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Rings etc.

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ABSTRACT

In [THE SPONGEBOB SQUAREPANTS DISK SURVEY], the first high angular resolution ALMA survey of protoplanetary disks, ring-like features were the most common type of substructure observed. We present an analysis of the eighteen protoplanetary disks around single stars. Ring-like substructures are observed in seventeen of these sources, and tentatively detected in the last source.

-Remark on diversity of ring structures observed

To be continued...

Keywords: protoplanetary disks—ISM: dust—techniques: high angular resolution

1. INTRODUCTION

In the past few years, moderate-to-high angular resolution ALMA observations have revealed concentric ring and gap structures in the millimeter continuum of [x number] of protoplanetary disks.

Boilerplate

2. OBSERVATIONS AND DATA REDUCTION

The calibration of the data are described in Andrews et al. (in prep).

Describe imaging (tapering and robust value choices for different disks)

3. DISK FEATURES

3.1. *Radial locations of rings and gaps*

3.1.1. *Nomenclature*

Table 1. Imaging parameters

Source	Briggs parameter	Taper	Synthesized beam
		mas × mas	mas × mas
AS 209			
DoAr 25	0.5	-	48 × 27 (79°.5)
Elias 20	0	-	32 × 23 (76°.3)
Elias 24	0	35 × 10 (166°)	36 × 34 (81°.6)
GW Lup	0.5	35 × 15 (0°)	45 × 43 (0°.5)
RU Lup	-0.5	22 × 10 (6°)	25 × 24 (-51°.0)
Sz 114	0.5	-	67 × 28 (-88°.0)

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We label annular features with the prefix "DA" (for Dark Annulus), followed by the radial location of the ring rounded to the nearest whole number, if the feature corresponds either to a local minimum in the radial profile or if the radial component of the gradient sharply transitions from steeply decreasing to nearly flat. Colloquially, such features are often referred to as "gaps" in the literature (REFS). Similarly, we label annular features with the prefix "BR" (for Bright Ring), also followed by their radial locations, if the feature corresponds either to a local maximum in the radial profile or to locations where the radial component of the gradient transitions from being nearly flat to being steeply decreasing.

In addition, we identify additional annular features of interest in the disk with the label "CF" (for Circular Feature) followed by the estimated radial location. Most of these features correspond to breaks or shoulders in the intensity profile that may correspond to the inward edge of a gap or be associated with dust evolution (e.g. Hogerheijde ref). Other features of interest are possible gaps and rings in disks where the spiral arms create ambiguity in the classification.

3.1.2. *Measurements*

The positions of the most distinct annular features are measured in a manner similar to that employed for the HL Tau disk in ALMA Partnership (REF). To start with, we assume that all of the features are circular. Using estimates of the disk orientation from either a Gaussian fit to the image or from existing literature measurements (Fedele for AS 209, Dipierro for Elias 24, Andrews 2018 for Sz 129, Sz 114, GW Lup), we perform a preliminary deprojection of the disk image. We then take radial cuts of the image along evenly spaced azimuthal angles, where the spacing for each feature is set to be on the order of the synthesized beam size to ensure that

Figure 1. ALMA 1.3 mm continuum observations of the 18 protoplanetary disks around single stars from the [SPONGEBOB SQUAREPANTS DISK SURVEY].

the different cuts are largely independent. For each radial cut, we search for a local extremum in the vicinity of the observed disk feature, generally using a search window of $\sim$ 6 to 20 AU depending on the apparent width of the feature. If an extremum is not present in a given radial cut (either because of insufficient angular resolution arising from the disk projection or from low signal-to-noise), we exclude that azimuthal angle from measurement. For the Elias 27 disk, we also exclude the azimuthal angles where the spiral arms cross the gap. When fitting ellipses to the features labeled BR65 in the HD 143006 disk, we excluded the azimuthal angles occupied by the asymmetry on the southeast side. ALSO HD 163296.

Ellipses are then fit to the coordinates extracted for each ring. We use a Gaussian likelihood

$$\log L =, \tag{1}$$

where d is the orthogonal distance of the measured coordinate from the model ellipse, and σ is the standard deviation of the orthogonal distances. The formulae for calculating the orthogonal distances from an ellipse are provided in Zhang (REF). We fit for six parameters: the offset of the ellipse center from the phase center (Δx and Δ y), the semimajor axis of the ellipse (r_0), the ratio of the lengths of the semiminor to semimajor axes (cos$i$), the position angle, and the natural log of the variance in the orthogonal distance offsets of the measured ellipse points from the presumed true ellipse ($\log \sigma^2$). Flat priors are specified for Δx, Δy, r_0, and $\log \sigma^2$. Gaussian priors for $\cos i$ and PA for Sz 129, AS 209 (needs to be re-run), Sz 114, Elias 24, GW Lup from previous literature estimates (REF). For disks where previous measurements of PA and inclination were not available, conflicting, or visibly inaccurate, we adopted flat priors for $\cos i$ and PA. The posterior is sampled using emcee (REF, and list the chain length, number of walkers, burn-in, and convergence criteria). The resulting measurements are listed in Table 2 (REF). The position angles and inclinations of the disks, listed in Table 3 (REF) were computed by taking weighted averages of the measurements for the individual annular features.

For disks where the annular substructure is not sufficiently high contrast to fit ellipses directly (i.e. WSB 52, MY Lup, DoAr 33, WaOph 6?, HD 142666), we compute the position angles and inclinations by fitting elliptical gaussians to the images.

Radial profiles were then calculated for each disk by deprojecting the disk, then binning the pixels in annuli one AU wide and averaging the intensities in each bin. For most disks, the average is taken through all azimuthal angles. For HD 143006 and HD 163296, we exclude the angles where the emission asymmetry is visible. For disks with very high inclination (Elias 20, DoAr 25, MY Lup, WSB 52, and HD 142666), we only average through azimuthal angles that are within 20 degrees of the major axis of the projected disk image, since the emission structures are not well-resolved along the minor axis.

The radial locations of additional ringlike substructure visible in the disk images are identified by searching for local maxima and minima in the averaged radial profiles. The uncertainty on the radial location is estimated as the width of the radial bin. For ring-like substructures that do not correspond to local maxima and minima as well and the additional "features of interest", we estimate their radial locations through visual inspection of the radial profile and image. Because this is somewhat subjective, the locations are given as approximations without formal error estimates, but the accuracy of the estimate should be on the order of the scale of the synthesized beam.

Table 2. Positions and orientations of emission rings and gaps

Source	Feature	Δx	Δy	Semi-major axis	Semi-major axis	Inclination	Position Angle
		(mas)	(mas)	(arcsec)	(AU)	(degrees)	(degrees)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
AS 209	DA9			0.0717±0.0008	8.7±0.1	35.5±0.6	85.8±0.5
	BR14			0.119±0.001	14.4±0.1	35.2±0.6	85.9±0.5
	DA24			0.196±0.001	23.8±0.2	35.5±0.5	85.9±0.5
	BR28			0.230±0.002	27.8±0.3	$35.1^{+0.6}_{-0.5}$	86.0±0.5

Table 2 continued

Table 2 *(continued)*

Source	Feature	Δx	Δy	Semi-major axis	Semi-major axis	Inclination	Position Angle
		(mas)	(mas)	(arcsec)	(AU)	(degrees)	(degrees)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	DA35			0.289±0.001	34.9±0.2	35.5±0.5	85.8±0.5
	BR39			0.318±0.002	38.5±0.3	34.7±0.5	85.8±0.5
	DA61			0.504±0.002	61.0±0.3	$35.8^{+0.4}_{-0.5}$	86.0±0.5
	BR74			0.612±0.001	74.0±0.1	34.7±0.3	85.7±0.4
	DA90			0.745±0.003	90.1±0.3	34.7±0.4	$86.1^{+0.4}_{-0.5}$
	BR99			0.818 ±0.003	99.0±0.4	$34.5^{+0.5}_{-0.4}$	85.9 ±0.5
	DA105			0.870±0.003	105.3±0.4	$34.6^{+0.5}_{-0.4}$	86.0 ±0.5
	BR120			0.994±0.001	120.3±0.1	35.0±0.2	85.8±0.3
	one more pair?						
DoAr 25	DA76				∼76		
	BR85				∼85		
	DA97	40±3	-49±2	0.702±0.004	96.8±0.3	67.4±0.3	110.5±0.3
	BR111	35±3	-49±3	0.804±0.004	110.9±0.3	66.1±0.3	110.1±0.3
	DA125				125±1		
	BR137				137±1		
Elias 20	DA25	-54.4±1.5	$-491^{+0.0012}_{-0.0013}$	$0.1816^{+0.0016}_{-0.0015}$	25.1±0.2	49±1	153.2±1.3
	BR29				29±1		
	DA33				33±1		
	BR36				36±1		
	DA45				45±1		
Elias 24	DA57	110±2	-386±2	0.418±0.002	56.8±0.3	27.7±0.9	51±2
	BR77	111±1	-387±1	$0.5641^{+0.0012}_{-0.0011}$	76.71±0.13	29.2±0.4	45.2±0.8
	DA89			0.654±0.007	89±1		
	BR123			0.904±0.007	123±1		
Elias 27	DA69	-6±4	-7±3	$0.594^{+0.7}_{-0.6}$	68.9±0.4	$55.9^{+0.7}_{-0.8}$	118.7±0.7
	BR87				87±1		
GW Lup	DA74	$-2.5^{+1.6}_{-1.4}$	0.8±1.5	0.479±0.002	74.3±0.2	$38.8^{+0.4}_{-0.5}$	$37.7^{+0.8}_{-0.7}$
	BR85	-2.3±0.2	1±2	0.551±0.002	85.4±0.3	$38.8^{+0.4}_{-0.5}$	37.6±0.8
	DA102			0.658±0.006	102±1		
	BR108			0.697±0.006	108±1		
HD 143006	BR6				6±1		
	DA24				24±1		
	BR41	-6.3±0.6	21.5±0.6	0.2472 ±0.0008	40.8±0.1	18.9±0.9	169±3
	DA52				52±1		
	BR65	-1±2	24±2	0.393±0.3	64.9±0.4	17±2	164^{+7}_{-6}
HD 163296							
RU Lup	DA14			∼ 0.088	∼14		
	BR17			∼ 0.107	∼ 17		

Table 2 continued

Table 2 *(continued)*

Source	Feature	Δx (mas)	Δy (mas)	Semi-major axis (arcsec)	Semi-major axis (AU)	Inclination (degrees)	Position Angle (degrees)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	DA22			0.138±0.006	22±1		
	BR24			0.159±0.006	24±1		
	DA29	-17±1	88±1	$0.1829^{+0.0014}_{-0.0015}$	29.1±0.2	20±2	118±6
	BR34	-17±1	87±1	0.214±0.002	34.0±0.2	16^{+2}_{-3}	123±9
	DA42			∼ 0.264	∼ 42		
	BR50			∼0.314	∼ 50		
SR 4	DA11				11±1		
	BR19	-64±3	-509±3	0.140±0.003	25^{+5}_{-6}	44^{+13}_{-12}	
Sz 114	DA39	0±5	3±4	0.238±0.003	38.6±0.6	21±2	165±7
	BR45	-2±3	4±3	0.280±0.003	45.4±0.5	$21.7^{+1.4}_{-1.7}$	166±5
Sz 129	BR10			0.062±0.006	10±1		
	DA41	7±3	4±3	0.254±0.003	40.9±0.5	31.6±0.9	154±2
	BR46	7±3	4^{+2}_{-3}	0.285±0.002	45.9±0.4	32.0±0.9	155±2
	DA63			0.391±0.006	64±1		
	BR66			0.410±0.006	66±1		

Table 3. Position angles and inclinations of disks

Source	P.A. deg	Incl. deg	method
AS 209			
DoAr 25	110.3±0.2	66.8±0.2	
Elias 20	153.2±1.3	49±1	
Elias 24	45.9±0.8	28.9±0.4	
Elias 27			
HD 143006	168.6	18.6	
GW Lup	37.7±0.6	38.8±0.4	
RU Lup	119±5	18.6±1.6	
SR 4	44^{+13}_{-12}	25^{+5}_{-6}	
Sz 114	165±4	21.4±1.3	
Sz 129	154.5±1.2	31.8±0.6	

3.2. *Non-axisymmetric structures*

3.2.1. *Azimuthal asymmetries*

-HD 143006 and HD 163296, obviously
-HD 142666 and HD 163296 have asymmetries in the inner disk that are most likely due to vertical structure
- Comment on limits on asymmetry for other rings based on amount of scatter in radial bins

Table 4. Radial locations of circular features of interest

Source	Feature	Radius arcsec	Notes
DoAr 25	CF63	∼ 0.46	Shoulder in intensity profile leading into gap
Elias 20	CF20	∼ 0.14	Shoulder in intensity profile leading into gap
Elias 24	CF14	∼0.10	Slope decrease in intensity profile
	CF42	∼ 0.31	Shoulder in intensity profile leading into gap
Elias 27	CF125	∼ 1.08	Possible gap intersected by spiral arms
GW Lup	CF10	∼0.07	Slope decrease in intensity profile
	CF65	∼ 0.42	Shoulder in intensity profile leading into gap

- Rings and gaps generally seem concentric but more reliable results would probably have to be derived by forward modeling

3.2.2. *Spirals*

-WaOph 6, IM Lup, Elias 27

3.2.3. *PSF effects*

Tell people to be careful with AS 209 and SR 4; prominent gaps near the center of the disk = gap-crossing artifacts

3.3. *Remarks on individual sources*

We comment on the results for individual sources and draw comparisons with other millimeter continuum, scattered light, and molecular line observations from the literature. Unless otherwise noted, the features remarked upon are resolved for the first time in this survey.

Figure 2. Radial profiles on a linear scale, with features labeled

Figure 3. Brightness temperature profiles (maybe additional annotations for snowline discussion?)

Figure 4. Radial profiles with the y-axis on a log scale, with features labeled

Figure 5. Deprojected disk images with features labeled

Figure 6. Some kind of histogram of the distribution of rings and gaps?

3.3.1. *AS 209*

3.3.2. *DoAr 25*

DoAr 25 hosts an extended, high inclination disk with three pairs of annular gaps and rings. Integration time shorter for this disk. Tentative additional rings in inner disk. Need higher res to confirm. Reference Cox paper, Weaver et al. in prep.

3.3.3. *Elias 20*

Higher resolution needed to confirm possible additional gap

3.3.4. *Elias 24*

Tentative additional rings Cox, Dipierro, Cieza papers

3.3.5. *Elias 27*

Prominent gap at See Huang et al. (in prep) for analysis of the spiral geometry. Comment on extinction?

3.3.6. *HD 143006*

HD 143006 hosts a nearly face-on disk consisting of three narrow rings separated by wide gaps. A central cavity/clearing is visible but not well-resolved. The most striking feature is the asymmetry on the southeast side of the outermost ring, noted previously in Barenfeld et al. (REF). See Pérez et al. (in prep.) for further analysis of HD 143006. Discuss Myriam's paper.

3.3.7. *MY Lup*

MY Lup hosts the most highly inclined disk in the survey. Although some studies have classified MY Lup as a transition disk (REFS), our ALMA image does not display a central cavity. However, there is radial substructure in the vicinity of where the cavity was previously inferred. Ref. Weaver et al. in prep

3.3.8. *RU Lup*

mention high activity of RU Lup

3.3.9. *SR 4*

PSF effects can be observed in the gap SR4 hosts one of the smallest disks in the sample. Because of the small size of the disk, the uncertainties on the disk viewing geometry are large.

3.3.10. *Sz 114 (V908 Sco)*

The disk around this T Tauri star features a marginally resolved gap at 38.6 AU, surrounded by an emission ring at 45.3 AU. Due to poor weather, the on-source integration time for this source was only about half as long as that for most of the sample. The comparatively low signal-to-noise, small radial extent of the disk, and low disk inclination lead to large uncertainties for the viewing geometry. However, because the disk is nearly face-on ($\cos i = 0.93$), the derived radial profile does not depend strongly on the inferred viewing geometry.

3.3.11. *Sz 129*

The direct imaging of a small central cavity in the Sz 129 disk confirms the tentative identification in Tazzari et al (REF) via visibility modeling of lower-resolution data.

3.4. *Spacings between gaps and rings*

-rings and gaps occur as far in as x and as far out as y -spacings occur as small as x and as large as y

3.4.1. *Possible resonances*

3.5. *Gap contrast levels?*

-Disks with gap depths that seem essentially cleared out: GW Lup, HD 143006, AS 209, HD 163296, Elias 24 -But a lot of gaps seem pretty shallow. Emphasize need for high sensitivity?

4. DISCUSSION

4.1. *Comparison to other millimeter detections of protoplanetary disks*

-Make the point that other observations by necessity were biased toward larger-scale structures

4.2. *Prevalence of millimeter continuum substructures*

Since our survey selected preferentially for bright protoplanetary disks, it is not straightforward to derive an occurrence rate for millimeter continuum substructures. Nevertheless, we can still set interesting lower bounds.

4.2.1. *Disks in Lupus*

4.2.2. *Disks in Ophiuchus*

4.2.3. *Relation with stellar parameters*

-Seen in a range of spectral types, but most of the disks observed so far are pretty bright, so the occurrence could be different if stellar mass/disk mass relationship is taken into account?

-No obvious trend seen so far with accretion rate, host star luminosity, host star age

-How early do these structures form? Comment on Class I disks

4.2.4. *Small versus large disks*

make a point about the marginally resolved gaps

4.3. *Possible origins of substructures*

4.3.1. *Planets*

-Discuss the various hydro papers (start with Lin and Papaloizou and keep going)

-Discuss previously proposed protoplanets for AS 209, HD 163296, Elias 24 (Isella, Teague, Pinte, Fedele, Dipierro)

-Discuss previous companion searches and limits (Guidi paper on arxiv)

4.3.2. *Snowlines*

-Discuss Zhang, Okuzumi, Pinilla -Comment on brightness temperatures and optical depth?

4.4. *Dead zones*

Discuss Flock, Ruge, Pinilla papers

4.4.1. *Other hypotheses*

-Secular gravitational instability
-Dipierro back reaction
-Streaming instability
-etc

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Software: `CASA` (?), `AstroPy` (?), `analysisUtils` (https://casaguides.nrao.edu/index.php/Analysis_Utilities)

Facilities: ALMA