A Pilot Survey for Substructures in Class I Disks

None Assigned

ABSTRACT

We propose to search for and characterize substructures (e.g., gaps, rings, spirals, clumps, etc.) in the spatial distributions of solid particles for a modest sample of 5 nearby Class I disks,
using very high spatial resolution (down to ~5 au scales) ALMA Band 6 (230 GHz) continuum observations. This pilot survey will be among the first to resolve material well into the planet-forming zones of Class I disks with a uniform sensitivity and resolution (in to a radius of ~2-3 au). In doing so, it will provide a homogenized look at the small-scale features that
directly trace the planet formation process, quantifying their prevalence, variety of form, spatial scales, spacings, symmetry, and amplitudes, in a sub-sample that helps construct an important comparison with the Class II disk Large Program we recently executed as a function of evolutionary state. This sample will fundamentally shape our understanding of how planet formation is aided by -- and perhaps reliant on -- disk substructures by constraining when such features form during the life cycle of circumstellar material. In doing so, it will provide essential context for the proper interpretation of all disk observations at coarser resolutions.

PI NAME:	Sean Andrews			**SCIENCE CATEGORY:**	Circumstellar disks, exoplanets and the solar system
ESTIMATED 12M TIME:	**19.7 h**	**ESTIMATED ACA TIME:**	**0.0 h**	**ESTIMATED NON-STANDARD MODE TIME (12-M):**	**0.0 h**
CO-PI NAME(S): (Large & VLBI Proposals only)					
CO-INVESTIGATOR NAME(S):	Jane Huang; Myriam Benisty; Tilman Birnstiel; Xuening Bai; John Carpenter; Laura Perez; David Wilner; Andrea Isella; Karin Oberg; Viviana Guzman; Luca Ricci				
DUPLICATE OBSERVATION JUSTIFICATION:	N/A				

REPRESENTATIVE SCIENCE GOALS (UP TO FIRST 30)

SCIENCE GOAL	POSITION	BAND	ANG.RES.(")	LAS.(")	ACA?	NON-STANDARD MODE
IRAS 04016+2610 long baselines	ICRS 04:04:43.0710, 26:18:56.390	6	0.050 - 0.025	0.300	N	N
IRAS 04108+2803B long baselines	ICRS 04:13:54.7170, 28:11:32.900	6	0.050 - 0.025	0.300	N	N
IRAS 04166+2706 long baselines	ICRS 04:19:42.6270, 27:13:38.430	6	0.050 - 0.025	0.300	N	N
IRAS 04169+2702 long baselines	ICRS 04:19:58.4490, 27:09:57.070	6	0.050 - 0.025	0.300	N	N
IRAS 04295+2251 long baselines	ICRS 04:32:32.0550, 22:57:26.670	6	0.050 - 0.025	0.300	N	N
Short-Spacings Cluster	ICRS 04:04:43.0710, 26:18:56.390	6	0.250 - 0.150	2.000	N	N
Total # Science Goals : 6						

SCHEDULING TIME CONSTRAINTS	NONE	**TIME ESTIMATES OVERRIDDEN ?**	No

A Pilot Survey for Substructures in Class I Disks

1. Background and Motivation

Planet formation has historically been a theoretical venture, unfortunately without enough useful guidance from observations. That is quickly changing, as ALMA measurements of continuum emission from mm/cm-sized "tracer" particles in protoplanetary disks can now constrain how disk solids are spatially distributed at exquisite resolution (a few au for the nearest disks). ALMA data have started to reveal azimuthal asymmetries (Casassus et al. 2013; van der Marel et al. 2013; Pérez et al. 2014), spiral patterns (Christiaens et al. 2014; Pérez et al. 2016), and concentric ring + gap morphologies (ALMA Partnership 2015; Andrews et al. 2016; Isella et al. 2016; Cieza et al. 2016; Loomis et al. 2017; van der Plas et al. 2017; Fedele et al. 2017) in a haphazard sample of disks. This past fall, our team conducted an ALMA Large Program to study the forms, prevalence, and diversity of such substructures in the general disk population. While there is still much to do in that program (data delivery was only completed in mid-March), we do find that substructures are ubiquitous and exhibit a wide variety of scales, amplitudes, and morphologies: a few representative examples are shown in Figure 1.

The evidence from ALMA strongly suggests that disk substructures are fundamental pieces of the planet formation puzzle. However, the interpretation of these features bifurcates into competing visions of their *origins*, and thereby their connections to the planet formation process. One branch considers an indirect link, postulating that the substructures trace particle "traps" where the migration of solids is stymied at local gas pressure maxima (Whipple 1972; Pinilla et al. 2012), induced by fluid instabilities (e.g., Bai & Stone 2014; Dipierro et al. 2015; Dullemond & Penzlin 2018) or steep gradients in material properties (e.g., Flock et al. 2015; Lyra et al. 2015; Okuzumi et al. 2016; Armitage et al. 2016). This ideology associates substructures with mechanisms that throttle solid migration rates and thereby strongly enhance the local solids-to-gas ratio. In that sense, the substructures are seen as essential environments for producing the planetesimal building blocks of terrestrial planets and giant planet cores (cf., Youdin & Shu 2002; Youdin & Goodman 2005; Johansen et al. 2009). The other interpretative branch draws a different conclusion: the substructures are instead a direct consequence of dynamical interactions between the disk material and *already-formed* planets. Such interactions can generate rings and gaps (e.g., Zhu et al. 2012; Dong et al. 2017; Bae et al. 2017), spirals (Zhu et al. 2015; Fung & Dong 2015; Bae & Zhu 2017), and asymmetries (e.g., vortices; Klahr & Henning 1997; Zhu & Stone 2014) if the formation of ∼super-Earths and giant planets occurs very early in the Class II phase, or preferably before the envelope reservoir is dissipated (e.g., Nixon et al. 2018). In this ideology, the emission we see is just the *debris* of planetesimal collisions, sculpted by nascent planetary systems (Boley 2017).

We aim to help develop a more comprehensive interpretation of the origins of these substructures and their roles in the planet formation process by probing their prevalence and forms *earlier* in the disk evolution sequence. The Class I disk population has a characteristic age of ∼0.5 Myr, much younger than the ∼2 Myr that is representative of the Class II disks that ALMA studies most frequently (Evans et al. 2009). A few recent results show that similar substructures are present in Class I disks (e.g., Sheehan & Eisner 2017b, 2018; see also ALMA Partnership et al. 2015), suggesting that crucial aspects of planet formation are well underway much earlier than we normally assume.

2. Immediate Objectives

We propose a pilot study to characterize substructures in the spatial distributions of solid particles for a modest sample of 5 nearby Class I disks, using very high spatial resolution (∼5 au) ALMA Band 6 (230 GHz) continuum observations. This program is designed to mimic the ALMA Large Program

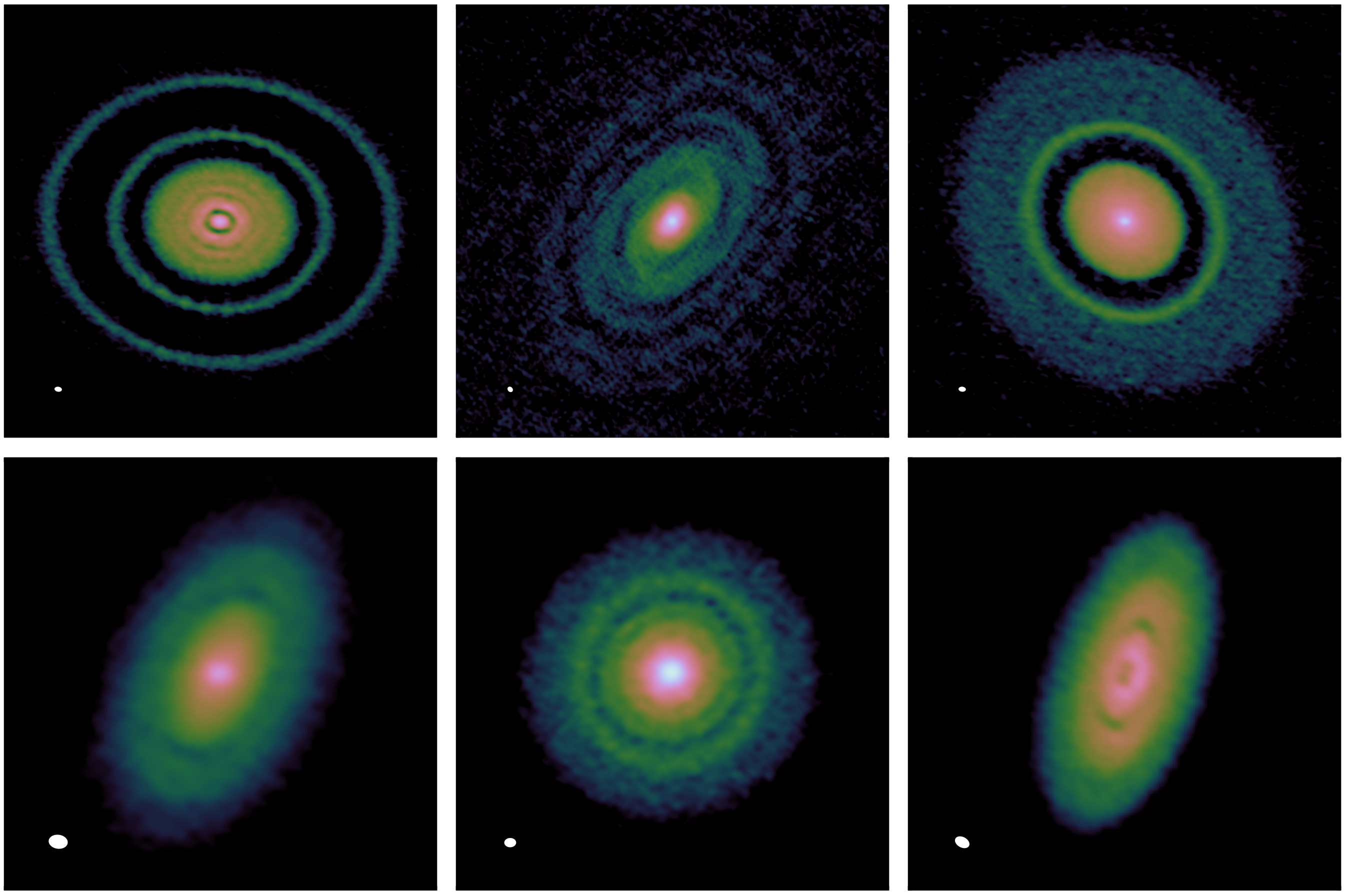

Figure 1: Some representative images of Class II disk substructures from the Cycle 4/5 Large Program we recently conducted, showing a full range of feature scales and amplitudes (and morphological diversity). The beam sizes are in the lower left corner of each panel, and give a sense of scale (each is ∼5 au in diameter). These disk targets have comparable inner disk brightnesses as the Class I disks being selected here, and the observational strategy is essentially identical: the expectation is that the proposed data will be of similar quality.

of Class II disks we have recently conducted, as well as the few Class I disks that have recently been observed at comparable resolution (but are also not yet public / published). In that sense, these observations are a useful complement to ongoing ALMA work; they will serve as an orthogonal sub-sample to probe the properties of disk substructures along the evolutionary dimension. These observations will be among the first to resolve material well into the planet-forming zones of Class I disks with a uniform sensitivity and resolution (in to a radius of ∼2–3 au). In doing so, they will provide a homogenized look at the small-scale features that directly trace the planet formation process at very early times, quantifying their prevalence, variety of form, spatial scales, spacings, symmetry, and amplitudes.

To construct a sample, we considered the Taurus-Auriga association ($d \approx 140$ pc) because it currently has the best-characterized Class I population and is well-suited to nighttime long-baseline observations during Cycle 6 (C43-8/9). There are ∼20 Class I sources in this region.[1] Seven of those have not yet been observed with an interferometer: we exclude those targets because we cannot reliably associate emission with a disk rather than an envelope, and therefore cannot estimate a required sensitivity at high resolution. Five of the remaining targets have already been observed with ALMA at sufficiently

[1]There is some ambiguity in the infrared spectrum-based definition; e.g., whether or not one includes "flat-spectrum" sources as Class I or II. But 20 is roughly speaking the size of the full population.

high resolution, although the results from only one of these have been published at the time of writing (HL Tau; ALMA Partnership et al. 2015). The remaining 8 targets were observed by the CARMA interferometer at 230 GHz with sub-arcsecond resolution (Eisner 2012; Sheehan & Eisner 2017a). We used those observations, and the associated modeling results that differentiate disk and envelope emission, to down-select following the same methodology as for the Class II ALMA Large Program. To do that, we conservatively assumed that the (as yet unresolved) emission in the disk centers (within a $\sim$60 au FWHM beam) is smooth (i.e., no substructure) and made simple power-law models of the brightness distribution at 5 au resolution. In that bound, the brightness distribution at all scales $\geq$5 au can be recovered in a reasonable observation for disks that emit $\geq$20 mJy from their inner regions ($r \leq 30$ AU). The target sensitivity is a $5\,\sigma$ limit of 85 μJy per 5 au beam (RMS = 17 μJy beam^{-1}). If substructures are present, they will be detected at even higher confidence (regardless of their optical depths). So, the final selection criterion is a cut on *surface brightness* in the inner disk.

The resulting sample includes 5 Class I sources: IRAS 04016+2610 (= L1489 IRS), IRAS 04108+2803B, IRAS 04166+2706, IRAS 04169+2702, and IRAS 04295+2251. Combined with the other cases that will eventually have high (sub-10 au) resolution images in the ALMA archive, our sample will complete a census for substructures in half the Taurus Class I disk population and span a significant range in host luminosity and disk-to-envelope mass ratios (presumably proxies for host mass and evolutionary state).

3. Strategy & Technical Feasibility

With the data we are proposing to obtain, we can expect to *resolve* gaps from giant planets (0.1–1 $M_{\rm Jup}$) in these disks at orbital radii down to $\sim$15–20 au; we should be able to detect (unresolved) gaps at orbital radii $\geq$5 au. The gas pressure scale height, h (where $h/r \sim 0.1$), is also a benchmark scale for turbulent substructures. We can *resolve* h-scale features in radius/azimuth at $r \geq$ 40–50 au, and should detect them down to $r \sim 10$ au. The proposed sensitivity enables firm detections of small-scale variations at the $\sim$2% (inner disk) to 10% (outer disk) level, enough to see the $\sim$20% contrasts expected for gaps opened by $>$0.1 $M_{\rm Jup}$ planets (Fung et al. 2014), zonal flows (Simon & Armitage 2014), and weak vortices (Goodman et al. 1987). Meeting these benchmarks for substructure at these physical scales is not possible at any coarser resolution. The Class II disk Large Program verifies that substructures are present down to these scales and amplitudes at that evolutionary stage: we seek to find out if they are present, and if so similar, or perhaps more or less pronounced, at earlier times.

One of the primary reasons we have not yet seen a large volume of ALMA results for Class I disks is the perception that the separation of inner envelope and disk emission remains a challenge (or, more accurately, strongly depends on relatively poorly-constrained model parameterizations). That conservatism is reasonable; this is a challenging problem. However, in the very specific context of the program we are proposing, distinguishing between the "inner envelope" and the "disk" on radial scales of a few tens of au, and at resolutions of $\sim$5 au, is besides the point. The answers to the basic question we are asking – are there substructures with similar morphologies and scales at comparable locations to those seen in the Class II disk population? – are agnostic about which circumstellar component is associated with that material. Nevertheless, we appreciate the utility of populating the ALMA archive with data that has multiple uses. To that end, we are including the CO J=2$-$1 main isotopologues in the accompanying short-spacings observations (C43-5/6), with the goal of helping to characterize the gas densities and kinematics on angular scales traditionally associated with the disk/envelope transition region in Class I sources. To be conservative, we will maximize the continuum bandwidth on the long baselines: the Class II disk Large Program makes clear that the line emission from most disks at sub-0.1″ resolution requires a substantially larger time investment that is not yet justified for this sample.

Our philosophy for analyzing such data is to focus first on a quantitative, (data-driven) phenomenological characterization of the substructure as observed (i.e., in terms of the scales and amplitudes of surface brightness features, rather than physical conditions). Without knowing what we are facing at these resolution scales, it seems pre-mature to force a parametric model/simulation to fit the data. Once the basic analysis of the sample is underway, we will endeavor to interpret key features in the contexts of detailed models for planet-disk interactions, the evolution of disk solids, and global-scale magnetic structures, all grounded in radiative transfer simulations (using `RADMC-3D`), all of which we are developing now for use on the Class II disks Large Program dataset. Ultimately, these observations and this template for analysis will serve as important guides for interpreting future observations of Class I disks in general and their substructures in particular.

References

ALMA Partnership 2015, *ApJ*, 808, L3 • Andrews et al. 2016, *ApJ*, 820, L40 • Armitage et al. 2016, *ApJ*, 828, L2 • Bae et al. 2017, *ApJ*, 850, 201 • Bae & Zhu 2017, *ApJ*, in press (arXiv:1711.08161) • Bai & Stone 2014, *ApJ*, 796, 31 • Boley 2017, *ApJ*, 850, 103 • Casassus et al. 2013, *Nature*, 493, 91 • Christiaens et al. 2014, *ApJ*, 785, L12 • Cieza et al. 2016, *Nature*, 535, 238 • Dipierro et al. 2015, *MNRAS*, 451, 974 • Dong et al. 2017, *ApJ*, 843, 147 • Dullemond & Penzlin 2018, *A&A*, 609, 50 • Eisner 2012, *ApJ*, 755, 23 • Evans et al. 2009, *ApJS*, 181, 231 • Fedele et al. 2017, *A&A*, 600, 72 • Flock et al. 2015, *A&A*, 574, 68 • Fung et al. 2014, *ApJ*, 782, 88 • Fung & Dong 2015, *ApJ*, 815, L21 • Goodman et al. 1987, *MNRAS*, 225, 695 • Isella et al. 2016, *PRL*, 117, 251101 • Johansen et al. 2009, *ApJ*, 697, 1269 • Klahr & Henning 1997, *Icarus*, 128, 213 • Loomis et al. 2017, *ApJ*, 840, 23 • Lyra et al. 2015, *A&A*, 574, 10 • Nixon et al. 2018, *MNRAS*, in press (arXiv:1803.14407) • Okuzumi et al. 2016, *ApJ*, 821, 82 • Pérez et al. 2014, *ApJ*, 783, L13 • Pérez et al. 2016, *Science*, 353, 1519 • Pinilla et al. 2012, *A&A*, 538, 114 • Sheehan & Eisner 2017a, *ApJ*, 851, 45 • Sheehan & Eisner 2017b, *ApJ*, 840, L12 • Sheehan & Eisner 2018, *ApJ*, in press (arXiv:1802.02847) • Simon & Armitage 2014, *ApJ*, 784, 15 • van der Marel et al. 2013, *Science*, 340, 1199 • van der Plas et al. 2017, *A&A*, 597, 32 • Whipple 1972, *From Plasma to Planet*, 211 • Youdin & Shu 2002, *ApJ*, 580, 494 • Youdin & Goodman 2005, *ApJ*, 620, 459 • Zhu et al. 2012, *ApJ*, 755, 6 • Zhu & Stone 2014, *ApJ*, 795, 53 • Zhu et al. 2015, *ApJ*, 813, 88

None Assigned

SG : 1 of 6   IRAS 04016+2610 long baselines   Band 6

C43-8/9 observations to 17 uJy/beam.

Science Goal Parameters

Ang.Res.	LAS	Requested RMS	RMS Bandwidth	Rep.Freq.	Cont. RMS	Cont. Bandwidth	Poln.Prod.	Non-standard mode
0.0500" - 0.0250"	0.3"	17 µJy, 151.2 mK-604.8 mK	9588.245 km/s, 7.5 GHz	234.500000 GHz	16.944 µJy, 150.7 mK-602.8 mK	7.500 GHz	XX,YY	No

Use of 12m Array (43 antennas)

t_total(all configs)	t_science(C43-8,C4...	t_total()	Imaged area	#12m pointing	12m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate
3.2 h	1.3 h	0.0 h	8.3 "	1	offset	24.8 "	4717.2 s	25.2 GB	3.3 MB/s

Use of ACA 7m Array (10 antennas) and TP Array

t_total(ACA)	t_total(7m)	t_total(TP)	Imaged area	#7m pointing	7m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate

Spectral Setup : Single Continuum

Center Freq (Sky)	Center Freqs. SPWs	Eff #Ch p.p.	Bandwidth	Resolution	Vel. Bandwidth	Vel. Resolution	RMS
225.500000	216.500000	128	1875.00 MHz	31.250 MHz	2596.4 km/s	43.273 km/s	30.84 µJy, 1.3 K
	218.500000	128	1875.00 MHz	31.250 MHz	2572.6 km/s	42.876 km/s	30.93 µJy, 1.3 K
	232.500000	128	1875.00 MHz	31.250 MHz	2417.7 km/s	40.295 km/s	32.74 µJy, 1.2 K
	234.500000	128	1875.00 MHz	31.250 MHz	2397.1 km/s	39.951 km/s	34 µJy, 1.2 K

1 Target

No.	Target	Ra,Dec (ICRS)	V,def,frame --OR--z
1	1-IRAS 04016+2...	04:04:43, 26:18:56	4.00 km/s,lsrk,RADIO

Expected Source Properties

	Peak Flux	SNR	Linewidth	RMS (over 1/3 linewidth)	linewidth / bandwidth used for sensitivity	Pol.	Pol. SNR
Line	0.00 uJy	0.0	0 km/s			0.0%	0.0
Continuum	3.00 mJy	177.1				0.0%	0.0

Dynamic range (cont flux/line rms): N/A

Justification for requested RMS and resulting S/N (and for spectral lines the bandwidth selected) for the sensitivity ca...

The continuum observations are the primary focus of this proposal. Although we do not know for sure what the detailed surface brightness distribution will be for the targets in this sample, conservative simulations with smooth, power-law brightness distributions constrained by available low-resolution (~0.4") data suggest that our inner disk surface brightness criterion (>20 mJy total inside a FWHM = 0.5" region) should provide >0.9 mJy per 50 mas beam inside a radius of ~0.25" (30 au). Note that the peak flux densities provided here could be significantly higher than this conservative lower bound. We are aiming for >5-sigma sensitivity to 10% brightness variations due to substructure in this region, which pushes us to the target RMS noise level of ~17 microJy per beam. Our direct experience with a large, similar dataset for Class II disks (from 2016.1.00484.L) confirms this criterion is sufficient for the stated goals.

Justification of the chosen angular resolution and largest angular scale for the source(s) in this Science Goal.

The angular resolution (range) we propose (25-50 mas) is designed to probe brightness features down to ~5 au (projected) spatial scales in the target disks, fine enough to resolve individual substructures like gaps carved by protoplanets or turbulent concentrations on scales comparable to the gas pressure scale height over most of the disk area. While the maximum angular scale of the proposed observations is quite small (0.3"), we have demonstrated in the comparably-designed Cycle 4/5 Large Program of Class II disks (2016.1.00484.L) that we can successfully recover all of the relevant flux and construct images with high fidelity by including compatible short spacings observations (see separate Science Goal). Again, the focus here is on appropriate measurements of the contrasts of substructure features in the inner disks, so resolving out larger scale envelope emission is not a problem (it is, in fact, desirable).

Justification of the correlator set-up with particular reference to the number of spectral resolution elements per line ...

The proposed correlator configuration is optimized for continuum bandwidth (for sensitivity), with all 4 spectral windows covering 1.875 GHz of bandwidth each (in TDM mode).

Justification for non standard continuum frequencies.

N/A

None Assigned

SG : 2 of 6 IRAS 04108+2803B long baselines Band 6

C43-8/9 observations to 17 uJy/beam.

Science Goal Parameters

Ang.Res.	LAS	Requested RMS	RMS Bandwidth	Rep.Freq.	Cont. RMS	Cont. Bandwidth	Poln.Prod.	Non-standard mode
0.0500" - 0.0250"	0.3"	17 µJy, 151.2 mK-604.8 mK	9588.245 km/s, 7.5 GHz	234.500000 GHz	16.946 µJy, 150.7 mK-602.9 mK	7.500 GHz	XX,YY	No

Use of 12m Array (43 antennas)

t_total(all configs)	t_science(C43-8,C4...	t_total()	Imaged area	#12m pointing	12m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate
3.3 h	1.4 h	0.0 h	8.3 "	1	offset	24.8 "	4898.7 s	26.4 GB	3.3 MB/s

Use of ACA 7m Array (10 antennas) and TP Array

t_total(ACA)	t_total(7m)	t_total(TP)	Imaged area	#7m pointing	7m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate

Spectral Setup : Single Continuum

Center Freq (Sky)	Center Freqs. SPWs	Eff #Ch p.p.	Bandwidth	Resolution	Vel. Bandwidth	Vel. Resolution	RMS
225.500000	216.500000	128	1875.00 MHz	31.250 MHz	2596.4 km/s	43.273 km/s	30.77 µJy, 1.3 K
	218.500000	128	1875.00 MHz	31.250 MHz	2572.6 km/s	42.876 km/s	30.86 µJy, 1.3 K
	232.500000	128	1875.00 MHz	31.250 MHz	2417.7 km/s	40.295 km/s	32.71 µJy, 1.2 K
	234.500000	128	1875.00 MHz	31.250 MHz	2397.1 km/s	39.951 km/s	34 µJy, 1.2 K

1 Target

No.	Target	Ra,Dec (ICRS)	V,def,frame --OR--z
1	1-IRAS 04108+2...	04:13:54, 28:11:32	4.00 km/s,lsrk,RADIO

Expected Source Properties

	Peak Flux	SNR	Linewidth	RMS (over 1/3 linewidth)	linewidth / bandwidth used for sensitivity	Pol.	Pol. SNR
Line	0.00 uJy	0.0	0 km/s			0.0%	0.0
Continuum	3.00 mJy	177.0				0.0%	0.0

Dynamic range (cont flux/line rms): N/A

Justification for requested RMS and resulting S/N (and for spectral lines the bandwidth selected) for the sensitivity ca...

The continuum observations are the primary focus of this proposal. Although we do not know for sure what the detailed surface brightness distribution will be for the targets in this sample, conservative simulations with smooth, power-law brightness distributions constrained by available low-resolution (~0.4") data suggest that our inner disk surface brightness criterion (>20 mJy total inside a FWHM = 0.5" region) should provide >0.9 mJy per 50 mas beam inside a radius of ~0.25" (30 au). Note that the peak flux densities provided here could be significantly higher than this conservative lower bound. We are aiming for >5-sigma sensitivity to 10% brightness variations due to substructure in this region, which pushes us to the target RMS noise level of ~17 microJy per beam. Our direct experience with a large, similar dataset for Class II disks (from 2016.1.00484.L) confirms this criterion is sufficient for the stated goals.

Justification of the chosen angular resolution and largest angular scale for the source(s) in this Science Goal.

The angular resolution (range) we propose (25-50 mas) is designed to probe brightness features down to ~5 au (projected) spatial scales in the target disks, fine enough to resolve individual substructures like gaps carved by protoplanets or turbulent concentrations on scales comparable to the gas pressure scale height over most of the disk area. While the maximum angular scale of the proposed observations is quite small (0.3"), we have demonstrated in the comparably-designed Cycle 4/5 Large Program of Class II disks (2016.1.00484.L) that we can successfully recover all of the relevant flux and construct images with high fidelity by including compatible short spacings observations (see separate Science Goal). Again, the focus here is on appropriate measurements of the contrasts of substructure features in the inner disks, so resolving out larger scale envelope emission is not a problem (it is, in fact, desirable).

Justification of the correlator set-up with particular reference to the number of spectral resolution elements per line ...

The proposed correlator configuration is optimized for continuum bandwidth (for sensitivity), with all 4 spectral windows covering 1.875 GHz of bandwidth each (in TDM mode).

Justification for non standard continuum frequencies.

N/A

None Assigned

SG : 3 of 6 IRAS 04166+2706 long baselines Band 6

C43-8/9 observations to 17 uJy/beam.

Science Goal Parameters

Ang.Res.	LAS	Requested RMS	RMS Bandwidth	Rep.Freq.	Cont. RMS	Cont. Bandwidth	Poln.Prod.	Non-standard mode
0.0500" - 0.0250"	0.3"	17 µJy, 151.2 mK-604.8 mK	9588.245 km/s, 7.5 GHz	234.500000 GHz	16.968 µJy, 150.9 mK-603.6 mK	7.500 GHz	XX,YY	No

Use of 12m Array (43 antennas)

t_total(all configs)	t_science(C43-8,C4...	t_total()	Imaged area	#12m pointing	12m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate
3.2 h	1.3 h	0.0 h	8.3 "	1	offset	24.8 "	4789.8 s	25.6 GB	3.3 MB/s

Use of ACA 7m Array (10 antennas) and TP Array

t_total(ACA)	t_total(7m)	t_total(TP)	Imaged area	#7m pointing	7m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate

Spectral Setup : Single Continuum

Center Freq (Sky)	Center Freqs. SPWs	Eff #Ch p.p.	Bandwidth	Resolution	Vel. Bandwidth	Vel. Resolution	RMS
225.500000	216.500000	128	1875.00 MHz	31.250 MHz	2596.4 km/s	43.273 km/s	30.81 µJy, 1.3 K
	218.500000	128	1875.00 MHz	31.250 MHz	2572.6 km/s	42.876 km/s	30.9 µJy, 1.3 K
	232.500000	128	1875.00 MHz	31.250 MHz	2417.7 km/s	40.295 km/s	32.72 µJy, 1.2 K
	234.500000	128	1875.00 MHz	31.250 MHz	2397.1 km/s	39.951 km/s	34 µJy, 1.2 K

1 Target

No.	Target	Ra,Dec (ICRS)	V,def,frame --OR--z
1	1-IRAS 04166+2...	04:19:42, 27:13:38	4.00 km/s,lsrk,RADIO

Expected Source Properties

	Peak Flux	SNR	Linewidth	RMS (over 1/3 linewidth)	linewidth / bandwidth used for sensitivity	Pol.	Pol. SNR
Line	0.00 uJy	0.0	0 km/s			0.0%	0.0
Continuum	3.00 mJy	176.8				0.0%	0.0

Dynamic range (cont flux/line rms): N/A

Justification for requested RMS and resulting S/N (and for spectral lines the bandwidth selected) for the sensitivity ca...

The continuum observations are the primary focus of this proposal. Although we do not know for sure what the detailed surface brightness distribution will be for the targets in this sample, conservative simulations with smooth, power-law brightness distributions constrained by available low-resolution (~0.4") data suggest that our inner disk surface brightness criterion (>20 mJy total inside a FWHM = 0.5" region) should provide >0.9 mJy per 50 mas beam inside a radius of ~0.25" (30 au). Note that the peak flux densities provided here could be significantly higher than this conservative lower bound. We are aiming for >5-sigma sensitivity to 10% brightness variations due to substructure in this region, which pushes us to the target RMS noise level of ~17 microJy per beam. Our direct experience with a large, similar dataset for Class II disks (from 2016.1.00484.L) confirms this criterion is sufficient for the stated goals.

Justification of the chosen angular resolution and largest angular scale for the source(s) in this Science Goal.

The angular resolution (range) we propose (25-50 mas) is designed to probe brightness features down to ~5 au (projected) spatial scales in the target disks, fine enough to resolve individual substructures like gaps carved by protoplanets or turbulent concentrations on scales comparable to the gas pressure scale height over most of the disk area. While the maximum angular scale of the proposed observations is quite small (0.3"), we have demonstrated in the comparably-designed Cycle 4/5 Large Program of Class II disks (2016.1.00484.L) that we can successfully recover all of the relevant flux and construct images with high fidelity by including compatible short spacings observations (see separate Science Goal). Again, the focus here is on appropriate measurements of the contrasts of substructure features in the inner disks, so resolving out larger scale envelope emission is not a problem (it is, in fact, desirable).

Justification of the correlator set-up with particular reference to the number of spectral resolution elements per line ...

The proposed correlator configuration is optimized for continuum bandwidth (for sensitivity), with all 4 spectral windows covering 1.875 GHz of bandwidth each (in TDM mode).

Justification for non standard continuum frequencies.

N/A

None Assigned

SG : 4 of 6 IRAS 04169+2702 long baselines Band 6

C43-8/9 observations to 17 uJy/beam.

Science Goal Parameters

Ang.Res.	LAS	Requested RMS	RMS Bandwidth	Rep.Freq.	Cont. RMS	Cont. Bandwidth	Poln.Prod.	Non-standard mode
0.0500" - 0.0250"	0.3"	17 µJy, 151.2 mK-604.8 mK	9588.245 km/s, 7.5 GHz	234.500000 GHz	16.957 µJy, 150.8 mK-603.3 mK	7.500 GHz	XX,YY	No

Use of 12m Array (43 antennas)

t_total(all configs)	t_science(C43-8,C4...	t_total()	Imaged area	#12m pointing	12m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate
3.2 h	1.3 h	0.0 h	8.3 "	1	offset	24.8 "	4789.8 s	25.6 GB	3.3 MB/s

Use of ACA 7m Array (10 antennas) and TP Array

t_total(ACA)	t_total(7m)	t_total(TP)	Imaged area	#7m pointing	7m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate

Spectral Setup : Single Continuum

Center Freq (Sky)	Center Freqs. SPWs	Eff #Ch p.p.	Bandwidth	Resolution	Vel. Bandwidth	Vel. Resolution	RMS
225.500000	216.500000	128	1875.00 MHz	31.250 MHz	2596.4 km/s	43.273 km/s	30.81 µJy, 1.3 K
	218.500000	128	1875.00 MHz	31.250 MHz	2572.6 km/s	42.876 km/s	30.9 µJy, 1.3 K
	232.500000	128	1875.00 MHz	31.250 MHz	2417.7 km/s	40.295 km/s	32.73 µJy, 1.2 K
	234.500000	128	1875.00 MHz	31.250 MHz	2397.1 km/s	39.951 km/s	34 µJy, 1.2 K

1 Target

No.	Target	Ra,Dec (ICRS)	V,def,frame --OR--z
1	1-IRAS 04169+2...	04:19:58, 27:09:57	4.00 km/s,lsrk,RADIO

Expected Source Properties

	Peak Flux	SNR	Linewidth	RMS (over 1/3 linewidth)	linewidth / bandwidth used for sensitivity	Pol.	Pol. SNR
Line	0.00 uJy	0.0	0 km/s			0.0%	0.0
Continuum	3.00 mJy	176.9				0.0%	0.0

Dynamic range (cont flux/line rms): N/A

Justification for requested RMS and resulting S/N (and for spectral lines the bandwidth selected) for the sensitivity ca...

The continuum observations are the primary focus of this proposal. Although we do not know for sure what the detailed surface brightness distribution will be for the targets in this sample, conservative simulations with smooth, power-law brightness distributions constrained by available low-resolution (~0.4") data suggest that our inner disk surface brightness criterion (>20 mJy total inside a FWHM = 0.5" region) should provide >0.9 mJy per 50 mas beam inside a radius of ~0.25" (30 au). Note that the peak flux densities provided here could be significantly higher than this conservative lower bound. We are aiming for >5-sigma sensitivity to 10% brightness variations due to substructure in this region, which pushes us to the target RMS noise level of ~17 microJy per beam. Our direct experience with a large, similar dataset for Class II disks (from 2016.1.00484.L) confirms this criterion is sufficient for the stated goals.

Justification of the chosen angular resolution and largest angular scale for the source(s) in this Science Goal.

The angular resolution (range) we propose (25-50 mas) is designed to probe brightness features down to ~5 au (projected) spatial scales in the target disks, fine enough to resolve individual substructures like gaps carved by protoplanets or turbulent concentrations on scales comparable to the gas pressure scale height over most of the disk area. While the maximum angular scale of the proposed observations is quite small (0.3"), we have demonstrated in the comparably-designed Cycle 4/5 Large Program of Class II disks (2016.1.00484.L) that we can successfully recover all of the relevant flux and construct images with high fidelity by including compatible short spacings observations (see separate Science Goal). Again, the focus here is on appropriate measurements of the contrasts of substructure features in the inner disks, so resolving out larger scale envelope emission is not a problem (it is, in fact, desirable).

Justification of the correlator set-up with particular reference to the number of spectral resolution elements per line ...

The proposed correlator configuration is optimized for continuum bandwidth (for sensitivity), with all 4 spectral windows covering 1.875 GHz of bandwidth each (in TDM mode).

Justification for non standard continuum frequencies.

N/A

None Assigned

SG : 5 of 6 IRAS 04295+2251 long baselines Band 6

C43-8/9 observations to 17 uJy/beam.

Science Goal Parameters

Ang.Res.	LAS	Requested RMS	RMS Bandwidth	Rep.Freq.	Cont. RMS	Cont. Bandwidth	Poln.Prod.	Non-standard mode
0.0500" - 0.0250"	0.3"	17 µJy, 151.2 mK-604.8 mK	9588.245 km/s, 7.5 GHz	234.500000 GHz	16.975 µJy, 151 mK-603.9 mK	7.500 GHz	XX,YY	No

Use of 12m Array (43 antennas)

t_total(all configs)	t_science(C43-8,C4...	t_total()	Imaged area	#12m pointing	12m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate
3.0 h	1.2 h	0.0 h	8.3 "	1	offset	24.8 "	4426.9 s	24.0 GB	3.3 MB/s

Use of ACA 7m Array (10 antennas) and TP Array

t_total(ACA)	t_total(7m)	t_total(TP)	Imaged area	#7m pointing	7m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate

Spectral Setup : Single Continuum

Center Freq (Sky)	Center Freqs. SPWs	Eff #Ch p.p.	Bandwidth	Resolution	Vel. Bandwidth	Vel. Resolution	RMS
225.500000	216.500000	128	1875.00 MHz	31.250 MHz	2596.4 km/s	43.273 km/s	30.97 µJy, 1.3 K
	218.500000	128	1875.00 MHz	31.250 MHz	2572.6 km/s	42.876 km/s	31.05 µJy, 1.3 K
	232.500000	128	1875.00 MHz	31.250 MHz	2417.7 km/s	40.295 km/s	32.79 µJy, 1.2 K
	234.500000	128	1875.00 MHz	31.250 MHz	2397.1 km/s	39.951 km/s	34 µJy, 1.2 K

1 Target

No.	Target	Ra,Dec (ICRS)	V,def,frame --OR--z
1	1-IRAS 04295+2...	04:32:32, 22:57:26	4.00 km/s,lsrk,RADIO

Expected Source Properties

	Peak Flux	SNR	Linewidth	RMS (over 1/3 linewidth)	linewidth / bandwidth used for sensitivity	Pol.	Pol. SNR
Line	0.00 uJy	0.0	0 km/s			0.0%	0.0
Continuum	3.00 mJy	176.7				0.0%	0.0

Dynamic range (cont flux/line rms): N/A

Justification for requested RMS and resulting S/N (and for spectral lines the bandwidth selected) for the sensitivity ca...

The continuum observations are the primary focus of this proposal. Although we do not know for sure what the detailed surface brightness distribution will be for the targets in this sample, conservative simulations with smooth, power-law brightness distributions constrained by available low-resolution (~0.4") data suggest that our inner disk surface brightness criterion (>20 mJy total inside a FWHM = 0.5" region) should provide >0.9 mJy per 50 mas beam inside a radius of ~0.25" (30 au). Note that the peak flux densities provided here could be significantly higher than this conservative lower bound. We are aiming for >5-sigma sensitivity to 10% brightness variations due to substructure in this region, which pushes us to the target RMS noise level of ~17 microJy per beam. Our direct experience with a large, similar dataset for Class II disks (from 2016.1.00484.L) confirms this criterion is sufficient for the stated goals.

Justification of the chosen angular resolution and largest angular scale for the source(s) in this Science Goal.

The angular resolution (range) we propose (25-50 mas) is designed to probe brightness features down to ~5 au (projected) spatial scales in the target disks, fine enough to resolve individual substructures like gaps carved by protoplanets or turbulent concentrations on scales comparable to the gas pressure scale height over most of the disk area. While the maximum angular scale of the proposed observations is quite small (0.3"), we have demonstrated in the comparably-designed Cycle 4/5 Large Program of Class II disks (2016.1.00484.L) that we can successfully recover all of the relevant flux and construct images with high fidelity by including compatible short spacings observations (see separate Science Goal). Again, the focus here is on appropriate measurements of the contrasts of substructure features in the inner disks, so resolving out larger scale envelope emission is not a problem (it is, in fact, desirable).

Justification of the correlator set-up with particular reference to the number of spectral resolution elements per line ...

The proposed correlator configuration is optimized for continuum bandwidth (for sensitivity), with all 4 spectral windows covering 1.875 GHz of bandwidth each (in TDM mode).

Justification for non standard continuum frequencies.

N/A

None Assigned

SG : 6 of 6 Short-Spacings Cluste Band 6

Observations at shorter spacings to improve self-calibration and imaging. All targets can be in a single cluster.

Science Goal Parameters

Ang.Res.	LAS	Requested RMS	RMS Bandwidth	Rep.Freq.	Cont. RMS	Cont. Bandwidth	Poln.Prod.	Non-standard mode
0.2500" - 0.1500"	2.0"	40 µJy, 14.3 mK-39.7 mK	5878.609 km/s, 4.6 GHz	234.000000 GHz	39.73 µJy, 14.2 mK-39.4 mK	4.588 GHz	XX,YY	No

Use of 12m Array (43 antennas)

t_total(all configs)	t_science(C43-6)	t_total()	Imaged area	#12m pointing	12m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate
3.7 h	2.2 h	0.0 h	8.3 "	5	offset	24.9 "	1632.7 s	170.0 GB	15.3 MB/s

Use of ACA 7m Array (10 antennas) and TP Array

t_total(ACA)	t_total(7m)	t_total(TP)	Imaged area	#7m pointing	7m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate

Spectral Setup : Spectral Line

BB	Center Freq Rest GHz	spw name	Eff #Ch p.p.	Bandwidth	Resolution	Vel. Bandwidth	Vel. Res.	Res. El. per FWHM
1	219.560358	C18O 2-1	3840	937.50 MHz	0.564 MHz	1280.1 km/s	0.771 km/s	0
2	220.398684	13CO v=0 2-1	3840	937.50 MHz	0.564 MHz	1275.3 km/s	0.768 km/s	0
3	230.538000	CO v=0 2-1	3840	937.50 MHz	564.453 kHz	1219.2 km/s	0.734 km/s	0
4	234.000000	continuum	128	1875.00 MHz	31.250 MHz	2402.3 km/s	40.038 km/s	0

5 Targets

No.	Target	Ra,Dec (ICRS)	V,def,frame --OR--z
1	1-IRAS 04016+2...	04:04:43, 26:18:56	4.00 km/s,lsrk,RADIO
2	2-IRAS 04108+2...	04:13:54, 28:11:32	4.00 km/s,lsrk,RADIO
3	3-IRAS 04166+2...	04:19:42, 27:13:38	4.00 km/s,lsrk,RADIO
4	4-IRAS 04169+2...	04:19:58, 27:09:57	4.00 km/s,lsrk,RADIO
5	5-IRAS 04295+2...	04:32:32, 22:57:26	4.00 km/s,lsrk,RADIO

Expected Source Properties

	Peak Flux	SNR	Linewidth	RMS (over 1/3 linewidth)	linewidth / bandwidth used for sensitivity	Pol.	Pol. SNR
Line	0.00 uJy	0.0	0 km/s			0.0%	0.0
Continuum	0.00 uJy	0.0				0.0%	0.0

Dynamic range (cont flux/line rms): N/A

1 Tuning

Tuning	Target	Rep. Freq. Sky GHz	RMS (Rep. Freq.)	RMS Achieved
1	1,2,3,4,5	233.996878	38.43 µJy, 38.1 mK	32.70 uJy - 38.43 uJy

Sensitivity Comments

Note that one or more of the S/N estimates are < 3. Please double-check the RMS and/or line fluxes entered and/or address the issue below.

Justification for requested RMS and resulting S/N (and for spectral lines the bandwidth selected) for the sensitivity calculation.

Our experience with comparable observations of a large sample of Class II disks (2016.1.00484.L) confirm that we can optimize our image fidelity and recover emission on all of the relevant spatial scales by including measurements with a maximum angular scale >2 arcseconds, provided they have high S/N. We are therefore targeting a continuum RMS noise level of 0.04
mJy/beam (aggregated over the full bandwidth), which should provide a peak S/N > 100 (our peak flux density estimates presume a flat intensity model for the brightness distribution based on ~0.4"-resolution previous observations) for all targets in this sample and would be sufficient to combine with the long-baseline observations and meet our science aims.

Justification of the chosen angular resolution and largest angular scale for the source(s) in this Science Goal.

These observations play a crucial support role to the primary focus of this proposal. Very long baselines are required to map small features in the targets, but the associated ALMA configurations lack the short spacings needed to recover the disk emission on all of the relevant spatia scales. We are targeting a maximum recoverable scale of >2 arcseconds, which is sufficient for all of the sample, given our knowledge of the source emission distributions from
previous observations at ~0.4" angular resolution. More important is that the observations with short spacings have substantial overlap in (u,v coverage with the longer-baseline observations we are proposing, to ensure a robust calibration and good image fidelity. Only the C43-5/6 configurations meet these goals.

Justification of the correlator set-up with particular reference to the number of spectral resolution elements per line width.

The proposed correlator configuration strikes a balance between continuum bandwidth (for sensitivity and the main focus of the proposal) and spectral resolution that covers the 3 main CO(2-1) isotopologue lines (just over ~0.7 km/s resolution, sufficient for rotating disks). The expected line widths from the typical source in the sample is ~3-10 km/s, so we expect them all to be spectrally resolved. The sensitivity to these lines at the nominal resolution should be good for standard assumptions (we estimate a peak S/N > 10 per channel on average in 12CO and 13CO, perhaps 3-5 for C18O), although realistically we do not know exactly what to expect when there is additional envelope emission.