The origin of large-scale gas spirals around a young T Tauri star

ABSTRACT

Multiple theories have emerged to explain spirals in protoplanetary disks, but observed spirals have yet to be definitively tied to a formation scenario. In Cycle 4, we serendipitously discovered spiral arms in 12CO emission extending out ~1000 AU from the star RU Lup. Whereas gas spirals have previously only been observed around Herbig Ae stars of intermediate age hosting transition disks, RU Lup is a young T Tauri star that hosts a full disk and likely probes a much earlier stage in disk evolution. RU Lup is perhaps most well-known for its large, irregular spectral variations over the past century, and its non-Keplerian 12CO kinematics have been compared to the younger, extremely active, and gravitationally unstable FU Ori sources. To assess whether gravitational instability can also create the spiral arms in RU Lup, we request deep observations of 12CO, 13CO, and C18O to develop a more accurate picture of the emission morphology and to derive the gas mass of the disk. Confirmation of GI in a Class II disk for the first time would suggest it can remain a viable planet-forming mechanism in the later stages of disk evolution.

PI NAME:	Jane Huang			**SCIENCE CATEGORY:**	Circumstellar disks, exoplanets and the solar system
ESTIMATED 12M TIME:	**2.5 h**	**ESTIMATED ACA TIME:**	**2.4 h**	**ESTIMATED NON-STANDARD MODE TIME (12-M):**	**0.0 h**
CO-PI NAME(S): (Large & VLBI Proposals only)					
CO-INVESTIGATOR NAME(S):	Sean Andrews; David Wilner; Karin Oberg; John Carpenter; Andrea Isella; Tilman Birnstiel; Zhaohuan Zhu; Cornelis Dullemond; Laura Perez; A. Meredith Hughes; Myriam Benisty; Viviana Guzman; Luca Ricci; Xuening Bai; Jonathan Williams; Megan Ansdell				
DUPLICATE OBSERVATION JUSTIFICATION:					

REPRESENTATIVE SCIENCE GOALS (UP TO FIRST 30)

SCIENCE GOAL	POSITION	BAND	ANG.RES.(")	LAS.(")	ACA?	NON-STANDARD MODE
Science Goal	ICRS 15:56:42.3115, -37:49:15.502	6	0.250 - 0.200	12.000	Y	N
Total # Science Goals : 1						

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

Scientific justification

Background and Motivation

Recent observations of spiral arms in protoplanetary disks (e.g. Muto et al. 2012, Grady et al. 2013, Pérez et al. 2016) have fueled a lively debate over their origins. Proposed formation mechanisms include planet-disk interactions (e.g. Goldreich et al. 1979, Tanaka et al. 2002), gravitational instability (e.g. Mayer et al. 2004, Lodato et al. 2004), and envelope infall (e.g. Lesur et al. 2016). Reliably distinguishing between these possibilities is crucial to developing a coherent picture of how disks evolve and planets form.

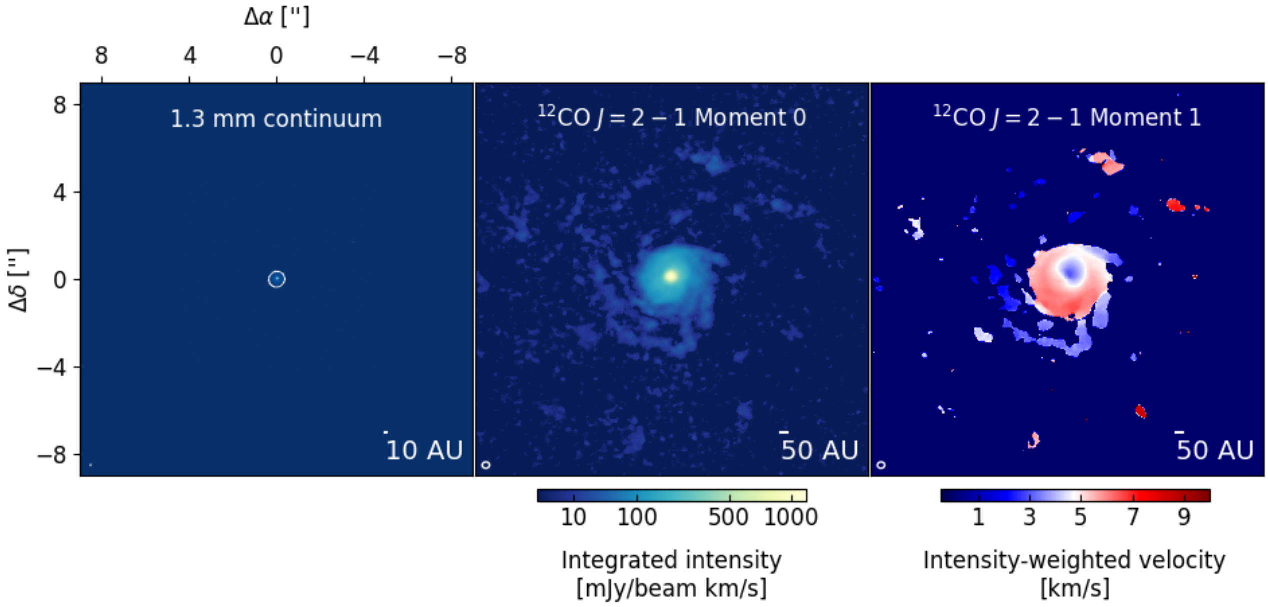

Figure 1: Cycle 4 ALMA Large Program observations of RU Lup. *Left:* 1.3 mm continuum with 5σ contour in white. *Middle:* ^{12}CO integrated intensity at a resolution of $0\farcs3$, on the same spatial scale as the continuum and clipped at 3σ. *Right:* Intensity-weighted ^{12}CO velocity field, clipped at 5σ.

As part of an ALMA Cycle 4 Large Program surveying substructures in the dust continuum of protoplanetary disks (2016.1.00484.L, PI: S.M. Andrews), we serendipitously discovered **multiple spiral arms in ^{12}CO $J = 2 - 1$ emission extending out to a radius of about 1000 AU from RU Lup** (see Fig. 1), a ~ 2 Myr, 1.15 $M_\odot$ T Tauri star located 167 pc away in the Lupus star-forming region (Alcalá et al. 2014, Gaia Collaboration et al. 2016). RU Lup stands out in several key ways from previous observations of spiral arms in molecular emission around protoplanetary disks; the three previous detections (AB Aur, HD 142527, and MWC 758) have been in ~ 4 to 12 Myr transition disks hosted by Herbig Ae stars (Corder et al. 2005, Christiaens et al. 2014, Tang et al. 2017, Boehler et al. 2018), whereas RU Lup is a younger, lower-mass star with no central cavity in its disk. These factors suggest that RU Lup may represent a new class of spiral-armed disks, probing an earlier stage of evolution.

The new detection of spiral arms is particularly intriguing given the suggestion in Siwak et al. (2016) that RU Lup's famously large and irregular spectral variations dating back more than 100 years (e.g. Joy 1945, Stempels et al. 2002) could be linked to variable mass accretion driven by disk spiral arms. This source has one of the highest accretion rates measured for a T Tauri star, at $7 \times 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ (Alcalá et al. 2017). The non-Keplerian kinematics of ^{12}CO emission at large radii, as shown in Figure 1 and reported for independent observations of RU Lup in Ansdell et al. (2018), are reminiscent of patterns observed for FU Orionis objects, which have large, irregular outbursts that have been attributed to gravitationally unstable disks (e.g. Zhu et al. 2009). In contrast to classical FU Orionis objects, though, RU Lup exhibits no envelope signatures—the SED is typical of a class II disk, A_v has been measured to be 0.0, and single-dish measurements of the 1.3 mm continuum flux match our resolved ALMA observations of RU Lup, indicating that the emission originates solely from disk material (Hughes et al. 1994, Nürnberger et al. 1997, Alcalá et al. 2014). We therefore hypothesize that RU Lup may reveal the state of a protoplanetary disk shortly after envelope dispersal and could thus represent an evolutionary link between the extremely active, embedded FU Orionis objects and the comparatively quiescent, more evolved classical T Tauri stars. Confirmation of gravitational instability in a Class II disk for the first time would suggest it can remain a viable planet-forming mechanism comparatively late in the disk evolution process.

Because RU Lup's large-scale gas structure was previously unknown and our ALMA Cycle 4 Large Program was primarily aimed at imaging the much more compact millimeter dust continuum (see Fig. 1), the observational setup was not optimal for recovering large-scale emission, and the only line targeted was ^{12}CO $J = 2-1$. The most compact array configuration used to observe RU Lup (C40-5) had a maximum recoverable scale of only $2\farcs6$, whereas the gas emission from RU Lup stretches out to a radius of $\approx 7''$ from the star, which raises the possibility that the current line image is substantially spatially filtered. The outer portions of the spiral arms are detected at $\sim 5\sigma$, but it is ambiguous whether the emission irregularity is due to a physical process such as fragmentation or is a consequence of spatial filtering and modest sensitivity. This presents an obstacle to obtaining reliable constraints on the line fluxes, kinematics, and emission geometry, which are all necessary to assess whether gravitational instability is at play.

Proposed observations and immediate objectives

To investigate whether disk instabilities are responsible for creating the spiral arms traced by ^{12}CO around RU Lup, **we propose deep imaging of the ^{12}CO, ^{13}CO, and C^{18}O $J = 2-1$ transitions at an angular resolution of $0\farcs25$**. As demonstrated by the ^{12}CO observations shown in Figure 1, the requested angular resolution is appropriate for resolving the spiral arms. Spectral line observations with ALMA are the *only* means of directly studying the spiral arm morphology; neither the millimeter dust continuum (see Fig. 2) nor scattered light observations (Avenhaus et al. 2018) exhibit spiral features, suggesting that the arms originate from a radius beyond where the dust observations are sensitive.

The ^{13}CO $J = 2-1$ line has previously been observed in a snapshot survey of Class II sources in Lupus (see Ansdell et al. 2018 and Fig. 2). However, because of the very brief integration time ($\sim$ 1 minute), the signal-to-noise of the existing ^{13}CO data is very low, and only detected out to a radius of $\sim$100 AU, far short of where we detect ^{12}CO in our deeper Large Program observations. Based on snapshot ^{13}CO $J = 3-2$ observations, Miotello et al. (2017) estimated a gas mass of 1.5×10^{-3} M$_\odot$, making it one of the most massive disks in Lupus. We argue that the true gas mass is likely much higher, given that the ^{13}CO observations were not sensitive to the radii we now know have very bright ^{12}CO emission. Since gravitational instability is more likely to originate in the cold outer regions of the disk (e.g. Kratter and Lodato 2013), it is essential to image ^{13}CO with sufficient sensitivity to trace the gas surface density out to hundreds of AU.

Radiative transfer modeling with RADMC-3D of existing high angular resolution millimeter continuum and scattered light observations will be used to constrain the thermal structure of the inner disk, while the brightness temperature of optically thick ^{12}CO will constrain the temperature of the gas at large radii. We will then measure the disk surface density by using RADMC-3D and parametric abundance and kinematic structures (e.g., Rosenfeld et al. 2014, Williams and McPartland 2016) to fit the emission of the lower optical depth isotopologues, ^{13}CO and C^{18}O. The temperature

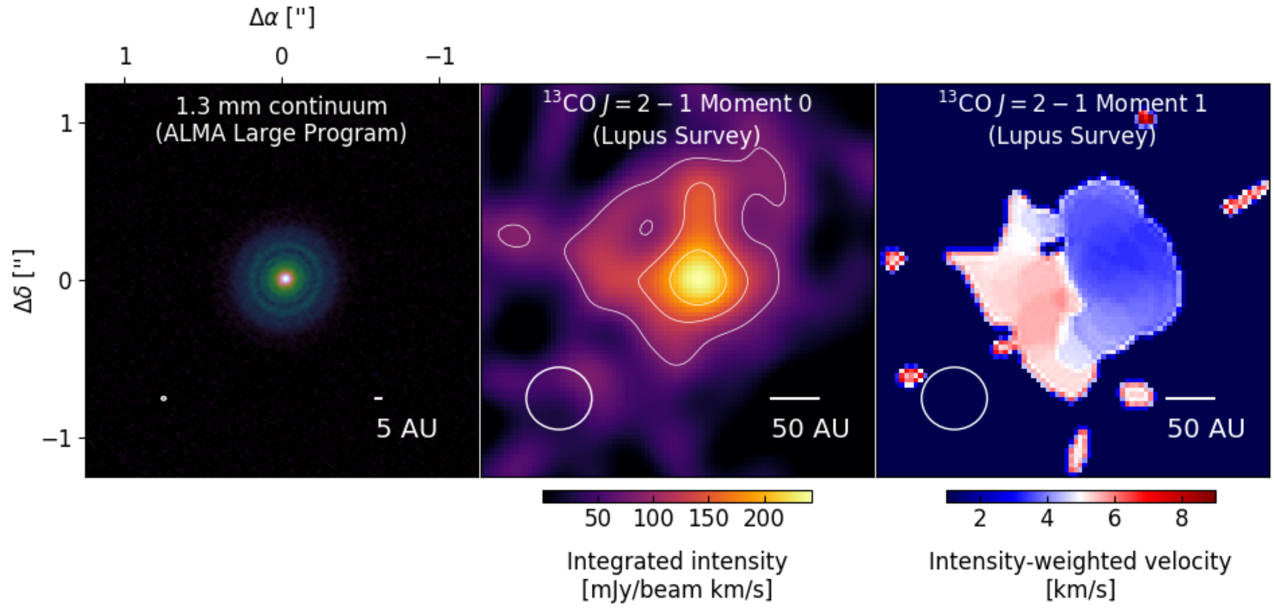

Figure 2: *Left:* 1.3 mm continuum from our ALMA Large Program. *Middle:* Integrated intensity map of ^{13}CO from a Lupus snapshot survey (Ansdell et al. 2018) at an angular resolution of $0\farcs4$, shown on the same spatial scale as the continuum. The 3, 5, 7σ contours are drawn in white. *Right:* Intensity-weighted velocity field of ^{13}CO.

and surface density measurements will thus allow us to derive the Toomre Q parameter and assess whether RU Lup's disk meets the stability criterion.

Since some uncertainty exists with respect to the CO-to-gas conversion for disks, our gas surface density estimates will take possible CO depletion into account based on the factors that have been derived for the Lupus region (Miotello et al. 2017). In any case, we can derive a lower limit for the gas surface density (and an upper limit on the Q parameter) because disk chemical processes are only expected to deplete, not enhance, CO abundances relative to the ISM (e.g. Schwarz et al. 2016). Alternatively, evidence of gravitational instability may manifest directly in the spectral line cubes in the form of a distinct emission clump offset from the regular spiral pattern, as predicted by hydrodynamical simulations (e.g., Vorobyov and Basu 2015). Since this line of evidence for instability requires no assumptions about disk chemistry, confirmation of such a feature toward RU Lup would offer an independent check of whether commonly used methods for deriving disk masses from CO emission yield reasonable results.

Furthermore, because the CO isotopologues have differing optical depths, they trace different scale heights in the disk. Compared to ^{12}CO, the ^{13}CO emission appears to trace the bulk Keplerian rotation of the disk more closely. More sensitive imaging, coupled with our parametric modeling procedure, will allow us to confirm whether the ^{13}CO emission remains consistent with Keplerian motion and will therefore constrain the height and radius from which the non-Keplerian kinematics observed in ^{12}CO originates.

The data will also allow us to explore alternate scenarios for spiral formation if we rule out disk instabilities for RU Lup. Perhaps the most popular hypothesis for spiral formation in Class II disks is that they are generated by embedded planets (e.g. Muto et al. 2012, Fung et al. 2015). With a higher-fidelity image, we can compare the observed spiral pitch angles and arm separations to the parameter space study presented in Bae et al. (2017), which used hydrodynamical simulations to predict spiral morphology as a function of companion mass and disk location. Placing limits on the properties of a potential companion can guide follow-up direct imaging searches with other facilities for confirmation of its existence.

Technical considerations

Our current ^{12}CO moment 1 map (Figure 1) shows emission with at least a 5σ level with a coherent velocity pattern extending out to $\sim$ 1000 AU. However, it is unclear whether the apparent emission discontinuities in the arms are a consequence of the signal-to-noise/spatial filtering, or whether it genuinely traces localized emission enhancements. To enable measurements of the emission contrast, we seek to image the extended spiral arms in ^{12}CO at the $\sim 10\ \sigma$ level, requiring a sensitivity of 3 mJy beam^{-1} in 0.25 km s^{-1} channels. Using resolved Band 6 Lupus survey observations of the $J = 2 - 1$ lines of ^{13}CO and C^{18}O toward RU Lup, we estimate that the requested sensitivity will also yield a peak SNR of 30 for ^{13}CO and 15 for C^{18}O. In addition, using the integrated flux ratios of ^{12}CO $J = 2 - 1$ and ^{13}CO $J = 2 - 1$, we estimate that ^{13}CO can be imaged with a least a SNR of 4 at 300 AU, covering the entire "nucleus" of the spiral structure and allowing us to probe very cold regions of the disk. We also require a maximum recoverable scale of 12″, commensurate with the scale of ^{12}CO emission observed. In accordance with the Observing Tool guidelines, our aims are best achieved through observations in the moderately-extended C43-5 configuration to achieve the appropriate angular resolution combined with additional observations in the C43-2 configuration and the ACA 7-m array to recover the larger-scale emission. Our total time request is 2.5 hours with the 12-m arrays and 2.4 hours with the ACA 7-m array, including overhead.

The three CO isotopologues can be observed with a single spectral setting. Within the same spectral setting, we place an auxiliary window on DCO$^+$ $J = 3 - 2$, which has been observed in a number of disks and can be a useful complementary kinematics tracer near the midplane of the outer disk (e.g., Flaherty et al. 2017).

We were also recently allocated time on APEX for the April to August 2018 observing period to measure the CO isotopologue zero-spacing fluxes, which will complement the requested ALMA observations if even larger-scale emission is present.

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ID Not Assigned

SG : 1 of 1 Science Goal Band 6

Observations of the RU Lup spiral arms as traced by 12CO 2-1, 13CO 2-1, and C18O 2-1

Science Goal Parameters

Ang.Res.	LAS	Requested RMS	RMS Bandwidth	Rep.Freq.	Cont. RMS	Cont. Bandwidth	Poln.Prod.	Non-standard mode
0.2500" - 0.2000"	12.0"	3 mJy, 1.1 K-1.7 K	250 m/s, 192.2 kHz	230.538000 GHz	27.794 µJy, 10.2 mK-16 mK	2.227 GHz	XX,YY	No

Use of 12m Array (43 antennas)

t_total(all configs)	t_science(C43-5)	t_total(C43-2)	Imaged area	#12m pointing	12m Mosaic spacing	HPBW	t_per_point	Data Vol	Avg. Data Rate
2.5 h	1.1 h	0.5 h	8.4 "	1	offset	25.3 "	3931.0 s	109.7 GB	15.0 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
2.4 h	2.4 h	0.0 h	14.4 "	1	offset	43.3 "	4777.7 s	2.3 GB	0.3 MB/s

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	230.538000	CO v=0 2-1	3840	117.19 MHz	0.071 MHz	152.4 km/s	0.092 km/s	22
2	232.800000	Continuum	128	1875.00 MHz	31.250 MHz	2414.6 km/s	40.243 km/s	0
3	216.112580	DCO+ v=0 J=3-2	3840	117.19 MHz	70.557 kHz	162.6 km/s	0.098 km/s	20
4	220.398684	13CO v=0 2-1	1920	58.59 MHz	0.071 MHz	79.7 km/s	0.096 km/s	21
4	219.560358	C18O 2-1	1920	58.59 MHz	0.071 MHz	80.0 km/s	0.096 km/s	21

1 Target

No.	Target	Ra,Dec (ICRS)	V,def,frame --OR--z
1	1-RU_Lup	15:56:42, -37:49:15	4.00 km/s,lsrk,RADIO

Expected Source Properties

	Peak Flux	SNR	Linewidth	RMS (over 1/3 linewidth	linewidth / bandwidtl used for sensitivity	Pol.	Pol. SNR
Line	290.00 mJy	158.3	2 km/s	1.83 mJy, 1.1 K	8.00	0.0%	0.0
Continuum	200.00 mJy	7195.8				0.0%	0.0

Dynamic range (cont flux/line rms): 66.9

1 Tuning

Tuning	Target	Rep. Freq. Sky GHz	RMS (Rep. Freq.)	RMS Achieved
1	1	230.534924	2.99 mJy, 1.7 K	2.89 mJy - 3.04 mJy

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

The line width at the location of the spiral arms is ~2 km/s, as measured in our Cycle 4 observations. The bandwidth we use for the sensitivity calculation, 0.25 km/s, is chosen such that the spiral arms are well-resolved spectrally (8 elements across the line). Good spectral resolution is necessary to measure the velocity at which the gas in the spiral arms is moving.

In order to measure the geometry of the spiral arms accurately and to determine whether the emission levels in the arms are genuinely irregular or simply an outcome of spatial filtering and modest sensitivity, we seek to detect the spiral arms in 12CO out to large distances to at least the 10sigma level, requiring an rms of 3 mJy/beam.

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

Our previous 12CO observations from Cycle 4 (Figure 1 of Science Justification) show that an angular resolution of 0.2" to 0.3" can resolve the spiral arm features, which is necessary for measuring the geometry of the arms and comparing to theoretical predictions for how spiral morphology manifests for different generating mechanisms. Our largest angula scale of 12" is based on the extent of emission observed above 5sigma in the moment 1 map.

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

We target 12CO 2-1 to constrain the spiral emission geometry and estimate the gas kinetic temperatures, while 13CO 2-1 and C18O 2-1 will be used to constrain the gas mass. DCO+ 3-2 is included as an auxiliary tracer of disk kinematics in the outer disk midplane We have selected a spectral resolution of ~0.09 km/s to provide ~25 elements per line width at the locations of the spiral arms in the outer disk. Our existing observations exhibit some deviations from the standard Keplerian velocity curve, so high spectral resolution would allow us to more precisely quantify the size of the deviations and whether they could be related to a spiral generating mechanism (e.g., infall, outflows, or winds). If necessary, we can spectrally average the calibrated visibilities to improve the SNR while still spectrally resolving the lines.

We also include one continuum window to aid with self-calibration of the lines, since RU Lup is a relatively strong continuum source.