Is there really a debris disc around \( \zeta^2 \) Reticuli?

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ABSTRACT
The presence of a debris disc around the Gyr-old solar-type star \( \zeta^2 \) Reticuli was suggested by the Spitzer infrared excess detection. Follow-up observations with Herschel/PACS revealed a double-lobed feature, that displayed asymmetries both in brightness and position. Therefore, the disc was thought to be edge-on and significantly eccentric. Here we present ALMA/ACA observations in Band 6 and 7 which unambiguously reveal that these lobes show no common proper motion with \( \zeta^2 \) Reticuli. In these observations, no flux has been detected around \( \zeta^2 \) Reticuli that exceeds the 3σ levels. We conclude that surface brightness upper limits of a debris disc around \( \zeta^2 \) Reticuli are 5.7 µJy/arcsec² at 1.3 mm, and 26 µJy/arcsec² at 870 microns. Our results overall demonstrate the capability of the ALMA/ACA to follow-up Herschel observations of debris discs and clarify the effects of background confusion.

Key words: Stars: \( \zeta^2 \) Reticuli – Circumstellar matter

1 INTRODUCTION
\( \zeta^2 \) Reticuli (HR 1010, HIP 15371, HD 20807) is a 3 Gyr-old G1V solar-type star (Eiroa et al. 2013; Sierchio et al. 2014), located at 12 pc (van Leeuwen 2007; Gaia Collaboration et al. 2016, 2018). The presence of a debris disc surrounding \( \zeta^2 \) Reticuli was first suggested by observations carried out with Spitzer/MIPS (Rieke et al. 2004), which detected a 5% infrared excess of this star compared to the predicted photospheric flux at 24 microns, as well as a more significant, 77% infrared excess at 70 microns (Trilling et al. 2008). \( \zeta^2 \) Reticuli was later observed with Herschel/PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010), in the frame of the Herschel Open Time Key Programme DUst around NEarby Stars (DUNES). While Herschel/SPIRE’s resolution is insufficient to discern much structural detail, that of Herschel/PACS at 70 and 100 microns, \( \sim 6 - 7\)”, allowed the resolution of a double-lobed structure at these wavelengths. The lobes are seen asymmetrically distributed on each side of the star, with the lobe closest to the star (South-East) being brighter than its North-West counterpart (Eiroa et al. 2010; Faramaz et al. 2014). This feature was interpreted as a debris disc extending from \( \sim 70 \) AU (6”) to \( \sim 120 \) AU (10”), seen close to edge-on and significantly eccentric (\( e \geq 0.3 \)). This interpretation was supported by several arguments.
(i) The inclination of the star’s rotation axis with respect to the line of sight, which was found to be \(65^\circ \pm 31.5^\circ\) (Faramaz et al. 2014, Appendix B). Indeed, since observations suggest that debris disc orientations differ little from that of their host star (Watson et al. 2011; Greaves et al. 2014) a debris disc surrounding \(ζ^2\) Reticuli would be expected to be seen close to edge-on.

(ii) The position asymmetry of the lobes. Indeed, stars surrounded by an eccentric debris disc are offset from the disc centre of symmetry, as exemplified by the debris discs of Fomalhaut (Kalas et al. 2005; Marsh et al. 2005), HD 202628 (Krist et al. 2012, Faramaz et al., in prep.), and HR4796 (Schneider et al. 2009; Thalmann et al. 2011).

(iii) The brightness asymmetry. At (far) infrared wavelengths, eccentric debris discs are expected to show a "apocentre-glow" at the inferred position ofperiastron (Wyatt et al. 1999), as material closer to the star is expected to be hotter and brighter, again exemplified by observations of the debris disc of Fomalhaut (Stapelfeldt et al. 2004; Acke et al. 2012), HD 202628 (Faramaz et al., in prep.), and HR 4796 (Teleseco et al. 2000; Moerchen et al. 2011).

At longer (sub)mm wavelengths, the brightness asymmetry of such eccentric debris discs is expected to reverse, with the apocenter being this time brighter than the pericenter. This phenomenon, called "apocentre-glow" (Pan et al. 2016), is due to the fact that eccentric debris discs naturally exhibit an overdensity at apoastron, because lower orbital velocities at this location make material spend a larger part of their orbital period there. At (sub)mm wavelengths, apocenter brightness due to this overdensity is expected to become predominant over that of the pericenter, which was indeed observed in the debris disc of Fomalhaut with ALMA observations at 1.3 mm (MacGregor et al. 2017). As the ALMA/Atacama Compact Array (ACA) performs (sub)mm observations with resolutions similar to that of Herschel/PACS, we proposed to resolve the double-lobed feature around \(ζ^2\) Reticuli with the ALMA/ACA in both Band 6 and Band 7, that is, at 1.3mm and 870 microns, respectively. Our goal was to reveal this apocenter-glow and study the evolution of the lobes’ brightness asymmetry from one wavelength to another, as it provides crucial information on the debris disc dust grains population (Pan et al. 2016). However, because of Herschel’s large beam size, the possibility of background contamination of Herschel’s observations is by no mean negligible, which led Sibthorpe et al. (2018) to suggest that the lobes seen in Herschel/PACS observations are likely background objects. In addition, a final reduction of the Spitzer/MIPS data by Sierchio et al. (2014) found there was no infrared excess at 24 microns. Therefore, our ALMA observations, which were carried out nearly 8 years after the Herschel ones, were also potentially expected to assess critically the debris disc interpretation of the Herschel/PACS observations. Indeed, as \(ζ^2\) Reticuli exhibits a high proper motion, the double lobe structure would retain its position relative to the star if it were a debris disc, while background objects would instead retain their absolute position.

### 2 Observations

We present here ALMA/ACA observations of \(ζ^2\) Reticuli in Band 6 (230 GHz, 1.3mm), that were carried out from Nov 4th to Nov 18th 2017, and in Band 7 (345 GHz, 870 microns), that were carried out from Oct 27th to Nov 22nd 2017, both under the project 2017.1.00786.S (PI: V. Faramaz).

Our Band 7 and Band 6 data comprised 8 and 9 separate observations, respectively, for which we summarize the characteristics in Table 1 and 2. These were both taken using baselines ranging from 8.9 to 48.9 m. In Band 7, these correspond to angular scales of 20′′.14 and 3′′.67, respectively. Given the distance of the star (12 pc), this means that the spatial scales that were probed ranged from 44 to 242 AU. In Band 6, these baselines correspond to angular scales of 30′′.21 and 5′′.5, respectively, which in turn translates into probed spatial scales ranging from 66 to 363 AU.

The spectral setup in Band 7 consisted of three 2 GHz-wide spectral windows, centred on 334, 336, and 348 GHz, each one divided into 128 channels of width 15.625 MHz (≈14 km.s\(^{-1}\)). Although we did not expect primordial gas to be present in a system as old as \(ζ^2\) Reticuli, we nevertheless used the fourth spectral window to probe CO gas, via the J=3-2 emission line, as CO can be released from collisions among planetesimals. Therefore, this 1 GHz-wide spectral window was centred on 346 GHz, and set with a larger number (2048) of finer channels, leading to a spectral resolution of 0.5 MHz (≈0.5 km.s\(^{-1}\)). Following the same strategy, the spectral setup in Band 6 consisted of four spectral windows, each 2 GHz-wide, with three of them centred on 232.5, 245.5, and 247.5 GHz, and divided into 128 channels of width 15.625 MHz (≈20 km.s\(^{-1}\)), while the fourth spectral window was set to search for CO gas via the J=2-1 emission line and was centred on 230.5 GHz, with a larger number (2048) of finer channels, leading to a spectral resolution of 1 MHz (≈1.3 km.s\(^{-1}\)).

Since in Band 7, the primary beam has a diameter of 41′′ and the presumed apocenter of the debris disc surrounding \(ζ^2\) Reticuli on Herschel images is located approximately 15′′ from the star, we expected it to fall outside the central third of the primary beam, where sensitivity decreases. Therefore, we requested mosaic observations, and chose to set a pointing offset by 11′′.2 from the star along the major axis in the direction of the presumed apocenter of the disc, and set another pointing towards the presumed pericenter, while adjusting the distance between both pointings to be half of the primary beam Half Power Beamwidth (HPBW).

The total on-source time was 6 h in Band 7. In the case of our Band 6 observations, the primary beam has a diameter of 62′′ and the presumed apocenter of the debris disc surrounding \(ζ^2\) Reticuli was expected to fall within the central third of the primary beam. Therefore there was no need for mosaic observations and we requested single-pointing observations. The total on-source time was 6.8 h in Band 6.

The data were calibrated using the pipeline provided by ALMA. We used the TCLEAN algorithm and task in CASA version 5.1.1 (McMullin et al. 2007) to perform the image reconstruction of the continuum emission, that is, to obtain the inverse Fourier transform of the observed visibilities. In both cases, we combined the four spectral windows in order to recover the maximum signal-to-noise (S/N) ratio, and used a Briggs weighting scheme with robustness parameter...
set to 0.5. We further corrected the images for the primary beam, and show the results in Figure 1, where the position of \( \zeta^2 \) Reticuli is marked with a black star. For our Band 7 image, we used a cell size of 0.72, and an image size of 286 × 286 pixels in order to cover the primary beam. The resulting synthesized beam has dimensions 4.77 × 3.72, with position angle 88°. The rms was measured in a large region far from the sources present in the field of view, and was found to be \( \sigma = 150 \mu\text{Jy/beam} \). For our Band 6 image, we used a cell size of 0.3, and an image size of 210 × 210 pixels. The resulting synthesized beam has dimensions 6.62 × 4.60, with position angle 88°, while the rms was found to be \( \sigma = 66 \mu\text{Jy/beam} \).

3 RESULTS

We recover a double-lobe structure similar to that seen in \( \zeta \) Reticuli, and show the results in Figure 1, where the position of \( \zeta^2 \) Reticuli is found to have major axis 5" ± 83" and an image size of 210 × 210 pixels. The resulting synthesized beam has dimensions 6" × 77", with position angle 87° ± 5". This choice was made based on the fact that such a disc is an extended structure which requires 4 ALMA-ACA beams in Band 6 and 6 beams in Band 7 to be covered, it should have been detected in our observations at SNR of at least 2.5 in Band 7 and at least 3 in Band 6. In addition, the surface brightness of such a hypothesized eccentric (e ≥ 0.3) disc is not expected to be uniform: the pericenter and apocenter of the disc are expected to be the brightest portions of the disc, with the apocenter being in addition up to 30% brighter than the pericenter due to the apocenter-glow phenomenon at these wavelengths (see Equation (8) of Pan et al. 2016). Hence the SNR quoted above are very conservative lower limits, and we should have detected such a disc in our observations if it truly existed. Therefore, we exclude this scenario.

Finally, no CO line emission was detected in Band 6, nor in Band 7.

4 CONCLUSIONS

The position of the A2 lobe seen with ALMA coincides with the H2 lobe seen with Herschel. If these two emissions are related, then it is stationary and most likely a background source, but they might as well not be related. It is also difficult to say whether the A1 lobe seen with ALMA and the H1 lobe seen with Herschel are related emissions. If they are, then it is a nearby source that has displaced South East since Herschel observations, and thus is not co-moving with \( \zeta^2 \) Reticuli. If they are not related, then the source H1 has become too faint at ALMA wavelengths while A1 appeared South East to the Herschel location of H1.

Nevertheless, we can exclude the possibility that the
Figure 1. Left: ALMA/ACA 870 microns continuum observations of ζ² Reticuli. Contours show the ±2, 4, 6... σ significance levels, with \( \sigma = 150 \mu\text{Jy/beam} \). The synthesized beam, shown on the lower left side of the image, has dimensions 4.77 x 3.2, with position angle 88°. Right: ALMA/ACA 1.3 mm continuum observations of ζ² Reticuli. Contours show the ±2, 4, 6... σ significance levels, with \( \sigma = 66 \mu\text{Jy/beam} \). The synthesized beam, shown on the lower left side of the image, has dimensions 6.62 x 4.60, with position angle 88°. In both images, the position of the star is marked with a black star, while its position at the time of Herschel/PACS observations is marked with a white star. The white line indicates the 50% response of the primary beam, and the colorbars show the fluxes in mJy per beam.

Figure 2. Comparison of the double lobe structure position between Herschel/PACS and ALMA/ACA observations. Left: ALMA/ACA 870 microns ±2, 4, 6... σ significance levels contours (with \( \sigma = 150 \mu\text{Jy/beam} \)), overlayed on Herschel/PACS colormap at 70 microns. Right: ALMA/ACA 1.3 mm ±2, 4, 6... σ significance levels contours (with \( \sigma = 66 \mu\text{Jy/beam} \)), overlayed on Herschel/PACS colormap at 100 microns. In both images, the position of the star in ALMA observations is marked with a black star, while its position at the time of Herschel/PACS observations is marked with a white star. The grey line shows the limits of the ALMA images.
double-lobe feature seen with Herschel really is a debris disc, as even a very faint counterpart (sub-\mu)Jy emission should have been detected at the sensitivities achieved in our ALMA observations. Therefore, our ALMA/ACA observations show without ambiguity that the double lobe structure seen in Herschel observations was not the signature of an eccentric debris disc.

Revisiting the Herschel/PACS photometry and SED reported in Eiroa et al. (2010) in the light of our findings, then \(\zeta^2\) Reticuli possesses no detectable infrared excess above its expected photospheric flux. These results are in accordance with those of Sibthorpe et al. (2018), who found no significant infrared excess to \(\zeta^2\) Reticuli at Herschel/PACS wavelengths, and thus concluded that the features seen near this star are the result of background confusion.

As the photometric measurement of Herschel/PACS at 70 microns is in accordance with that of Spitzer, we further conclude that Spitzer observations at 70 microns were contaminated as well.

In conjunction with our ALMA data, and since \(\zeta^2\) Reticuli has been observed with sensitivities of \(\sigma = 66 \mu\)Jy/beam and \(\sigma = 150 \mu\)Jy/beam in Band 6 and Band 7, respectively, we conclude that if there is any debris disc around \(\zeta^2\) Reticuli, then its surface brightness falls below the 3\sigma detection limits, that is, it does not exceed 5.7 \mu\)Jy/arcsec\(^2\) at 1.3 mm, and 26 \mu\)Jy/arcsec\(^2\) at 870 microns. It would be one and two orders of magnitude dimmer than the well-studied discs around HD 20628 (Faramaz et al., in prep.) and Fomalhaut (MacGregor et al. 2017), respectively.

Although these observations report a non-detection around \(\zeta^2\) Reticuli, this study overall demonstrates that using the ALMA/ACA can be a powerful technique to clarify the effects of background confusion for Herschel-detected debris discs. In particular, peculiar Herschel/PACS observations of infrared excesses peaking at 160 microns among the DUNES sample have been interpreted to be "cold debris discs" (Eiroa et al. 2011; Krivov et al. 2013), whereas Gáspár & Rieke (2014) showed that this hypothesis was indistinguishable from background confusion. Therefore, we advocate the use of ALMA-ACA to disentangle these two hypotheses.

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**Table 1. Summary of our ALMA/ACA observations at 870 microns (Band 7)**

| Date       | Time           | On source | \(N_{\text{Ant}}\) | PWV (mm)  | Avg Elev. (deg) | Flux (\mu Jy)     | Calibrators       |
|------------|----------------|-----------|----------------------|-----------|-----------------|-------------------|-------------------|
| dd/mm/yyyy | (UTC)          | (min)     |                      |           |                 |                   |                   |
| 04/11/2017 | 02:59:33.5     | 45.4      | 11                   | 0.54-0.70 | 48.4            | J2258-2758         | J0303-6211        |
| 05/11/2017 | 06:32:44.0     | 45.4      | 10                   | 1.11-1.28 | 43.7            | J0522-3627         | J0522-3627        |
| 06/11/2017 | 06:16:37.7     | 45.4      | 10                   | 1.45-1.51 | 44.8            | J0522-3627         | J0522-3627        |
| 07/11/2017 | 05:17:42.0     | 45.4      | 10                   | 1.06-1.20 | 48.2            | J0522-3627         | J0522-3627        |
| 08/11/2017 | 06:11:54.7     | 45.4      | 10                   | 1.10-1.20 | 41.9            | J0522-3627         | J0522-3627        |
| 09/11/2017 | 06:46:38.0     | 45.4      | 10                   | 0.56-0.61 | 40.3            | J0522-3627         | J0522-3627        |
| 11/11/2017 | 04:58:05.7     | 45.4      | 11                   | 1.82-2.35 | 47.8            | J0522-3627         | J0522-3627        |
| 12/11/2017 | 04:32:52.9     | 45.4      | 11                   | 0.64-0.69 | 48.9            | J0522-3627         | J0522-3627        |
| 13/11/2017 | 05:21:43.9     | 45.4      | 10                   | 1.09-1.12 | 44.9            | J0522-3627         | J0522-3627        |

**Table 2. Summary of our ALMA/ACA observations at 1.3 mm (Band 6)**

| Date       | Time           | On source | \(N_{\text{Ant}}\) | PWV (mm)  | Avg Elev. (deg) | Flux (\mu Jy)     | Calibrators       |
|------------|----------------|-----------|----------------------|-----------|-----------------|-------------------|-------------------|
| dd/mm/yyyy | (UTC)          | (min)     |                      |           |                 |                   |                   |
| 04/11/2017 | 02:38:39.9     | 44.9      | 11                   | 0.56-0.61 | 46.3            | J2258-2758         | J0303-6211        |
| 05/11/2017 | 05:15:49.7     | 44.9      | 11                   | 0.48-0.50 | 48.2            | J0522-3627         | J0522-3627        |
| 06/11/2017 | 07:02:55.6     | 44.9      | 10                   | 0.55-0.64 | 37.6            | J0522-3627         | J0522-3627        |
| 10/11/2017 | 06:24:53.3     | 44.9      | 10                   | 1.06-1.20 | 41.1            | J0522-3627         | J0522-3627        |
| 11/11/2017 | 04:59:43.7     | 44.9      | 10                   | 0.64-0.69 | 47.5            | J0522-3627         | J0522-3627        |
| 12/11/2017 | 04:56:19.4     | 44.9      | 10                   | 0.56-0.61 | 47.5            | J0522-3627         | J0522-3627        |
| 19/11/2017 | 05:17:49.6     | 44.9      | 11                   | 0.60-0.68 | 44.1            | J0522-3627         | J0516-6207        |
| 22/11/2017 | 04:22:05.9     | 44.9      | 11                   | 0.53-0.57 | 47.2            | J0522-3627         | J0522-3627        |

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