Tau observations, have revealed the presence of similar ringed substructures in the transitional disk of TW Hya (Andrews et al. 2016) and in the protoplanetary disk of HD 163296 (Isella et al. 2016). Similar observations of protoplanetary disks at these high angular resolutions could show whether multigap structures are ubiquitous in protoplanetary disks, and will help to identify the physical mechanisms responsible for their creation.

HD 169142 is a Herbig Ae star ($M_* \simeq 1.65–2 M_\odot$, age $\simeq 5–11$ Myr; Blondel & Dje 2006; Manoj et al. 2006) surrounded by an almost face-on ($i \simeq 13^\circ$; Raman et al. 2006) pre-transitional disk (Osorio et al. 2014, and references therein). Osorio et al. (2014) presented VLA observations at 7 mm toward HD 169142, detecting a bright ring of dust emission at a radius of $\sim 0\arcsec 2$ surrounding a central cavity, as well as an outer gap from $\sim 0\arcsec 28$ to $\sim 0\arcsec 48$, coincident with the results from IR-polarized scattered-light images (Quanz et al. 2013; Momose et al. 2015; Monnier et al. 2017). These results have been confirmed by recent ALMA 1.3 mm continuum and CO observations, showing that the two dust gaps are filled in with gas, with a significantly reduced density at radii smaller than $\sim 0\arcsec 48$ (Fedele et al. 2017). The 7 mm emission ring imaged by Osorio et al. (2014) shows an azimuthally asymmetric morphology, reminiscent of the lopsided morphology produced as a consequence of dust trapping in planet-induced vortices (Birnstiel et al. 2013). These authors also reproduced the SED and 7 mm radial intensity profile of HD 169142 with a disk model that included the central cavity and the outer gap. Their results show that an inner residual disk is required to fit the SED, and they concluded that the disk of HD 169142 is a pre-transitional disk with two gaps. Their results also suggested that planet formation is the most likely origin for both detected gaps. In fact, a substellar or planetary companion candidate has been detected within the inner gap of the disk (Biller et al. 2014; Reggiani et al. 2014), which supports a planet-induced origin for this gap.

We note that most of the previous studies of HD 169142 adopted a distance of 145 pc (van Boekel et al. 2005). However, the recent publication of the first data release of Gaia has revealed that the distance to HD 169142 is $117 \pm 4$ pc (Gaia Collaboration et al. 2016). This represents a decrease of $\sim 20\%$ from the value of 145 pc adopted in the literature. The same reduction has been therefore applied throughout this article to the sizes of the disk structures measured here and in the literature.

In this paper we present new high angular resolution VLA observations at 7 mm, 9 mm, and 3 cm toward the pre-transitional disk around HD 169142, revealing the presence of a new third gap in the disk, as well as a free-free thermal emission source inside the inner gap.

2. Observations

We performed observations using the VLA of the National Radio Astronomy Observatory (NRAO)6 in the A and BnA configurations at Q ($\sim 7$ mm), Ka ($\sim 9$ mm), and X ($\sim 3$ cm) bands. Archival observations at K ($\sim 1.3$ cm; C and DnC configurations) and C bands ($\sim 5$ cm; A configuration) were also used (see Table 1). Amplitude calibration was performed by observing 3C 286, with an expected uncertainty in the flux scale of $\sim 10\%$. 3C 286 was also used as the bandpass and delay calibrator, whereas J1820-2528 was used as the complex gain calibrator.

The observations were reduced and calibrated with the reduction package Common Astronomy Software Applications (CASA; version 4.5.3; McMullin et al. 2007). Each data set was processed through the VLA calibration pipeline integrated within CASA. After each run of the pipeline, the calibrated data were inspected. Then, we performed additional data flagging and reran the pipeline as many times as needed.

Deconvolved images were produced with the CLEAN task of CASA. A multiscale, multifrequency deconvolution algorithm was used to take into account the frequency dependence of the emission within each band (Rau & Cornwell 2011). Data from each observing session were first imaged independently to check for possible errors in the absolute position, without finding any significant shift. Then, for each band, we combined the data from the different epochs and configurations in order to obtain higher-sensitivity images. A $uv$ taper was applied to the Ka band visibilities in order to improve the signal-to-noise ratio (S/N) of the image.

In addition, we report unpublished archival ALMA data of the $^{13}$CO (3–2) transition (rest frequency 216.112 GHz), and we reanalyze data of the $^{18}$O(2–1) transition (rest frequency 219.560 GHz). The observations were carried out on 2015 August 30 (project code: 2013.1.00592.S) and are described in Fedele et al. (2017), where the $^{13}$CO(2–1) data were first reported. Data calibration was performed using the ALMA pipeline within CASA (version 4.3.1). Deconvolved images were then obtained using the CLEAN task with natural weighting. In addition, a $uv$ taper was applied to the $^{13}$CO (3–2) visibilities in order to achieve a higher S/N. The rms noise of the $^{18}$O(2–1) observations is $\sim 6$ mJy beam$^{-1}$ (synthesized beam of $0\arcsec 35 \times 0\arcsec 23$, PA = $-74^\circ$) for a channel width of $\sim 0.25$ km s$^{-1}$, whereas the rms noise of the $^{13}$CO (3–2) observations is $\sim 7$ mJy beam$^{-1}$ (synthesized beam of $0\arcsec 50 \times 0\arcsec 48$, PA = $-65^\circ$) for a channel width of $\sim 0.25$ km s$^{-1}$.

3. Results and Discussion

A natural-weighted image of the 7 mm emission of HD 169142, obtained from the combination of A, BnA, and B configuration data, is shown in Figure 1. The image shows a narrow ring of emission of radius $\sim 0\arcsec 21$ ($\sim 25$ au at 117 pc) with significant substructure. In addition, the image shows a hint of a second ring of emission at $\sim 0\arcsec 50$ ($\sim 59$ au) tracing the rim of the second gap detected by Osorio et al. (2014). A compact emission component is detected inside the inner ring, with its peak of emission displaced a projected distance of $\sim 0\arcsec 023$ ($\sim 2.7$ au) from its center. In the images made from a single configuration, this central component of emission is only detected in the A configuration data, which have enough angular resolution and sensitivity to separate it from the ring of emission. We do not expect significant proper motions within the time span of the A configuration observations (1 week).
Thus, we expect that our images obtained combining the A, BnA, and B configuration data will not be affected by these proper motions. The total flux density of the 7 mm emission is 2.0 ± 0.4 mJy, which is consistent with previous measurements (Osorio et al. 2014). The flux density of the central component is 74 ± 15 μJy.

Our new A configuration data, with higher sensitivity and angular resolution, do not confirm the knot of 7 mm emission located ~0″.34 (~40 au) to the south of the central position, suggestive of a protoplanet candidate inside the second gap, that was observed in the Osorio et al. (2014) images. Also, we do not identify radio emission associated with the IR source detected by Reggiani et al. (2014) and Biller et al. (2014) at radius 0″.16 and PA = 7°.

The left panel in Figure 2 presents the 9 mm image of HD 169142. This image shows a similar morphology to the 7 mm image: a ring of emission with a central radio source inside its cavity. The ring of emission also seems to show some substructure, although the low S/N makes it difficult to determine whether this substructure in the 9 mm image is real or due to rms fluctuations. The total flux density of the 9 mm emission is 850 ± 150 μJy, while the flux density of the central emission inside the inner ring is 45 ± 14 μJy.

The right panel in Figure 2 shows an image of the 3 cm emission of HD 169142, obtained by combining the A, BnA, and B configuration observations using natural weighting. The emission is only marginally resolved, with its peak of emission located inside the inner dust gap, very close to the central star. The total flux density at 3 cm is 50 ± 10 μJy. Due to the lower angular resolution of the 3 cm observations, we cannot directly separate in our natural-weighted image the emission of the extended disk from the central radio source. By using a higher weight for the most extended visibilities, we can filter out the extended disk emission and estimate the flux density of the compact central radio source. We used Briggs weighting with a robust parameter of 0.5 (as defined in task CLEAN of CASA) and estimated a flux density at 3 cm of ~20 ± 5 μJy for the central radio source. The remaining emission in the natural-weighted image at 3 cm is consistent with the dust flux density of ~30 μJy predicted by the model of Osorio et al. (2014).

Finally, no emission was detected in the K- and C-band observations, with 3σ upper limits of 420 and 27 μJy beam−1, respectively. The C-band image was obtained by combining our new data with those previously reported by Osorio et al. (2014) in order to obtain a tighter upper limit. Both limits are consistent with the model presented by Osorio et al. (2014).
3.1. Narrow Ring

As can be seen in Figure 1, our 7 mm image shows a narrow ring of emission with a radius of ≈25 au. For the width of the ring we estimate a deconvolved FWHM of ≈8 au, measured along the E–W direction, where the synthesized beam size is smaller. The ring in our images coincides quite well with the ring imaged in previous near-IR (Quanz et al. 2013; Monnier et al. 2017), 7 mm (Osorio et al. 2014), and 1.3 mm (Fedele et al. 2017) observations, but our images reveal additional details.

We have estimated the position of the center of the ring by fitting an ellipse with its major axis along the position angle of the disk, as estimated from previous molecular observations (PA = 5°; Raman et al. 2006), to the ring image, excluding the regions where two dips and a knot of emission are found (see below). From this fit we estimate that the center of the ring in the 7 mm image (epoch ~2014.17) is located at α(J2000) = 18h24m29s7798 ± 0s00018, δ(J2000) = −29°46′49″8673 ± 0″0028, which coincides within ≈4 ± 3 mas with the position of the star HD 169142 given in the Gaia catalog, after correcting for proper motions (Gaia Collaboration et al. 2016). This result indicates that the ring is very well centered on the star, and that the alignment of the data to make the final image and the quality of its astrometry are very good. From our fit we also estimate a radius of the ring of 0″214 ± 0″004 (25.0 ± 0.5 au), which is slightly larger than the radius of ~0″19 (~22 au) estimated from the near-IR scattered-light images (Quanz et al. 2013). This suggests that the scattered-light emission arises mainly from the inner rim or wall of the ring, whereas the 7 mm emission traces mainly the surface density of the large dust grains that peaks at slightly larger radii.

The intensity of the ring in our 7 mm image is significantly asymmetric in azimuth, showing a knot of emission ~4σ above the average intensity of the ring at PA ≈ −40°, in agreement with the previous results of Osorio et al. (2014), who noted this azimuthal asymmetry from 7 mm data of lower angular resolution. We think that this knot represents a real azimuthal asymmetry since an intensity enhancement appears both in the images made from the new A configuration data alone and in the lower angular resolution maps reported in Osorio et al. (2014). The ALMA 1.3 mm images also show a hint of this asymmetry (Fedele et al. 2017), although at a lower significance, probably due to the higher optical depth of the ring at shorter wavelengths, or an accumulation of the large dust grains preferentially traced at 7 mm.

On the other hand, our new 7 mm image also shows significant decreases of intensity or dips in the ring at PA ≈ 0° and PA ≈ −170°. As shown by Osorio et al. (2014), an elongated beam can produce depressions of emission along the direction of the major axis of the beam in an axisymmetric ring. Additionally, noise fluctuations can produce spurious clumpy structures during the deconvolution process. In order to check whether the substructure detected in our images is real or due to these spurious effects, we obtained simulated images with random thermal noise using the model presented by Osorio et al. (2014) and the SIMOBSERVE task in CASA. These simulations showed that, for certain noise structures, intensity depressions similar to the ones in our observations could be formed in the narrow ring, suggesting that the observed dips in our 7 mm observations could be produced because of the combined effect of noise fluctuations and the elongated beam. Nevertheless, none of our simulations produced a bright knot similar to the one detected in our 7 mm observations, indicating that it is tracing a real azimuthal asymmetry in the ring.

Polarized scattered-light images at H band show an axisymmetric ring with only a possible dip at a PA ≈ 80° (Quanz et al. 2013), where no significant drop of emission is seen in our images. The fact that the knot of emission in the ring is not present at near-IR wavelengths indicates that it is
probably produced by azimuthal asymmetries in the density near the disk midplane, to which our 7 mm images are more sensitive, without affecting significantly the distribution of small dust grains in the disk atmosphere, which are traced by the scattered-light images.

Azimuthal asymmetries in the large dust grain distribution are expected to be produced by tidal interactions between a forming planet and the disk (e.g., Baruteau et al. 2014). Hydrodynamic simulations show that planets can create relatively large cavities with vortices at their outer edges. These vortices, in turn, are able to trap the large dust grains in their pressure maxima, producing lopsided asymmetries at millimeter wavelengths (Birnstiel et al. 2013; Zhu & Stone 2014). Thus, the interaction between the disk of HD 169142 and the possible forming planets at the inner (Biller et al. 2014; Reggiani et al. 2014) and second gaps could be responsible for the observed nonaxisymmetric structure.

3.2. Central Compact Radio Source

Our 7 mm, 9 mm, and 3 cm images have revealed the presence of compact emission inside the bright emission ring, originating near its center (Figures 1 and 2). The emission at 7 mm is slightly extended along the E–W direction, with its intensity peak at a projected distance of \( \sim 3 \pm 1 \) au (\( \sim 0"025 \pm 0"010 \)) from the central star toward the W direction. The quoted uncertainty is probably only a lower limit, corresponding to the formal error in the position of the emission peak relative to the center of the ring, estimated as \( \sim 0.5(\theta/S/N) \) (Reid et al. 1988), assuming an unresolved source (\( \theta = 0"1 \)) and an S/N of 5. Further observations are needed to confirm the reality and origin of this possible displacement (see below).

The insufficient sensitivity and angular resolution of the images at 9 mm and 3 cm, respectively, make it difficult to estimate the morphology of the central emission observed at these wavelengths. This central radio source could not be detected in previous observations by Osorio et al. (2014) toward HD 169142 at 7 mm, due to the lack of angular resolution. We do not identify radio emission associated with the IR source detected by Biller et al. (2014) and Reggiani et al. (2014) located \( \sim 0"16 \) (\( \sim 19 \) au) north from the central star.

In principle, both dust and ionized gas could be contributing to the radio emission at the innermost regions of transitional disks. To our knowledge, very few transitional disks have been observed with high enough angular resolution to detect and resolve compact emission at millimeter and centimeter wavelengths inside their central cavities or gaps. LkCa 15 (Isella et al. 2014) and AB Aur (Rodríguez et al. 2014) were imaged with the VLA at 7 mm and 3 cm, respectively, whereas TW Hya was observed with ALMA at 0.87 mm (Andrews et al. 2016). The emission in TW Hya has been attributed to inner residual dust located close to the star, although it has also been recently suggested that a contribution of free–free emission from photoionized gas could be present (Ercolano et al. 2017). The morphology and spectral index of the emission in AB Aur indicates that it is associated with free–free emission from an accretion-driven jet. In LkCa 15, however, the lack of observations at other wavelengths makes it impossible to distinguish between a dust or a free–free origin for the emission. In the following we discuss the origin of the observed compact central radio source in HD 169142.

The near-IR excess in the SED of HD 169142 indicates that its disk is a pre-transitional disk, with a hot dust component located very close to the star. Osorio et al. (2014) modeled the broadband SED and the 7 mm images of HD 169142 and found that an inner disk of 0.6 au in radius, together with its inner wall at the dust sublimation radius (\( \sim 0.2 \) au), could fit the near-IR emission of HD 169142. According to their model, this inner dust component would produce only \( \sim 9, \sim 5, \) and \( <1 \mu d \) of emission at 7 mm, 9 mm, and 3 cm, respectively. These values are much lower than the observed \( 74 \pm 15 \mu d \), \( 45 \pm 14 \mu d \), and \( \sim 20 \pm 5 \mu d \) at these wavelengths for the central radio source. From a power-law fit to these observed values of the flux density (\( S_{\nu} \propto \nu^{\alpha} \)), we estimate a spectral index \( \alpha = 0.82 \pm 0.17 \) (see Figure 3), which is too low to correspond to dust thermal emission (dust thermal emission presents \( \alpha \geq 2 \)). Therefore, both the flux density and spectral index of the central radio source indicate that its emission is mainly dominated by partially optically thick free–free emission from ionized gas.

Gas near young stellar objects has been found to be ionized by two main mechanisms: shocks in accretion-driven jets (Anglada et al. 2015), and photoionization due to the high-energy radiation from the central star (Alexander et al. 2014). Since accretion and ejection of material are correlated (Cabrit 2007), low-mass-accretion rate objects, such as transitional disks, are expected to present relatively weak radio jets. However, recent studies with the VLA have shown that radio jets in this type of source can produce free–free emission at levels that are detectable with the improved sensitivity of the VLA (Rodríguez et al. 2014). In particular, Macías et al. (2016) presented VLA observations at 3 cm toward the transitional disk of GM Aur, revealing resolved free–free emission from a radio jet and from a photoevaporating disk, showing that both
mechanisms can contribute at the same level to the total free–
free emission.

The central radio source detected at 7 mm in HD 169142
presents a slight elongation with a PA \( \approx -80^\circ \), which is
consistent with the position angle of the disk rotation axis
\( \text{PA} \approx -85^\circ \), as shown by molecular line observations
(Raman et al. 2006). This suggests that the central radio
source in our images could be tracing an accretion-driven radio
jet. We can obtain a rough estimate of the free–free emission
of an accretion-driven jet in HD 169142 with the empirical
correlation between the radio luminosity of a source, \( S_d d^2 \), and
its outflow momentum rate, \( P_{\text{out}} \) (Anglada 1995; Anglada et al.
2015): \( P_{\text{out}} / M_\odot \text{ yr}^{-1} \text{ km s}^{-1} = 10^{25.0 \pm 0.3} (S_d d^2 / \text{mJy kpc}^2)^{1.1 \pm 0.2} \).
Wagner et al. (2015) measured a mass accretion rate onto the
star HD 169142 of \( M_{\text{acc}} \approx (1.5-2.7) \times 10^{-9} M_\odot \text{ yr}^{-1} \). Assuming
a ratio between mass-loss rate in jets and mass accretion
rate \( M_{\text{out}} / M_{\text{acc}} \approx 0.1 \) (Cabrit 2007), we estimate that the
outflow momentum rate should be \( P_{\text{out}} \approx 10^{-7} M_\odot \text{ yr}^{-1} \text{ km s}^{-1} \).
Therefore, the correlation would predict a flux density at 3 cm
of \( S_d \approx 5 \mu\text{Jy} \), which is lower than our estimated flux density
of 20 \( \pm 5 \mu\text{Jy} \) for the central radio source. Even though this
estimate has large uncertainties, it suggests that an additional
mechanism other than shocks associated with the outflow could
contribute to the ionization of this jet.

Another possibility is that the observed central radio source
was originated as a result of photoionization by high-energy
radiation from the central star. Extreme-UV (EUV) and, to a
lesser extent, X-ray radiation impinging on the inner disk can
ionize its surface (Clarke et al. 2001; Gorti et al. 2009; Owen
et al. 2010) and contribute to the observed free–free emission.
An inhomogeneous inner disk could lead to an inhomogeneous
irradiation of its surface, which could result in the asymmetric
morphology of the central radio source observed at 7 mm.
Additionally, the ejected gas in the accretion-driven jet could
also be significantly photoionized by the high-energy radiation
emitted by the star (Hollenbach & Gorti 2009).

Finally, the peak of emission of the central radio source
could be tracing the position of an independent object at a
radius of \( \approx 3 \text{ au} \) from the central star. Given the proximity
to the central star, the dynamical timescales involved would be
short. An orbiting object at a radius of \( \lesssim 3 \text{ au} \) would have an
orbital period \( \lesssim 4 \text{ yr} \) and would show detectable orbital proper
motions in a few months. On the other hand, knots of emission
in a radio jet are expected to be ejected with velocities of
\( \approx 300 \text{ km s}^{-1} \). Given the small inclination angle of the disk
\( i = 13^\circ \); Raman et al. 2006), after projection on the plane of
the sky, this would result in proper motions of \( \approx 0.12 \text{ yr}^{-1} \)
away from the central star along PA \( \approx -80^\circ \). Future observations
should reveal detectable variations and/or proper motions
in the observed emission that will allow us to discriminate
whether it traces material ejected from the central star (jet) or
orbiting around it (disk or independent object).

### 3.3. Outer Gaps

In order to improve the S/N of the detected intensity, we
have obtained the averaged radial intensity profiles of the 7 and
9 mm images (see Figure 4). These profiles were produced by
averaging the intensity within concentric elliptical rings,
marching the inclination and position angle of the disk major
axis determined by previous molecular line observations
\( i = 13^\circ \) and PA = 5\(^\circ\); Raman et al. 2006). The width of the
concentric rings was set to the size of the beam, since the rms
noise at spatial scales smaller than a beam is not independent.

Besides the inner gap (hereafter G1), two other gaps at radii
\( \approx 0.28 \text{ au} \) (G2) and \( \approx 0.73 \text{ au} \) (G3) are revealed at
both 7 and 9 mm. The inner (G1) and second gaps (G2) were
already detected at near-IR wavelengths (with G1 at radii
\( \lesssim 0.19 \text{ au} \) and G2 extending from \( \approx 0.28 \) to \( \approx 0.48 \); Quanz
et al. 2013; Momose et al. 2015), at 7 mm (Osorio et al. 2014),
and at 1.3 mm (Fedele et al. 2017). Our observations detect the
G1 and G2 gaps at the same radii as precedent studies, while
the G3 gap is reported here for the first time.

We point out that a sharp cutoff in the \( \nu \sigma \) coverage of the
observations can result in the creation of a spurious annular
structure during the deconvolution process. However, this
artifact would appear at different radii in the images at different
frequencies, whereas the G3 gap appears at the same radius in
our observations at 7 and 9 mm. Additionally, our simulated
images (see Section 3.1) do not show the presence of spurious
features mimicking the G3 gap when an actual gap is not
included in the model. Therefore, we conclude that the G3 gap
is probably a real annular gap in the disk of HD 169142. We
note, however, that the G3 gap is not visible in the ALMA
1.3 mm images (Fedele et al. 2017). This could indicate that the

![Figure 4. Averaged radial intensity profiles of the 7 mm (top panel) and 9 mm (bottom panel) images. The width of the lines indicates the 1σ uncertainty.](image-url)
G3 gap is more prominent in the distribution of the centimeter-sized dust grains traced by our VLA observations.

As mentioned above, different studies have proposed that G1 and G2 are probably formed because of dynamical interactions between the disk and forming planets within each gap (Osorio et al. 2014; Reggiani et al. 2014; Momose et al. 2015; Wagner et al. 2015; Fedele et al. 2017). However, the origin of the third gap (G3) is more difficult to understand. Detection of gaps at such large distances, like G3, is very difficult. So far, similar gaps have only been detected in the protoplanetary disks around HL Tau (ALMA Partnership et al. 2015), TW Hya (Andrews et al. 2016), and HD 163296 (Isella et al. 2016), through recent extremely high angular resolution ALMA observations. The density in the disk midplane at such large distances is probably too low to create a planet responsible for clearing the observed gap. Alternatively, the MRI in magnetized disks can produce pressure bumps at the outer edges of the dead zones in the disk, which can in turn trap the large dust grains and create gaps in the millimeter emission of the disk (Flock et al. 2015). However, dead zones are expected to be closer to the central star (at radii \( \sim 50 \text{ au} \)), so models do not predict gaps as far as the observed G3 gap in HD 169142.

Another possible origin for G3 would be grain growth and/or an increase in the solids’ surface density close to condensation fronts (i.e., snowlines) of volatiles in the disk. This process has been suggested as the one responsible for some of the rings and gaps that were detected by ALMA in the disk around the younger T Tauri star HL Tau (ALMA Partnership et al. 2015; Zhang et al. 2015; Okuzumi et al. 2016). Models and laboratory experiments suggest that dust grains can grow significantly when surrounded by an icy mantle, which would form on the surface of the grains beyond these snowlines (Ros & Johansen 2013; Testi et al. 2014, and references therein). In addition, it has been suggested that the enhanced surface density of solids beyond the snowline can produce viscosity gradients and pressure bumps because of a reduction in the column depth of the MRI-active layer. These pressure bumps could in turn trap the large dust grains (Kretke & Lin 2007), although more recent studies have found that, at least for the water snowline, which is located at much smaller radii, the viscosity gradient would need to be unrealistically high to be able to form a dust trap (Bitsch et al. 2014).

Based on the composition of comets, the most abundant volatiles in protoplanetary disks are thought to be water, CO, and CO\(_2\). These molecules have, for typical disk midplane densities, condensation temperatures of 128–155 K, 23–28 K, and 60–72 K, respectively (Zhang et al. 2015). Comparing these temperatures with the midplane temperatures obtained from the model presented by Osorio et al. (2014), we find that the water and CO\(_2\) snowlines would fall inside G1, while the CO snowline would be located at a distance of 90–130 au.\(^8\) The lower end of the range of radii for the CO snowline is coincident with the outer edge of G3, favoring grain growth and an increase in the solids’ surface density close to the CO snowline as a possible mechanism to explain the origin of the G3 gap.

An independent measurement of the position of the CO snowline in protoplanetary disks can be obtained through observations of molecules whose chemistry is sensitive to the CO (Qi et al. 2013). One of these molecules is the DCO\(^+\), which is expected to form mainly in the regions of protoplanetary disks where gas-phase CO and low temperatures \(T < 30 \text{ K}\) coexist. Because of this, the DCO\(^+\) emission has been used as a tracer of the CO freezeout in disks, showing a ring-like morphology peaking at just a slightly smaller radius than the CO snowline (Mathews et al. 2013; Öberg et al. 2015). However, recent studies suggest that, in some cases, the DCO\(^+\) molecule might have a more complex relationship with the CO snowline, and that optically thin CO isotopologues such as C\(^{18}\)O could represent better tracers by showing a decrease of emission at the radius of the snowline (Qi et al. 2015; Huang et al. 2017).

In order to estimate the position of the CO snowline in HD 169142, we have analyzed ALMA archival observations of both the DCO\(^+\)(3–2) and C\(^{18}\)O(2–1) molecular transitions. An image of the velocity-integrated DCO\(^+\)(3–2) emission of the disk around HD 169142 (synthesized beam = 0''50 \times 0''48, PA = −65\(^\circ\); shown in the lower left corner). Contour levels are −3, 3, 5, 7, and 9 times the rms of the map, 6.0 \(\mu\)Jy beam\(^{-1}\) km s\(^{-1}\). The dashed ellipse indicates our fit to the ring image at 7 mm (Figure 1). The white plus sign shows the position of the star.

8 We note that the Osorio et al. (2014) model used a distance of 145 pc, which is \(\sim 20\%\) larger than the recent distance of 117 pc measured by Gaia. However, we do not expect important changes in the physical structure of the disk.
Our 7 and 9 mm observations show a narrow (∼8 au in width) azimuthally asymmetric ring of emission of radius ∼25 au, apparently tracing the outer rim of the innermost gap. The radius of the ring is consistent with that of previous 7 mm and near-IR-polarized scattered-light images (Quanz et al. 2013; Osorio et al. 2014; Momose et al. 2015). A bright knot of emission in the ring is revealed at 7 mm. This knot of emission is not present in the near-IR images, indicating that it is probably tracing an azimuthal asymmetry in the density of the disk midplane, to which our 7 mm images are more sensitive. We interpret this asymmetry as probably produced by tidal interactions between the disk and forming planets.

2. A central component of emission is detected inside the inner gap at 7 mm, 9 mm, and 3 cm. The 7 mm source shows a slightly elongated morphology approximately along the E–W direction, with its peak of emission displaced a projected distance of ∼3 au (∼0″025) to the west of the central star. The flux density and spectral index of this central radio source indicate that it is dominated by free–free emission from ionized gas, which could be associated with an inhomogeneous photoionization of the inner disk, with an independent orbiting object, or with an (asymmetric) ionized jet. Although data currently available seem to favor the latter scenario, future observations should reveal significant proper motions either away from or around the central star that will allow us to discriminate between ejection and orbital motions.

3. The radial intensity profiles of the 7 and 9 mm images reveal the presence of multiple gaps in the disk of HD 169142. Our 7 and 9 mm observations not only confirm the presence of the previously reported inner (G1) and second (G2) gaps, which approximately extend through radii ∼0–25 au and ∼32–56 au, respectively, but also detect, for the first time, a new gap comprising the radii ∼77–96 au (G3). This proposed gap, one of the farthest gaps ever detected in a protoplanetary disk, is not detected in ALMA 1.3 mm images, suggesting that it might be more prominent in the distribution of the larger dust grains traced by our VLA observations.

4. Our analysis of DCO⁺(3–2) and C¹⁸O(2–1) ALMA observations, as well as the results of the Osorio et al. (2014) model, indicate that the CO snowline is located at ∼100 au. This suggests that dust grain growth and an increase in the solids’ surface density close to the CO snowline could be the mechanism responsible for the origin of the proposed G3 outer gap.

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Software: CASA (v 4.3.1, 4.5.3; McMullin et al. 2007).

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