3.3 CM JVLA OBSERVATIONS OF TRANSITIONAL DISKS: SEARCHING FOR CENTIMETER PEBBLES

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ABSTRACT

We present sensitive (rms-noises ~4–25 μJy) and high angular resolution (~1″–2″) 8.9 GHz (3.3 cm) Karl G. Jansky Very Large Array radio continuum observations of 10 presumed transitional disks associated with young low-mass stars. We report the detection of radio continuum emission in 5 out of the 10 objects (RXJ1615, UX Tau A, LkCa15, RXJ1633, and SR 24s). In the case of LkCa15, the centimeter emission is extended, and has a similar morphology to that of the transitional disk observed at millimeter wavelengths with an inner depression. For these five detections, we construct the spectral energy distributions from the centimeter to submillimeter wavelengths, and find that they can be well fitted with a single (RXJ1633 and UX Tau A) or a two-component power law (LkCa15, RXJ1615, and SR 24s). For the cases where a single power law fits the data well, the centimeter emission is likely produced by optically thin dust with large grains (i.e., centimeter-size pebbles) present in the transitional disks. For the cases where a double power law fits the data, the centimeter emission might be produced by the combination of photoevaporation and a free–free jet. We conclude that RXJ1633 and UX Tau A are excellent examples of transitional disks where the structure of the emission from centimeter/millimeter pebbles can be studied. In the other cases, some other physical emitting mechanisms are also important in the centimeter regime.

Key words: accretion, accretion disks – methods: observational – radiation mechanisms: thermal – radio continuum: ISM – stars: formation – techniques: high angular resolution

1. INTRODUCTION

One of the first steps in the process of planet formation is that of dust grain growth. The dust grains in a protoplanetary disk are expected to grow from sub-micron size (as observed in the Interstellar Medium (ISM)) to millimeter/centimeter sizes, and then to large pebbles. The best evidence of such change comes from the relatively shallow wavelength dependence of the millimeter/centimeter thermal emission from dust (e.g., CY Tau, CQ Tau, and DoAr 25: Testi et al. 2003; Pérez et al. 2015). If we assume that the dust emission is optically thin, then the estimated spectral index α (of the form S ν ∝ ν^α, where S ν is the flux density and ν is the frequency) is directly related to the dependence of the opacity on the wavelength. Thus, the grain size can be deduced by the opacity law, but taking into account the optical depth and geometrical effects (Testi et al. 2003). A clear example of the application of this technique has been done by Wilner et al. (2005). Using self-consistent disk models and deep VLA observations at 3.5 cm wavelengths toward the transitional disk of the T-Tauri star TW Hya, Wilner et al. (2005) reported that a large amount of the orbiting particles in such disk should have agglomerated to centimeter and millimeter sizes, providing some evidence at the beginning of the planet formation process.

The transitional disks were first indirectly inferred from their infrared spectra obtained by the Infrared Astronomical Satellite (IRAS) and the Spitzer Space Telescope (Strom et al. 1989; Calvet et al. 2002; D’Alessio et al. 2005; Kim et al. 2013). This new class of disks are (proto)planetary disks around young stars that are optically thick and gas-rich, but which have AU-scale radial gaps or central depressions in their dust distribution. This gap is revealed as a deficit in the T Tau and Herbig Ae/Be star’s infrared excess (e.g., Kim et al. 2013; van der Marel et al. 2016b), in more recently spatially resolved images of reflected light in the optical and infrared (i.e., Thalmann et al. 2010; Mayama et al. 2012; Canovas et al. 2013; Avenhaus et al. 2014), and in the (sub)millimeter regime (Pietu et al. 2006; Andrews & Williams 2007; Andrews et al. 2011; Cieza et al. 2012; Isella et al. 2014; Osorio et al. 2014).

However, the nature of the cavity has remained in dispute. To date, there are many possibilities to explain its nature, some of which include: photoevaporative winds, dust size evolution, and tidal interactions with stellar or planetary companions (Williams & Cieza 2011). Moreover, there is clearly molecular gas inside these cavities; see, for example, Canovas et al. (2015), van der Marel et al. (2016a), and Tang et al. (2012), which indicate that such cavities are not really fully empty.

Optical and radio observations have revealed that the transitional and pre-transitional disks (for a more complete review about these kinds of disks, see Espaillat et al. 2014) have associated ionized jets, and can be detected as weak free–free sources (Eislöffel et al. 2000; Rodríguez et al. 2014; Macías et al. 2016). In the case of AB Aur, a well-studied transitional disk, Rodríguez et al. (2014) concluded that the radio centimeter emission is tracing a collimated and ionized outflow, given the morphology, orientation, spectral index, and lack of temporal variability of the centimeter source. This case supports the interpretation that probably the radio emission at these wavelengths, and from this class of objects, could be arising from a faint free–free jet that is still present at the most evolved phases of the formation of a star. AB Aur is a Herbig Ae star with a mass of 2.4 ± 0.2 M☉, a total luminosity of about 38 L☉, a spectral type A0, and an estimated age of 4 ± 1 Myr (DeWarf et al. 2003). These properties make AB Aur certainly a bigger and hotter young star hosting a transitional disk compared to the group of stars analyzed here, which are more typically associated with colder solar-type objects in probably a more evolved phase; see Andrews & Williams (2007). AB Aur is also surrounded by a large envelope (Tang et al. 2012). However, in the case of GM Aur, a transitional disk that is associated with a T-Tauri young star (d ∼ 140 pc, K5 spectral type, Lb ∼ 0.9 L☉, Mb ∼ 1.1 M☉; Kenyon & Hartmann 1995), Macías et al. (2016) reported a...
Notes.

- We report here on deep Jansky Very Large Array (JVLA) 3.3 cm observations of 10 presumed transitional disks associated with young low-mass stars. We detected radio emission in only 5 out of the 10 observed disks. The radio emission is mostly unresolved and very faint. However, in the case of LkCa15 the emission is well resolved. The nature of the radio emission present in the disks is discussed in the following sections.

2. OBSERVATIONS

The observations were carried out with the Karl G. Jansky Very Large Array of NRAO\(^1\) centered at a rest frequency of 8.9 GHz (3.3 cm) during 2013 October and 2014 January. At that time the array was in its B configuration. We used 26 antennas of the array, yielding baselines with projected lengths from 10 to 350 kλ.

The absolute amplitude calibrators were J1331+3030 and J0137+3309, while the gain-phase calibrators are presented in Table 1. The integration time in each source shown in Table 1 was about 20 minutes. The weather conditions were good and stable, with an average precipitable water vapour of about 7.0 mm.

The digital correlator of the JVLA was configured in 16 spectral windows of 128 MHz width divided in 64 channels. The total bandwidth for the observations was 2.048 GHz in a dual-polarization mode.

The data were analyzed in the standard manner using the CASA (Common Astronomy Software Applications) package of NRAO. We tried to apply self-calibration to the data, however, given that all sources are very faint objects (<1 mJy), we were not successful in improving the images. We used a natural weighting in order to obtain a slightly better sensitivity losing some angular resolution. To construct the continuum we used a bandwidth of 2.048 GHz. The resulting

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Table 3

| Source  | λ/Freq. (cm/GHz) | Flux Density (mJy) | References |
|---------|-----------------|-------------------|------------|
| RXJ16   | 0.088/340       | 430 ± 30          | Andrews et al. (2011) |
|         | 0.140/214       | 169 ± 10          | Ubach et al. (2012) |
|         | 0.318/94        | 6.8 ± 1.2         | Ubach et al. (2012) |
|         | 0.700/43        | 0.8 ± 0.2         | Ubach et al. (2012) |
|         | 3.300/8.9       | 0.062 ± 0.015     | This paper |
| UXTauA  | 0.045/666       | 523 ± 37          | Andrews & Williams (2005) |
|         | 0.088/340       | 173 ± 3           | Andrews & Williams (2005) |
|         | 0.130/230       | 52 ± 2            | Jensen & Akeson (2003) |
|         | 0.300/100       | 101 ± 0.3         | Pinilla et al. (2014) |
|         | 0.710/44        | 1.01 ± 0.06       | VLA Archive |
|         | 0.920/3.2       | 0.47 ± 0.02       | VLA Archive |
|         | 3.300/8.9       | 0.057 ± 0.008     | This paper |
| LkCa15  | 0.088/340       | 430 ± 30          | Andrews & Williams (2005) |
|         | 0.130/230       | 167 ± 6           | Andrews & Williams (2005) |
|         | 0.280/107       | 17 ± 0.8          | Piétu et al. (2006) |
|         | 0.700/43        | 0.60 ± 0.10       | VLA Archive |
|         | 3.300/8.9       | 0.045 ± 0.017     | This paper |
|         | 6.000/5.0       | ≤0.021            | VLA Archive |
| RXJ1633 | 0.088/340       | 2200 ± 300        | Cieza et al. (2012) |
|         | 0.130/230       | 818 ± 100         | Cieza et al. (2012) |
|         | 3.300/8.9       | 0.218 ± 0.009     | This paper |
| SR 24s  | 0.088/340       | 430 ± 30          | Andrews & Williams (2007) |
|         | 0.150/230       | 197 ± 20          | Isella et al. (2009) |
|         | 0.300/100       | 266 ± 1.5         | Ricci et al. (2010) |
|         | 0.730/44        | 1.03 ± 0.18       | VLA Archive |
|         | 0.880/34        | 0.67 ± 0.03       | VLA Archive |
|         | 3.300/8.9       | 0.096 ± 0.004     | This paper |
| AB Aur  | 0.075/400       | 530 ± 90          | Acke et al. (2004) |
|         | 0.085/352       | 360 ± 70          | Acke et al. (2004) |
|         | 0.110/272       | 150 ± 20          | Acke et al. (2004) |
|         | 0.270/111       | 11 ± 0.5          | Acke et al. (2004) |
|         | 0.700/43        | 0.85 ± 0.03       | Rodríguez et al. (2014) |
|         | 3.300/8.9       | 0.13 ± 0.02       | Rodríguez et al. (2014) |
|         | 4.500/6.6       | 0.085 ± 0.01      | Rodríguez et al. (2014) |

We have observed 10 transitional disks at a wavelength of 3.3 cm using the Karl G. Jvla as a continuation of our study to better understand the nature of the centimeter emission in these systems (Rodríguez et al. 2014). We detected compact emission in only five transitional disks: RXJ1615, UX Tau A, LkCa15, RXJ1633, and SR 24s. We looked for a specific trend (in the mass accretion rates, ages, and even spectral types) to explain the absence of radio emission in the rest of the transitional disks (DM Tau, SAO 206, SR 21, WSB 60, and DOAR 44). Unfortunately a trend is not obvious; see Table 2.

In Table 2, we give the physical parameters of the five detected disks at these radio wavelengths as well as the upper limits for the non-detections. We detected these sources at more than a 4σ level, equivalent to a range of 20–100 μJy. The radio emission arising from the five sources is mostly unresolved, with LkCa15 being the only source resolved.

The centimeter emission from LkCa15 is extended, and has a similar morphology (2.6 × 0.8 ± 0.2; PA: 67° ± 2°; this corresponds to spatial scales of 364 AU × 196 AU) to that of its associated millimeter transitional disk (1.3 × 0.6 ± 0.04; PA: 65° ± 4°; Andrews et al. 2011) with an inner depression; see Figure 1. We have plotted the real component of the visibility profile (Figure 2), which shows the characteristic null and negative region that confirm the central hole in the disk; see for example Osorio et al. (2016). The null falls around 200 kλ, corresponding to hole radius of about 70 AU. The centimeter radio emission is resolved, and shows a similar morphology to the disk. This therefore suggests that the 3.3 cm radio emission from LkCa15 is originating from the transitional disk instead of, for example, a thermal free–free jet; see Rodríguez et al. (2014). We discuss in detail the nature of the centimeter emission in LkCa15 below.

For the rest of the disks, RXJ1615, UX Tau A, RXJ1633, and SR 24s, the 3.3 cm radio emission is unresolved; see Figure 1. However, the radio emission is well centered at the position of the central young star; see Tables 1 and 2. None of these objects show a central depression, as in the case of LkCa15. This is probably due to the poor angular resolution of our radio observations as compared to that obtained with the Submillimeter Array observations (Andrews et al. 2011). There is a factor of about four between both angular resolutions. Deep 3.3 cm radio observations with the JVLA in the A configuration will help in resolving the emission at these wavelengths from the transitional disks, perhaps revealing the inner holes, as those mapped at submillimeter wavelengths.

In Table 3 we give the values of the flux densities from submillimeter to centimeter wavelengths of the five detected transitional disks that were compiled from the literature, the JVLA archive, and from our centimeter observations. From these data, we constructed the SEDs from the submillimeter to centimeter regimes, and found that they can be well fitted with a double or single power law. In order to fit the data, the error bars were calculated adding in quadrature systematic errors of the order of 5%–25% (which are typical observational flux uncertainties) to the formal flux uncertainties (obtained from a Gaussian fitting in our data) to obtain a reduced χ² = 1. We used a least-squares fitting.
routine to obtain these results. If a single power law failed to fit all data with the introduced errors of around 5%–25%, we then tried to use a two-component law to fit the centimeter and (sub)millimeter data separately. Here, we consider the centimeter regimen to have wavelengths > 1 cm.

The best cases for this single power-law fitting are UX Tau A and RXJ1633. However, for the latter case, we only found three flux measurements at these wavelengths; see Table 2 and Figure 3. For the cases of LkCa15, RXJ1615, and SR 24s, these can be fitted by a two-component power law; see Figure 3.
These two power laws fit the centimeter and submillimeter regimes.

4. DISCUSSION

In Figure 3, we have additionally included the SED of AB Aur (a transitional disk with a free–free jet) at these similar wavelengths (Rodríguez et al. 2014; see Figure 3). The SED of AB Aur has a two-component spectrum in which the centimeter emission is dominated by a slowly rising spectrum ($\alpha = 1.18$), which can be interpreted as moderately optically thick free–free emission (from a faint jet), while the millimeter and submillimeter emission is dominated by a component that rises rapidly with frequency ($\alpha = 2.88$), which is interpreted as thermal emission from optically thin dust; see Figure 3. This spectrum is very similar to that observed in LkCa15, RXJ1615, and SR 24s. This suggests that the centimeter emission from these three sources might be arising from a thermal free–free jet. However, as this radio emission is resolved in the case of LkCa15, and has a similar morphology to that of the transitional disk, then we propose that it is more likely the radio emission could come from a photo-evaporated disk in this case. Photoevaporation, together with viscous accretion, is expected to play an important role in the dispersal of protoplanetary disks (Macias et al. 2016). High energy radiation—i.e., UV and X-ray radiation—originating at the stellar chromosphere of low-mass stars can ionize and heat the disk surface, thus forming a photo evaporative wind (Gorti & Hollenbach 2009). For the cases of RXJ1615 and SR 24s, their radio emission is unresolved and it is not possible to discard if a thermal jet is present or if the photoevaporation is playing an important role in producing the radio emission.

For the cases of UX Tau A and RXJ1633, none of their spectra from the detected transitional disks has such a behavior and they can be well fitted by a single component. Such a single component, which rises rapidly with frequency, is produced by optically thin dust emission with approximately a Rayleigh–Jeans exponent from the transitional disks (Piétu et al. 2006; Hughes et al. 2009; Andrews et al. 2011). This is the case even at centimeter wavelengths for the two disks as our SEDs demonstrate. For pre-transitional or transitional disks it is expected to find inner holes at similar wavelengths. However, at the submillimeter regime, it is expected that the innermost parts of younger disks will be optically thick; see for example the case of the disk IRAS 16293–2422B (Zapata et al. 2013).

As the 3.3 cm continuum emission is arising from optically thin dust from the transitional disks in the cases of UX Tau A and RXJ1633—as it is shown by their SEDs at centimeter and submillimeter wavelengths—we then suggest that such a centimeter emission detected here is arising from the disk instead from a thermal free–free jet. The dust grains contained in the disks must then be larger than the ISM grains, probably with sizes of the order of some centimeters. The $\nu$-values of 2.22 and 2.54 found in their SEDs imply a $\beta$ (the power-law spectral index of the dust opacity with the form $\kappa_\nu = \nu^\beta$, where $\kappa$ is the dust opacity coefficient and $\nu$ is the frequency) less than unity, so grain growth should occur (Ricci et al. 2010; Ubach et al. 2012; Pinilla et al. 2014; Pérez et al. 2015). We would like to note again that as the emission from the transitional disks is mostly optically thin, then $\beta \lesssim 1$ might imply grain growth; see Canovas et al. (2015), Draine (2006), van der Marel et al. (2013), and Pinilla et al. (2015). This physical phenomenon is expected as the transitional disks are protoplanetary disks in an evolved stage, where the planet formation is supposedly occurring (Kim et al. 2013). However, we note that in addition to optically thick clumps in the disk, there are several factors that can influence $\beta$, e.g., porosity or grain size distribution. While ISM grains are characterized by a grain size distribution following a power law with index $p = 3.5$, the size distribution when grains grow up to large sizes is not well constrained; see for a review Draine (2006). We also note that the $\alpha$-values determined in this study for the (sub)millimeter regimen and shown in Figure 3 are well in agreement to the mean value reported in Pinilla et al. (2014) for a group of transitional disks.

Further sensitive observations with high angular resolution at these centimeter wavelengths might confirm the presence of two families of transitional disks. On one hand, there are disks like the ones reported in this study and in others (e.g., Pérez et al. 2015; UX Tau A, RXJ1633, and TW Hya, and CQ Tau) where the centimeter emission is arising from large grains located in the disks, and without the presence of a thermal radio jet or strong photoevaporation. On the other hand, there are objects like AB Aur, LkCa15, RXJ1615, and GM Aur with a transitional disk and with the presence of a faint ionized jet or photoevaporation. The SEDs and this kind of centimeter observations will help in discriminating between both cases. However, we speculate that these two populations of transitional disks might be explained as part of an evolutionary trend, where younger transitional disks still would have important accretion, generating the presence of ionized jets, i.e., AB and GM Aur-like objects. More cases where ionized jets are (or not) present in transitional disks could help in a better understanding of this tentative hypothesis.
5. CONCLUSIONS

The high sensitivity and angular resolution of the Karl G. J VLA observations allowed us to detect some of the classical transitional disks at these radio wavelengths. The main results of our work can be summarized as follows.

1. We report the detection of unresolved (with the exception of LkCa15) radio continuum emission in 5 out of the 10 disks. In the case of LkCa15, the radio emission is extended, and has a similar morphology to that of the millimeter transitional disk with an inner depression. We suggest that the centimeter emission is tracing a photoevaporating disk. For the rest of the disks, the unresolved radio emission peaks close to the position of the young star.
2. For these five detections, we construct the SEDs from centimeter to submillimeter wavelengths, and find that they can be well fitted with a single power law or with two power laws, with $\alpha$-values being flat or very steep.
3. Our results suggest that the emission detected at these centimeter wavelengths is likely produced by optically thin dust with large grains (i.e., centimeter-size pebbles) present in the transitional disks UX Tau A and RXJ1633, and from a thermal jet or a photoeaphorative wind in the cases of LkCa15, RXJ1615, and SR 24s.
4. We conclude that higher angular resolution JVLA observations, especially in the A configuration, and

![Figure 3. Spectral energy distributions (SEDs) of the detected transitional disks from the centimeter to (sub)millimeter wavelengths. The dashed lines are a least-squares power-law fit (of the form $S \propto \nu^{\alpha}$) to the spectrum. The $\alpha$-values of the fitting for the different components of the spectrum are shown in the panels. The data are presented in Table 3. The axis scales are the same for all objects, but only in the case of RXJ1633 is the scale in the y-axis different.](image-url)
maybe using the X or Ka bands are needed to resolve the radio emission present in the other four transitional disks (RXJ1615, UX Tau A, RXJ1633, and SR 24s). For the case of LkCa15, such observations will help in better tracing its morphology. This might help in testing our hypothesis that the centimeter emission is arising from large dust grains in the disks in the cases of UX Tau A and RXJ1633.

5. Our data suggest the possibility of having two populations of transitional disks, one with the presence of ionized jets and the other one without these jets. Radio images of a larger number of transitional disks may help in confirming this trend.

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