Radio Monitoring of Protoplanetary Discs

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ABSTRACT

Protoplanetary disc systems observed at radio wavelengths often show excess emission above that expected from a simple extrapolation of thermal dust emission observed at short millimetre wavelengths. Monitoring the emission at radio wavelengths can be used to help disentangle the physical mechanisms responsible for this excess, including free-free emission from a wind or jet, and chromospheric emission associated with stellar activity. We present new results from a radio monitoring survey conducted with Australia Telescope Compact Array over the course of several years with observation intervals spanning days, months and years, where the flux variability of 11 T Tauri stars in the Chamaeleon and Lupus star forming regions was measured at 7 and 15 mm and 3 and 6 cm. Results show that for most sources are variable to some degree at 7 mm, indicating the presence of emission mechanisms other than thermal dust in some sources. Additionally, evidence of grain growth to cm-sized pebbles was found for some sources that also have signs of variable flux at 7 mm. We conclude that multiple processes contributing to the emission are common in T Tauri stars at 7 mm and beyond, and that a detection at a single epoch at radio wavelengths should not be used to determine all processes contributing to the emission.

Key words: protoplanetary discs, star: variables: T Tauri, radio continuum: planetary systems, radiation mechanisms: thermal, non-thermal

1 INTRODUCTION

Signatures of cm-sized pebbles have been detected in protoplanetary discs by extending the relationship between the dust opacity index, $\beta$, and the 1 to 3 mm spectral slope, $\alpha$, to longer centimetre wavelengths (e.g. Testi et al. 2003; Rodmann et al. 2006; Wilner et al. 2005; Lommen et al. 2009). The results from this relationship ($\beta \sim \alpha - 2$) can indicate grain growth up to $3\lambda$ (where $\lambda$ is the observed wavelength) when $\beta < 1$, and limited to no grain growth (ISM sized grains) for $\beta > 1$, as long as the grain size $\ll \lambda$ (Draine 2006).

This approach assumes that the long wavelength emission follows the 1 to 3 mm emission, which is dominated by thermal dust emission and is constant over time, which is not always the case at longer wavelengths (e.g. Lommen et al. 2010; Ubach et al. 2012).

A dozen protoplanetary discs show a “break” in the spectral slope near 7 mm, with a shallower spectral slope at longer wavelengths (Rodmann et al. 2006; Lommen et al. 2009, 2010; Ubach et al. 2012). This “break” has been attributed to emission mechanisms related to ionized plasma, adding to the emission from thermal dust in these discs. This excess emission at long millimetre wavelengths could be caused by either thermal free-free emission from an ionised wind or by non-thermal processes such as chromospheric emission from the young star, or a combination of both. At 7 mm, both thermal dust emission and thermal free-free emission from an ionised wind have been detected in young stellar objects (e.g. Rodmann et al. 2006; Lommen et al. 2009), while variable emission at 3 and 6 cm has been used to demonstrate a combination of all three emission mechanisms (e.g. Lommen et al. 2009).

Temporal monitoring of the disc emission has been used to disentangle these three emission mechanisms (Lommen et al. 2009; Ubach et al. 2012). Flux originating from thermal dust emission is generally assumed to be constant over time, whereas the flux from thermal free-free and non-thermal emission may be temporally variable. Thermal free-free emission can vary by a factor of $\sim 20$–$40$ per cent over a timescale measured in years.
2 Observations and Data Reduction

This survey targeted 11 T Tauri stars in the Chamaeleon and Lupus star forming regions – see Table 1. The sources were selected to overlap with the Lommen et al. (2009, 2010) and Ubach et al. (2012) samples, maximising the number of sources and increasing the monitoring baseline to years – see Tables A1 and A2.

Continuum observations were conducted with Australia Telescope Compact Array (ATCA) during the winter 2012 season. Three compact hybrid array configurations were used, providing synthesized beams between 5 to 15 arcsec at 7 mm, corresponding to ~0.8 to ~2400 au assuming a distance of 160 pc to the sources. The two CABB\(^1\) intermediate frequency bands were divided into 2048 channels of 1 MHz width.

All targets were observed with frequency pairs centred at 43 + 45 GHz (7 mm band), five targets\(^2\) at 17 + 19 GHz (15 mm band) and three targets at 5.5 + 9.9 GHz (6 and 3 cm bands, respectively). The mm frequency bands setup provided a 4 GHz wide band with an expected RMS of 0.1 and 0.03 mJy for 30 minutes on source for the 7 and 15 mm bands, respectively. The 3 and 6 mm bands were 2 GHz wide with an expected RMS of 0.027 and 0.034 mJy for 30 minutes on source, respectively. In total this survey covered frequencies ranging from 4.5 to 46 GHz.

QSO B1057-79 and QSO B1600-44 were used as gain calibrators for Chamaeleon and Lupus, respectively. For all the observations the absolute flux calibration was performed using PKS 1934-638. Weather conditions were good throughout the observations. Due to poor u-v coverage at the longer baselines when using the compact hybrid arrays, and given that fluxes rather than images were the required data products, antenna 6 was not included in the data processing and analysis.

The data calibration followed the standard CABB procedure described in the ATCA user guide\(^3\) for all wavelengths using the software package MIRIAD version 1.5 (Sault et al. 1995). In order to determine the source fluxes, we used a point source fit. To ensure that this was appropriate, we checked the visibility amplitudes were constant over u-v distance for all 11 sources at each epoch.

For this analysis, the data from each day at each frequency was calibrated separately and then the frequency pairs were combined. The flux (from the point source fit) and RMS values for all observations were then extracted from the visibilities using UVFIT and UVRMS.

1 Compact Array Broadband Backend (Wilson et al. 2011).
2 Only two of the sources have previous 15 mm observations.
3 http://www.narrabri.atnf.csiro.au/observing/users_guide/html/atug.html For specific data reduction procedure see Ubach (2014).

3 Results and Discussion

A summary of the continuum fluxes for the combined frequency pairs are presented in Table 2, complemented with fluxes obtained from literature. The detection rates for the sources observed in this study are as follows: 9/11 sources were detected at 7 mm, 3/5 at 15 mm\(^4\), and 0/3 sources at both 3 cm and 6 cm. A 3σ upper limit is provided for non-detections.

We present in Figure 1 both the spectrum, or radio flux as a function of wavelength (left), and the 7 mm flux versus time (right) for the 11 sources in our survey. Detections are denoted by a star symbol and upper limits by an arrow. Error bars include the uncertainty in the flux fit, as well as the primary flux calibration uncertainties of 20 per cent for 1.2 mm, 30 per cent for 3 mm, and 10 per cent for 7 mm, 15 mm, 3 cm and 6 cm. In the spectrum plots, the red solid line represents the estimated emission due to thermal dust, which was fit using the least squares method between the 1 mm and 3 mm fluxes and extrapolating this spectral slope, \(\alpha\), to longer wavelengths. Fluxes at 1 and 3 mm were taken from Ubach et al. (2012) and references therein. The estimated 7 mm thermal dust component, \(F_{\text{7mm}}(\text{therm})\), is denoted by a green diamond. The grey shaded area represents the region of uncertainty in the spectral slope using standard quadratic error propagation. If we take a ‘slice’ through the radio spectrum at 7 mm, and plot each observed 44 GHz flux against time (as presented in Table 2), this gives us the temporal monitoring plots on the right. Here the grey region is the same as in the spectrum plot, and represents the uncertainty of the extrapolation of the 7 mm thermal flux estimate, \(F_{\text{7mm}}(\text{therm})\), which is now represented by a green line. We will use both of these plots to help understand the emission processes in each system.

3.1 Temporal monitoring

The aim of our temporal monitoring campaign is to try and disentangle the different physical processes contributing to the radio emission in this sample of T Tauri stars. While a number of millimetre and centimetre surveys of YSOs have been conducted (e.g. Henning et al. 1993; Andrews & Williams 2007), few monitoring surveys have been carried out due to their intense resources requirement. Given that YSOs are inherently variable (e.g. Herbdt et al. 1994), flux monitoring on timescales of a day, weeks and years are required to understand the contributing processes to their emission. Here we compare fluxes obtained from a few days apart to 100s of days apart, as presented in Table 2.

From our previous observations (Ubach et al. 2012), our sample could be divided into two distinct groups: (i) those with a constant spectral slope from 1-7 mm (CS Cha, Glass I, SZ Cha, WW Cha, MY Lup, Sz 111, GQ Lup), and (ii) those with a “break” in the mm spectral slope at 7 mm (CR Cha, DI Cha, T Cha and Sz 32). This “break” is an indication that other forms of emission at 7 mm are present in addition to thermal dust emission. In Ubach et al. (2012) a least squares fit was used to determine the spectral slope between 1 and 3 mm, \(\alpha\), and extrapolated to 7 mm to estimate the thermal dust component \(F_{\text{7mm}}(\text{therm})\). Table 3 presents the estimated thermal dust emission at 7 mm, the maximum observed 7 mm flux, \(F_{\text{7mm}}(\text{max})\), and the fractional 7 mm excess, given by \((F_{\text{7mm}}(\text{max}) - F_{\text{7mm}}(\text{therm}))/F_{\text{7mm}}(\text{therm})\), for this sample of 11 protoplanetary discs.

4 See Table B1 for results of sources observed at 15 mm with no previously reported 15 mm fluxes.
Using a combination of the spectrum and the temporal monitoring plots in Figure 1, along with the data in Table 3, we can start to understand the degree and potential source of variability in each system. If we start with the (crude) fractional 7 mm excess, we can place the 11 sources into three groups: those with high to extreme fractional excesses above 1.5; those with a moderate fractional excess between 0.5–1.0; and those with a small fractional excess less than 0.5.

Of the high to extreme 7 mm fractional excess sources, we can see that CR Cha and DI Cha have excesses of order 2 above expected thermal dust, while T Cha and Sz 32 have much larger excesses of order 4–5. Looking at the radio spectrum of the two most extreme sources, we can clearly see a break in the spectral slope at 7 mm, excess emission and flux variability in T Cha and Sz 32. Their 7 mm temporal monitoring plots show fluxes well in excess of that estimated for thermal dust, i.e. the observed fluxes are outside of the grey regions of the plots. Over the 3 year period of almost 1.3 years, and all three fluxes are consistent within the flux fit errors – see Figure 2. While not exactly simultaneous, the two 7 mm and 15 mm observations that were made about 470 days apart give consistent (non-varying) fluxes in both bands.

There have been many observations of WW Cha – see Table C1 for a summary. In Table 2 we present just the 44, 18, 9.9 and 5.5 GHz observations for the sources in our survey, while as it can be seen in Table C1, WW Cha has been observed at various wavelengths in the 7 mm, 15 mm and 3 & 6 cm bands. In the spectrum of WW Cha in Figure 1 we present all the data from Table C1, with the red inverted triangles representing detections and upper limits obtained by Lommen et al. (2009). The 7 mm monitoring data shows only the 44 GHz data for consistency. The cm-band data clearly shows a lot of variability, by factors of 2–4, and the two 7 mm fluxes taken 3.2 years apart vary by a factor of 2.3. With the radio monitoring data to date, it appears that Sz 111 and GQ Lup are dominated by thermal dust emission, though there is variability at 7 mm in GQ Lup. WW Cha likely has a mix of thermal dust, thermal free-free emission and non-thermal processes contributing to the radio emission.

The sources with low fractional excess include CS Cha and Glass I. Once again, none show a break in their spectral slope at 7 mm, and their 7 mm fluxes all lie within the region of uncertainty of the extrapolated 7 mm thermal dust emission. Glass I vary by a factor of 2.3 and 2 over 3.2 years. CS Cha varies by about a factor of 3 over 3 months. This magnitude of variability for Glass I and CS Cha suggests that the non-thermal emission as well as thermal dust contribute to the overall emission.

Finally, we find that just three sources in our sample, SZ Cha, Sz 111 and MY Lup, have no observed variability at 7 mm over a timescale of 100s of days, suggesting that the detected continuum flux emission is due to thermal dust emission, whereas all other sources exhibit flux variability on the time scale of months to years of at least 30 per cent and up to a factor of 3 at 7 mm is observed, which provides evidence of the presence of excess emission from mechanisms other than thermal dust emission. However, the 7 mm fluxes for these three sources are also lower than expected from spectral fit. This perhaps is indicative that the calculated $\alpha$ is too shallow. This appears to be supported by the lower 15 mm fluxes in

| Source   | RA (J2000) | DEC (J2000) | Cloud     | Distances (pc) | $T_{\text{eff}}$ (K) | Wavelengths (mm) |
|----------|------------|-------------|-----------|----------------|----------------------|------------------|
| CR Cha   | 10 59 06.9 | -77 01 39.7 | Cha I     | 160            | 4900                 | 7                |
| CS Cha   | 11 02 24.9 | -77 33 35.9 | Cha I     | 160            | 4205                 | 7,15             |
| DI Cha   | 11 07 21.6 | -77 38 12.0 | Cha I     | 160            | 8560                 | 7                |
| T Cha    | 11 57 13.6 | -79 21 31.7 | Isolated  | 100            | 5600                 | 7,30,60          |
| Glass I  | 11 08 15.1 | -77 33 59.0 | Cha I     | 160            | 5630                 | 7                |
| SZ Cha   | 10 58 16.7 | -77 17 17.1 | Cha I     | 160            | 5250                 | 7,15             |
| Sz 32    | 11 09 53.4 | -76 34 25.5 | Cha I     | 160            | 4350                 | 7,30,60          |
| WW Cha   | 11 10 00.1 | -76 34 57.9 | Cha I     | 160            | 4350                 | 7,30,60          |
| Lupus    |             |             |           |                |                      |                  |
| Sz 111   | 16 08 54.7 | -39 37 43.1 | Lupus 4   | 200            | 3573                 | 7,15             |
| MY Lup   | 16 00 44.6 | -41 55 29.6 | Lupus 3   | 165            | 5248                 | 7,15             |
| GQ Lup   | 15 49 12.1 | -35 39 03.9 | Lupus 1   | 156            | 4300                 | 7,15             |

Distances and effective temperatures taken from: (1) Whittet et al. (1997), (2) van den Ancker et al. (1998), (3) Luhman (2004), (4) Hughes et al. (1994), (5) Comerón (2008), (6) Neuhauser et al. (2008), (7) Donati et al. (2012).

$^a$ Binary separations of $\leq 1''$, 4.6", 2.5" for CS Cha, DI Cha and Glass I, respectively (Guenther et al. 2007; Ghez et al. 1997; Feigelson & Kriss 1989).

5 Note that the fractional 7 mm excess presented in Table 3 does not take into consideration the errors in the estimated 7 mm thermal dust emission, and so can only be considered a very crude measure of any emission excess above thermal dust.
Table 2. Summary of the temporal monitoring results at 7 and 15 mm and 3 and 6 cm for our sample of 11 T Tauri stars. (1) Source name. (2) Julian date of the observation. (3) Time from previous observation in days. (4) Combined frequency. (5) Point flux (3σ upper limit for non-detections). (6) RMS. (7) Reference. See Table B1 for new 15 mm observations of sources with no previously reported 15 mm fluxes.

| Source   | Julian date | Time from prev. obs. (days) | Freq. (GHz) | Flux (mJy) | RMS (mJy/Beam) | Reference       |
|----------|-------------|------------------------------|-------------|------------|----------------|----------------|
| CR Cha   | 2454980     | 44                           | 1.7 ± 0.1   | 0.1        | 0.1            | Ubach et al. (2012) |
|          | 2456143     | 1163                         | 44          | 1.3 ± 0.2  | 0.1            | This work       |
| CS Cha   | 2454583     | 94                           | 1.00 ± 0.28 | 0.129      | 0.128          | Lommen et al. (2009) |
|          | 2454677     | 44                           | < 0.71      | 0.238      | 0.238          | Lommen et al. (2009) |
|          | 2454678     | 44                           | 1.38 ± 0.26 | 0.218      | 0.218          | Lommen et al. (2009) |
|          | 2454980     | 302                          | 1.5 ± 0.1   | 0.1        | 0.1            | Ubach et al. (2012) |
|          | 2456143     | 1163                         | 44          | 1.5 ± 0.2  | 0.1            | This work       |
|          | 2456223     | 81                           | 0.6 ± 0.1   | 0.3        | 0.3            | This work       |
|          | 2455753     | 18                           | < 0.3       | 0.1        | 0.1            | Ubach et al. (2012) |
|          | 2456315     | 378                          | 0.20 ± 0.02 | 0.03       | 0.03           | This work       |
| DI Cha   | 2454980     | 44                           | 0.9 ± 0.1   | 0.1        | 0.1            | Ubach et al. (2012) |
|          | 2456143     | 1163                         | 44          | < 0.2      | 0.1            | This work       |
| T Cha    | 2454980     | 44                           | 3.0 ± 0.1   | 0.1        | 0.1            | Ubach et al. (2012) |
|          | 2456143     | 1163                         | 44          | 4.1 ± 0.2  | 0.1            | This work       |
|          | 2455761     | 9.9                          | < 0.3       | 0.1        | 0.1            | Ubach et al. (2012) |
|          | 2456123     | 363                          | 9.9         | < 0.15     | 0.05           | This work       |
|          | 2455761     | 5.5                          | 0.3 ± 0.1   | 0.1        | 0.1            | Ubach et al. (2012) |
|          | 2456123     | 363                          | 5.5         | < 0.2      | 0.08           | This work       |
| Glass I  | 2454980     | 44                           | 0.6 ± 0.2   | 0.1        | 0.1            | Ubach et al. (2012) |
|          | 2456143     | 1163                         | 44          | < 0.3      | 0.1            | This work       |
| SZ Cha   | 2454980     | 44                           | 0.7 ± 0.1   | 0.1        | 0.1            | Ubach et al. (2012) |
|          | 2456143     | 1163                         | 44          | 0.6 ± 0.1  | 0.1            | This work       |
|          | 2456223     | 81                           | 44          | < 0.3      | 0.1            | This work       |
| Sz 32    | 2454558     | 44                           | 0.8 ± 0.1   | 0.2        | 0.2            | Lommen et al. (2009) |
|          | 2454980     | 44                           | 1.2 ± 0.1   | 0.2        | 0.2            | Ubach et al. (2012) |
|          | 2456143     | 1163                         | 44          | 0.5 ± 0.2  | 0.1            | This work       |
|          | 2455761     | 9.9                          | < 0.3       | 0.1        | 0.1            | Ubach et al. (2012) |
|          | 2456123     | 363                          | 9.9         | < 0.15     | 0.05           | This work       |
|          | 2455761     | 5.5                          | < 0.3       | 0.1        | 0.1            | Ubach et al. (2012) |
|          | 2456123     | 363                          | 5.5         | < 0.1      | 0.04           | This work       |
| WW Cha   | 2454980     | 44                           | 9.1 ± 0.35  | 0.2        | 0.2            | Ubach et al. (2012) |
|          | 2456143     | 1163                         | 44          | 3.9 ± 0.2  | 0.1            | This work       |
|          | 2455761     | 9.9                          | < 0.3       | 0.1        | 0.1            | Ubach et al. (2012) |
|          | 2456123     | 363                          | 9.9         | < 0.15     | 0.05           | This work       |
|          | 2455761     | 5.5                          | < 0.45      | 0.1        | 0.1            | Ubach et al. (2012) |
|          | 2456123     | 363                          | 5.5         | < 0.12     | 0.04           | This work       |
| Sz 111   | 2454680     | 44                           | < 0.6       | 0.2        | 0.2            | Lommen et al. (2010) |
|          | 2454980     | 300                          | 44          | 0.5 ± 0.1  | 0.1            | Ubach et al. (2012) |
|          | 2456143     | 1163                         | 44          | 0.6 ± 0.2  | 0.1            | This work       |
|          | 2456223     | 81                           | 44          | 0.4 ± 0.1  | 0.03           | This work       |
| MY Lup   | 2454680     | 45                           | 1.3         | 0.1        | 0.1            | Lommen et al. (2010) |
|          | 2454980     | 300                          | 44          | 1.1 ± 0.1  | 0.1            | Ubach et al. (2012) |
|          | 2456143     | 1163                         | 44          | 1.0 ± 0.2  | 0.1            | This work       |
|          | 2456223     | 81                           | 44          | 1.2 ± 0.2  | 0.03           | This work       |
| GQ Lup   | 2455430     | 44                           | 0.6 ± 0.1   | 0.04       | 0.04           | Ubach et al. (2012) |
|          | 2455753     | 44                           | 0.6 ± 0.3   | 0.07       | 0.07           | Ubach et al. (2012) |
|          | 2456144     | 391                          | 1.2 ± 0.1   | 0.05       | 0.05           | This work       |
|          | 2456223     | 79                           | 44          | 0.5 ± 0.1  | 0.04           | This work       |
|          | 2455751     | 18                           | 0.07 ± 0.03 | 0.01       | 0.01           | Ubach (2014)    |
|          | 2455761     | 10                           | 0.08 ± 0.04 | 0.02       | 0.02           | Ubach (2014)    |
|          | 2456223     | 462                          | 18          | < 0.09     | 0.03           | This work       |

Sz 111 and MY Lup. This survey highlights the significance of flux monitoring over multiple timescales, for one flux detection will not always be a good indication of a pure thermal dust emission source at 7 mm and beyond.

3.2 Grain growth

For this sample of 11 protoplanetary discs, the two sources with no detected flux variability at 7 mm, MY Lup and Sz 111, also have $\alpha < 3$. The four sources with high to extreme 7 mm fractional excess all have $\alpha > 3$, while all sources with moderate to low fractional excess—with the exception of Glass I—have $\alpha < 3$.
Figure 1. Radio spectrum (left) and temporal flux monitoring (right) for each source in the survey. Detections are denoted by a star and upper limits by an arrow. Errors bars include the flux fit uncertainty and primary flux calibration uncertainties. The red solid line in the spectrum (left) represents the 1–3 mm spectral slope $\alpha$, the red dashed line the expected $\alpha_{\text{ff}} = -0.6$, and the grey shaded area represents the region of uncertainty in the estimated thermal dust emission from standard error propagation in the spectral slope calculation. The green diamond (left) and green line (right) correspond to the estimated thermal dust emission at 7 mm. Continued on the next page.
Applying the simplified Draine (2006) relationship of $\beta \sim \alpha - 2$, our results suggest that the majority of the sources have $\beta < 1$, indicative of grain growth up to cm sizes, and the four most active sources with clear signs of excess emission above thermal dust have $\beta > 1$, suggesting little grain growth. These results show that both variability and evidence for grain growth can be present for the same protoplanetary disc, but that grain growth appears inhibited in the most active sources, at least for this small sample.

### 3.3 Excess emission at millimetre wavelengths

We have thus far determined that the presence of emission mechanisms other than thermal dust emission at 7 mm is common in protoplanetary discs, and that signatures of grain growth can be found in sources with and without 7 mm flux variability. The 7 mm flux variability of $\sim 30$ per cent over a period of 100s of days is consistent with the characteristics of thermal free-free emission. The presence of flux variability has also been detected at other wavelengths, such as in the X-ray, optical, and in the near-infrared (NIR).

All the sources in our sample (with the exception of MY Lup and Sz 111) have been detected in the X-ray with a $\log (L_x/L_{bol})$ between $-3$ and $-4$, classifying these stars as X-ray active (e.g. Stelzer et al. 2004; Feigelson & Lawson 2004). A few sources in our sample have been studied more closely in the literature. Using the XMM-Newton observations of CR Cha, Robrade & Schmitt (2006) detected a small flare and flux variability consistent with coronal activity and the presence of accretion. CS Cha, T Cha and GQ Lup were included in Giedel et al. (2010) analyses of Spitzer [Ne II] line and XMM-Newton archive data, where they classified CS Cha as a jet-driving object with a transitional disc, T Cha as a transitional disc and GQ Lup as an optically thick disc without a known jet. Similarly, X-ray flares have also been detected for Sz 32 and WW Cha (Feigelson & Lawson 2004). It is interesting to note that sources with flux variability at mm wavelengths are also variable in the X-ray; specifically the sources with high amplitude variability in the radio (CS Cha, GQ Lup, Sz 32, WW Cha) are also very active in the X-ray. This suggests that the cause of the variability could be the same at both wavelengths. Simultaneous observations at both wavelengths would be needed to confirm this relationship.

Flux variability of up to 20 per cent is commonly found in young stellar objects in the optical and NIR wavebands (Scholz 2012; Rodgers-Lee et al. 2014). This variability can be caused by hot spots created by an accretion shock, variable circumstellar extinction, or a combination of these processes (Scholz 2012). Although variability above 20 per cent in the optical and NIR is rare, it has been documented. Additional optical images in the R and I bands and NIR images in the J and K bands have provided evidence that Sz 32 is variable at these wavelengths by more than the expected 20 per cent (Rodgers-Lee et al. 2014). The cause of the additional flux variability is still under investigation.

### 4 CONCLUSIONS

We present a radio flux monitoring survey of 11 T Tauri stars in the Chamaeleon and Lupus Southern star forming regions over timescales of 100s of days. We found that the 7 mm flux varies by at least 30 per cent and up to a factor of 3 for most sources, indicating that processes other than just thermal dust are contributing to the emission. Flux monitoring of CS Cha and GQ Lup at 15 mm over the course of a year found consistent fluxes, suggesting no variability over these timescales for these observations. Monitoring of T Cha, Sz 32 and WW Cha at 3 cm and 6 cm also suggests excess emission above thermal dust. From our analysis of the radio spectrum and flux monitoring, only two sources show no variability and seem to be dominated by thermal dust emission: Sz 111 and MY Lup.

Additionally, we looked at the flux variability in the X-ray, optical and near-infrared wavelengths, and found further support for the need for multiple epoch and multi-wavelength observations to determine the cause of the flux variability.

We found seven sources with $\beta < 1$, indicative of grain growth up to centimetre sized grains and four sources with a $\beta > 1$, suggesting little to no grain growth. These results, with the exception of Sz 32, are consistent with reported values for spectral slope from 1–3 mm. Of the seven sources with signatures of grain growth, only CR Cha and MY Lup have no reported 7 mm flux variability. Thus, these results show that both signatures of grain growth and evidence of other emission mechanism at 7 mm may be present for the same protoplanetary disc.

In the near future, the high resolution and sensitivity of Atacama Large Millimeter/Submillimeter Array (ALMA) will play an important role in answering these questions by significantly reducing the uncertainties in the 1 mm fluxes for the Chamaeleon sources, and thus reducing the uncertainties in the 1–3 mm spec...
tral slope and $\beta$ values, and providing a better understanding of the signatures of grain growth in these protoplanetary discs.

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**Figure 1.** Continued.
Figure 2. The 15 mm continuum fluxes for GQ Lup plotted from the first recorded epoch. The error bars represented the flux uncertainties. No flux variability was observed over a year timescale, suggesting the emission detected is primarily from thermal dust. The green diamond symbol/line correspond to the thermal dust emission component of the fluxes at 15 mm, error bars are the uncertainties for the estimated value. Continued in the next page.
Table A1. ATCA observing log for Lupus sources from this work and literature. (1) Source name. (2) Date of observations. (3) Frequency pair. (4) Flux calibrator. (5) ATCA array configuration. (6) Synthesized beam size. (7) Total integration time used for analysis. (8) RMS. (9) Reference.

| Source | Date       | Freq. Pair (GHz) | Flux Cal. | Antenna(s) | Beam size | $T_{\text{int}}$ (min) | RMS (mJy/Beam) | Reference                  |
|--------|------------|------------------|-----------|------------|-----------|-------------------------|----------------|----------------------------|
| Sz 111 | Aug-08     | 43+45            | Uranus    | H214       | 4.0       | 0.2                     | Lommen et al. (2010) |
|        | Mar-09     | 43+45            | Uranus    | H214       | 5.2 x 3.5 | 60                      | 0.1            | Ubach et al. (2012)        |
|        | Aug-12     | 43+45            | PKS B1934-638 | H75       | 14.6 x 10.3 | 60                      | 0.1            | This work                  |
|        | Oct-12     | 43+45            | PKS B1934-638 | H214       | 5.0 x 3.6 | 60                      | 0.03           | This work                  |
|        | Oct-12     | 17+19            | PKS B1934-638 | H214       | 13.1 x 9.8 | 90                      | 0.02           | This work                  |
| MY Lup | Aug-08     | 44.2+46.2        | Uranus    | H214       | 4.0       | 0.1                     | Lommen et al. (2010) |
|        | May-09     | 43+45            | Uranus    | H214       | 4.8 x 3.4 | 50                      | 0.1            | Ubach et al. (2012)        |
|        | Aug-12     | 43+45            | PKS B1934-638 | H75       | 14.8 x 10.5 | 50                      | 0.1            | This work                  |
|        | Oct-12     | 43+45            | PKS B1934-638 | H214       | 4.7 x 3.4 | 80                      | 0.03           | This work                  |
|        | Oct-12     | 17+19            | PKS B1934-638 | H214       | 13.6 x 9.7 | 40                      | 0.02           | This work                  |
| GQ Lup | 21-Aug-10  | 43+45            | Uranus    | H168       | 6.7 x 4.4 | 80                      | 0.04           | Ubach et al. (2012)        |
|        | 10-Jul-11  | 43+45            | Uranus    | H214       | 6.8 x 3.6 | 18                      | 0.07           | Ubach et al. (2012)        |
|        | 4-Aug-12   | 43+45            | PKS B1934-638 | H75       | 22.2 x 9.2 | 53                      | 0.05           | This work                  |
|        | 22-Oct-12  | 43+45            | PKS B1934-638 | H214       | 5.0 x 3.6 | 30                      | 0.04           | This work                  |
|        | 8-Jul-11   | 17+19            | PKS B1934-638 | H214       | 18.3 x 9.7 | 24                      | 0.01           | Ubach (2014)               |
|        | 18-Jul-11  | 17+19            | PKS B1934-638 | H214       | 17.8 x 9.1 | 20                      | 0.02           | Ubach (2014)               |
|        | 22-Oct-12  | 17+19            | PKS B1934-638 | H214       | 13.2 x 9.4 | 30                      | 0.03           | This work                  |
Table A2. ATCA observing log for Chamaeleon sources from this work and the literature. (1) Source name. (2) Date of observation. (3) Frequency pair. (4) Flux calibrator. (5) ATCA array configuration. (6) Synthesized beam size. (7) Total integration time used for analysis. (8) RMS. (9) Reference.

| Source | Date       | Freq. Pair (GHz) | Flux Caliber | Antenna(s) | Beam size (arcsec) | T_{int} (min) | RMS (mJy/Beam) | Reference |
|--------|------------|------------------|--------------|------------|--------------------|---------------|----------------|-----------|
| CR Cha | May-09     | 43+45            | Uranus       | H214       | 5.0 × 4.3          | 80            | 0.1            | Ubach et al. (2012) |
|        | Aug-12     | 43+45            | PKS B1934-638 | H75       | 16.3 × 10.6        | 20            | 0.1            | This work |
| CS Cha | 26-Apr-08  | 43+45            | PKS B1921-293 | 6A        | 2.4 × 1.4          | 413           | 0.1            | Lommen et al. (2009) |
|        | 05-Jul-08  | 43+45            | Uranus       | 1.5B       | 11.3 × 0.6         | 49            | 0.2            | Lommen et al. (2009) |
|        | 06-Jul-08  | 43+45            | Uranus       | 1.5B       | 4.5 × 0.6          | 103           | 0.2            | Lommen et al. (2009) |
|        | May-09     | 43+45            | Uranus       | H214       | 5.0 × 4.3          | 80            | 0.1            | Ubach et al. (2012) |
|        | Aug-12     | 43+45            | PKS B1934-638 | H75       | 15.9 × 10.3        | 20            | 0.1            | This work |
|        | Oct-12     | 43+45            | PKS B1934-638 | H214       | 5.4 × 4.1          | 80            | 0.3            | This work |
|        | Jul-11     | 17+19            | PKS B1934-638 | H214       | 15.5 × 12.6        | 105           | 0.1            | Ubach et al. (2012) |
|        | Oct-12     | 17+19            | PKS B1934-638 | H214       | 13.9 × 11.4        | 126           | 0.03           | This work |
| DI Cha | May-09     | 43+45            | Uranus       | H214       | 4.8 × 4.2          | 100           | 0.1            | Ubach et al. (2012) |
|        | Aug-12     | 43+45            | PKS B1934-638 | H75       | 13.8 × 10.7        | 30            | 0.1            | This work |
| T Cha  | May-09     | 43+45            | Uranus       | H214       | 5.1 × 4.1          | 60            | 0.1            | Ubach et al. (2012) |
|        | Aug-12     | 43+45            | PKS B1934-638 | H75       | 17.0 × 10.4        | 30            | 0.1            | This work |
|        | Jul-11     | 9                | PKS B1934-638 | H214       | 3.2 × 1.1          | 170           | 0.1            | Ubach et al. (2012) |
|        | Jul-12     | 9                | PKS B1934-638 | H168       | 5.3 × 1.1          | 20            | 0.05           | This work |
|        | Jul-11     | 5.5              | PKS B1934-638 | H214       | 3.4 × 1.9          | 170           | 0.1            | Ubach et al. (2012) |
|        | Jul-12     | 5.5              | PKS B1934-638 | H168       | 8.9 × 1.7          | 20            | 0.08           | This work |
| Glass I | May-09    | 43+45            | Uranus       | H214       | 4.9 × 4.1          | 150           | 0.1            | Ubach et al. (2012) |
|        | Aug-12     | 43+45            | PKS B1934-638 | H75       | 14.0 × 11.4        | 30            | 0.1            | This work |
|        | Oct-12     | 43+45            | PKS B1934-638 | H214       | 5.4 × 4.0          | 100           | 0.1            | This work |
|        | Oct-12     | 17+19            | PKS B1934-638 | H214       | 13.7 × 11.3        | 160           | 0.02           | This work |
| Sz. 32 | 31-Mar-08  | 43+45            | QSO B1057-797 | H168       | 5.8 × 5.3          | 119           | 0.2            | Lommen et al. (2010) |
| May-09 | 44+45      | Uranus           | H214         | 5.0 × 4.0  | 130               | 0.2           | Ubach et al. (2012) |
| Aug-12 | 43+45      | PKS B1934-638    | H75          | 14.6 × 11.3 | 20               | 0.1           | This work |
| Jul-11 | 9          | PKS B1934-638    | H214         | 2.4 × 1.8  | 125               | 0.1           | Ubach et al. (2012) |
| Jul-12 | 9          | PKS B1934-638    | H168         | 1.5 × 1.0  | 20                | 0.05          | This work |
| Jul-11 | 5.5        | PKS B1934-638    | H214         | 3.2 × 2.0  | 125               | 0.1           | Ubach et al. (2012) |
| Jul-12 | 5.5        | PKS B1934-638    | H168         | 3.3 × 1.7  | 20                | 0.04          | This work |
| WW Cha | May-09    | 43+45            | Uranus       | H215       | 5.0 × 4.0          | 130           | 0.2            | Ubach et al. (2012) |
|        | Aug-12     | 43+45            | PKS B1934-638 | H75       | 17.4 × 10.6        | 20            | 0.1            | This work |
| Jul-11* | 9          | PKS B1934-638    | EW352        | 2.4 × 1.8  | 125               | 0.1           | Ubach (2014) |
| Jul-12* | 9          | PKS B1934-638    | EW352        | H168       | 1.5 × 1.0          | 20            | 0.05           | This work |
| Jul-11* | 5.5        | PKS B1934-638    | EW352        | H168       | 3.2 × 2.0          | 125           | 0.1           | Ubach (2014) |
| Jul-12* | 5.5        | PKS B1934-638    | EW352        | H168       | 3.3 × 1.7          | 20            | 0.04           | This work |

* WW Cha was not the primary target but was in the field of Sz. 32.

Table B1. Summary of single 15 mm band observations. (1) Source name. (2) Date of observation. (3) Total integration time used to determine flux. (4) Combined frequency. (5) Point flux (3σ upper limit for non-detections). (6) RMS. (7) Beam size. (8) ATCA array configuration.

| Source | Date       | T_{int} (minutes) | Freq. (GHz) | Flux (mJy) | RMS (mJy/beam) | Beam size (arcsecs) | Array Config. |
|--------|------------|-------------------|-------------|------------|----------------|---------------------|---------------|
| SZ Cha | Oct-12     | 160               | 18          | 0.14 ± 0.03 | 0.02           | 13.7 × 11.3         | H214          |
| Sz 111 | Oct-12     | 90                | 18          | 0.08 ± 0.02 | 0.02           | 13.1 × 9.8          | H214          |
| MY Lup | Oct-12     | 40                | 18          | < 0.06     | 0.02           | 13.6 × 9.7          | H214          |
Table C1. Summary of results for WW Cha monitoring. (1) Source name. (2) Observation date. (3) Total integration time used to determine flux. (4) Frequency. (5) Point flux ($3\sigma$ for non-detections). (6) RMS. (7) Beam size. (8) ATCA array configuration. (9) References.

| Source | Date  | $T_{\text{inst}}$ (minutes) | Freq. (GHz) | Flux (mJy) | RMS (mJy/beam) | Beam size (arcsecs) | Array Config | References |
|--------|-------|----------------------------|-------------|------------|----------------|---------------------|--------------|------------|
| WW Cha | 5 Oct 2007 | 81.0 | 40.8 | 3.93±0.29 | 0.35 | 11×11 | H75C | Lommen et al. (2007) |
|        | 31 Mar 2008 | 119.4 | 40.8 | 5.19±0.17 | 0.194 | 6.1×5.6 | H168 | Lommen et al. (2007) |
|        | 5 Oct 2007 | 81.0 | 42.5 | 5.41±0.32 | 0.313 | 11×11 | H75C | Lommen et al. (2007) |
|        | 31 Mar 2008 | 119.4 | 42.5 | 5.10±0.17 | 0.231 | 5.8×5.3 | H168 | Lommen et al. (2007) |
|        | May-09 | 130 | 44 | 3.4±0.1 | 0.2 | 5.0×4.0 | H215 | Ubach et al. (2012) |
|        | Aug-12 | 20.0 | 44 | 3.9±0.2 | 0.1 | 17.4×10.6 | H75 | This work |
|        | Jul-11 | 70.0 | 18 | 0.75±0.02 | 0.1 | 15.6×12.3 | H214 | Ubach et al. (2012) |
|        | 8 May 2006 | 48.0 | 18.4 | 1.04±0.30 | 0.158 | 23×6 | H214C | Lommen et al. (2007) |
|        | 13 Oct 2006 | 78.6 | 18.4 | 1.08±0.21 | 0.217 | 26×9 | H214C | Lommen et al. (2007) |
|        | 18 Oct 2006 | 199.2 | 18.4 | 1.23±0.19 | 0.11 | 39×7 | EW352 | Lommen et al. (2007) |
|        | 24 Oct 2007 | 189.0 | 18.4 | 0.95±0.13 | 0.181 | 13×9 | H214C | Lommen et al. (2007) |
|        | 2 Nov 2007 | 508.8 | 18.4 | 0.48±0.130 | 0.089 | 2.0×1.4 | 1.5A | Lommen et al. (2007) |
|        | 31 Mar 2008 | 79.8 | 18.4 | 1.07±0.10 | 0.227 | 15×13 | H168 | Lommen et al. (2007) |
|        | 8 May 2006 | 48.0 | 18.4 | 1.16±0.31 | 0.329 | 23×6 | H214C | Lommen et al. (2007) |
|        | 13 Oct 2006 | 78.6 | 18.5 | <0.921 | 0.307 | 25×9 | H214C | Lommen et al. (2007) |
|        | 18 Oct 2006 | 199.2 | 18.5 | 0.81±0.20 | 0.222 | 38×7 | EW352 | Lommen et al. (2007) |
|        | 24 Oct 2007 | 189.0 | 19.4 | 1.01±0.16 | 0.209 | 12×8 | H214C | Lommen et al. (2007) |
|        | 2 Nov 2007 | 508.8 | 19.4 | 0.55±0.209 | 0.125 | 1.9×1.3 | 1.5A | Lommen et al. (2007) |
|        | 31 Mar 2008 | 79.8 | 19.4 | 0.88±0.12 | 0.232 | 14×13 | H168 | Lommen et al. (2007) |
|        | Jul-11 | 125.0 | 9.9 | <0.3 | 0.1 | 2.4×1.8 | EW352 | Ubach et al. (2012) |
|        | Jul-12 | 20.0 | 9.9 | <0.15 | 0.05 | 1.5×1.0 | H168 | This work |
|        | 18 Oct 2006 | 237.0 | 8.6 | <0.222 | 0.074 | 71×20 | EW352 | Lommen et al. (2007) |
|        | 9 June 2007 | 311.4 | 8.6 | 0.63±0.06 | 0.076 | 53×16 | EW352 | Lommen et al. (2007) |
|        | Jul-11 | 125.0 | 5.5 | <0.24 | 0.1 | 3.2×2.0 | EW352 | Ubach et al. (2012) |
|        | Jul-12 | 20.0 | 5.5 | <0.12 | 0.04 | 3.3×1.7 | H168 | This work |
|        | 18 Oct 2006 | 237.0 | 4.8 | <0.202 | 0.067 | 125×32 | EW352 | Lommen et al. (2007) |
|        | 9 June 2007 | 311.4 | 4.8 | <0.399 | 0.133 | 91×26 | EW352 | Lommen et al. (2007) |