TOM DOUGLAS None Assigned

PROJECT TITLE:	Shocks and Spirals Arms: the wild years of young protoplanetary discs				
PRINCIPAL INVESTIGATOR NAME:	Tom Douglas	PROJECT CODE:	None Assigned		
SCIENCE CATEGORY:	ISM, star formation and astrochemistry	ESTIMATED 12M TIME:	4.3 h	ESTIMATED ACA + TP TIME:	0.0 h
CO-PI NAME(S): (Large Proposals only)					
CO-INVESTIGATOR NAME(S):	Paola Caselli; Thomas Hartquist; John Ilee; Aaron Boley; Jaime Pineda; Jonathan Rawlings; Richard Durisen				
EXECUTIVE SHARES[%]:	NA : 0 EU : 100 EA : 0 CL : 0 OTHER : 0	STUDENT PROJECT? (Yes/No)	Yes	RESUBMISSION? (Yes/No)	No

ABSTRACT

We propose to test planet formation and disc evolution theory by investigating whether very young protoplanetary discs have asymmetric structure that would be consistent with global disc instabilities. ALMA observations of IRAS16293-2422 A and B (hereafter IRAS1629A and IRAS1629B) in band 7 will provide high-resolution spatial and kinematic data for direct comparison with state-of-the-art hydrodynamic, chemical and radiative transfer models of protoplanetary discs. The presence or absence of gravitational instabilities has tremendous implications for planet and brown dwarf formation by disc instability.

REPRESENTATIVE SCIENCE GOALS (UP TO FIRST 5)

SCIENCE GOAL	POSITION	FREQUENCY	BAND	ANG.RES.(")	ACA?
IRAS16293	J2000: 16:32:22.7500, -24:28:34.000	364.31150 GHz	7	0.2	N
Total # Science Goals : 1					

SCHEDULING TIME CONSTRAINTS (e.g. Co-ordinated observations already scheduled)	NONE	Extra Time Requested?	No

PI CONTACT INFORMATION

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Shocks and Spirals Arms: the wild years of young protoplanetary discs

PI: Tom Douglas

1 Scientific rationale

We propose to test planet formation and disc evolution theory by investigating whether very young protoplanetary discs have asymmetric structure that would be consistent with global disc instabilities. ALMA observations of IRAS16293-2422 A *and* B (hereafter IRAS1629A and IRAS1629B) in band 7 will provide high-resolution spatial and kinematic data for direct comparison with state-of-the-art hydrodynamic, chemical and radiative transfer models of protoplanetary discs. The presence or absence of gravitational instabilities has tremendous implications for planet and brown dwarf formation by disc instability.

Background. ALMA early science provides an excellent opportunity to test models of the first stages of planet formation and the early evolution of protoplanetary discs. Collapse models for star formation suggest that discs can be born massive, and are susceptible to gravitational instabilities (GIs, e.g., Boss 1984; Laughlin & Bodenheimer 1994; Pickett et alb. 1996; Voroybov & Basu 2006). Viscous spreading can cause even older discs to develop GIs at large disc radii (e.g., Clarke 2009), where the stability of gas that is moving outward drops due to increasing orbital times and decreasing gas temperatures. These instabilities create large-scale spiral structure, which in turn creates asymmetries, produces shocks, and under certain circumstances, leads to fragmentation. Heating along the spiral arms affects gas-phase chemistry (Ilee et al. 2011), and can form high abundances of molecules that would otherwise be frozen onto grains (see Figure 1), giving a diagnostic for spiral structure. At large disc radii, GIs can lead to disc fragmentation and the formation of transient and/or permanent clumps (e.g., Stamatellos et al. 2007; Rafikov 2009; Boley 2009; Clarke 2009). If clumps survive being tidally destroyed during pericenter passages, they will develop large circumplanetary discs, which may regulate the mass growth and keep the sub-stellar companion within the gas-giant/low-mass brown dwarf regime (Boley et al. 2010). However, if discs are inefficient as regulators, mass growth may continue unabated until the object reaches brown dwarf or stellar masses (e.g., Kratter et al. 2010). Observations are required to test whether GIs and large-scale spiral structure are ever present during the early stages of disc evolution and whether fragmentation can lead to the in situ formation of wide-orbit, low-mass sub-stellar companions, such as the planets around HR8799 (Marois et al. 2008, 2010) and Fomalhaut b (Kalas et al. 2008).

The need for ALMA. Observing large-scale spiral structure in young protoplanetary discs is problematic with other instruments. Discs may be most likely to host GIs during and shortly after the embedded phase, where they will likely be obscured at optical wavelengths. Observations at millimetre wavelength can detect emission from embedded discs (e.g., Boogert et al. 2002; Andrews et al. 2010), but the necessary sensitivity at high spatial resolution has so far been insufficient at resolving spiral structure, even at very large radii. In contrast, ALMA, even in early science mode, will be able to resolve spiral structure at large disc radii, providing an immediate opportunity to constrain disc evolution and planet formation models. To illustrate this further, consider the Wentzel-Kramers-Brillouin approximation for spiral waves. A typical pitch angle i for GI-driven spiral arms in radiation hydrodynamics simulations of discs is $\sim 10^\circ$ (e.g., Boley & Durisen 2008). The inter-arm spacing is then given by $\Delta r = r_0(\tan(i))2\pi/m$, where m is the number of arms. Global, low-m modes are often dominant in GI-active discs (e.g., Lodato & Rice 2004; Mejia et al. 2005; Boley et al. 2006). A typical inter-arm spacing of an $m = 3$ spiral at $r_0 = 100\,\mathrm{AU}$ is $\sim 37\,\mathrm{AU}$. At the distance of Ophiuchus ($\sim 120\,\mathrm{pc}$), the resolution of band 7 in the most extended configuration is $\sim 21\,\mathrm{AU}$, so the three-arm spiral can just be resolved. Two or even one-arm spirals will be easier to distinguish, where the latter may be common in discs that have fragmented.

Proposed observations. *We propose to observe selected molecular transitions and continuum emission toward IRAS1629A and IRAS1629B, to investigate whether spiral structure is present early on in the evolution of protoplanetary discs. We found that combined constraints of spatial resolution and kinematics provide a powerful way to test disc evolution.* IRAS16293-2422 is unique amongst class 0 sources in that it is both bright and favourably inclined to best detect spiral structure morphologically and kinematically. Observations with ALMA cycle 0 (Pineda et al. 2012) reveal a velocity gradient in IRAS1629A (Figure 2) consistent with an inclination angle of 30-40° as inferred earlier in a study of outflow from the source (Rao et al. 2009). IRAS1629A and B were previously considered "hot corinos" showing complex organic chemistry and infall (Kaun et al. 2004, Chandler et al. 2005, Bisschop et al. 2008). Figure 3 shows a synthetic ALMA observation in Band 7 of a $\sim$200 AU disc at the distance of Ophiuchus (where IRAS1629A and B are embedded), using sensitivities and velocity resolution necessary to detect the selected molecular lines (see below). The right panel shows that some spiral structure is marginally resolvable even at 30° inclination. If closer to face-on, this would become clearer. In fact, although IRAS1629A and B show similar line features (Bisschop et al. 2008), IRAS129A shows a velocity gradient whereas B does not, which can simply be understood with IRAS1629B having a face-on disc. Continuum observations would then be able to resolve spiral arms if they exist and estimate the mass of the disc, providing a test for theoretical models of gravitational instabilities.

Radiative transfer calculations of a gravitationally unstable $0.4\,M_\odot$ disc, embedded within a pre-stellar core, were performed with the 3D radiative transfer code LIME (Brinch & Hogerheijde 2010). The code used as input the physical structure of a hydrodynamic disc model from Boley (2009) and the chemical composition from Ilee et al. (2011). To simulate the fact that young stellar objects are still embedded in the parent cloud core, the disc model was put in the center of a pre-stellar core, with physical structure derived by the comprehensive study of Keto & Caselli (2010), based on the comparison between detailed observations and coupled hydrodynamic/radiative transfer simulations. The combined disc/pre-stellar core model was used to check a wide variety of potential molecular lines for shock tracers and good kinematic probes. We found that: (1) OCS lines in band 7 are good tracers of the spiral structure. These were shown to be excited in models with spiral density and temperature waves but to be undetectable in smooth discs. (2) H_2CO lines are well tracing the disc kinematics and also have enough observeable lines to put constraints on the temperature structure across the disc. Lines from both these species are predicted to be in absorption and completely unaffected by the pre-stellar envelope material. Figure 4 shows an example of this modelling and of how it would look through ALMA in the cycle 1 most extended configuration. The figure shows the image of the line absorption and the position velocity diagrams that will be able to unveil the rotation curve predicted by our models.

2 Technical Justification

IRAS16293-2422 is a bright source with a continuum measured by SMA of $\sim$ 60mJy beam^{-1} channel^{-1} (Bisschop 2008). The 938 MHz FDM correlator mode with dual polarisation will provide the capability to observe spectral features with sufficient resolution ($0.49\ \mathrm{km\,s^{-1}}$) to detect kinematic features.

Table 1: *A summery of observing requirements.*

Correlator mode	FDM Bandwidth 938 MHz FDM Bandwidth 938 MHz FDM Bandwidth 938 MHz TDM Bandwidth 2000 MHz
Window centre	364.15 GHz 354.50 GHz 352.28 GHz 365.60 GHz
Total integration time	4.27h
Synthesised beam size	0.17 arcsec

These include a sequence of H_2CO lines which will allow us to put constraints on the temperature of the disc, and OCS lines only excited by spiral shocks. A TDM correlator mode can detect spiral structure with an expected contrast of $\sim$2mJy beam^{-1} over the background core to be resolved in IRAS1629B, if it is a face-on disc. The bandpasses are centred at 364.31, 352.29 and 354.50 GHz for the FDM correlator windows and 365.6GHz for the TDM correllator window. Some of the possible molecular lines which could be seen in these windows are HCN, OCS, SO_2, and H_2CO all of which have been modelled with radiative transfer codes to show up in absorption. Sensitivity of 1K in the narrowest channel will allow a 5σ detection of the weakest line expected to be seen. The time required to get this sensitivity ($\sim$ 4.3h) will give $\sim$0.37mJy of sensitivity in the continuum window. This will be sufficient to detect spiral structure in IRAS1629B if it is a face-on disc.

Potential for Publicity

Successful detection of spiral arms in protoplanetary discs will provide images of disc evolution and possibly planet formation in action. Such observations would give dramatic pictures of the birth-places of exoplanets.

References

Bisschop, S. E. et al. 2008 A&A, 488, 959 • Boley, A. C. (2009) ApJ. 695, 53 • Boley, A. C., & Durisen, R. H. 2006, ApJ, 641, 534 • Boley, A. C., & Durisen, R. H. 2008, ApJ, 685, 1193 • Boley, A. C. Hayfield, T. Mayer, L.and Durisen, R. H. (2010) Icar. 207 509 • Boss, A. P. 1984, ApJ, 277, 768 • Brinch, C., & Hogerheijde, M. R. 2010, A&A, 523, 25 • Clarke, C. 2009, MNRAS, 396, 1066• Chandler, C. J., Brogan, C. L., Shirley, Y. L., ApJ, 632, 371 • Ilee et al. 2011, MNRAS, 417, 2950 • Kalas, P., Graham, J., R. and Clampin, M. (2005) Nature, 435, 1067• Kalas et al. 2008, Sci., 322, 1345 • Keto, E., Caselli, P., MNRAS, 402, 1625 • Kratter, K. M., Murray-Clay, R. A., Youdin, A. N. 2010, ApJ, 710, 1375• Kuan, Y., ApJ, 616, 27 • Laughlin, G., & Bodenheimer, P. 1994, ApJ, 436, 335 • Lodato, G., & Rice, W. K. M. 2004, MNRAS, 351,630 • Marois, et al. 2008, Sci., 322, 1348 • Marois et al. 2010, Nature, 468, 1080 • Mejia et al. 2005, ApJ,619, 1098 • Pickett, B. K., Durisen, R. H., & Davis G. A. 1996, ApJ, 458, 714 • Pineda J. E. et al. 2012 A&A Letters, Accepted • Stamatellos, D., Hubber,D. A., Whitworth, A. P. 2007, MNRAS, 382, 30 • Rafikov, R. R. 2009, ApJ, 704, 281 • Rao, R. et al. ApJ, 707, 921 • Vorobyov, A., & Basu, S. 2006, ApJ, 650, 956

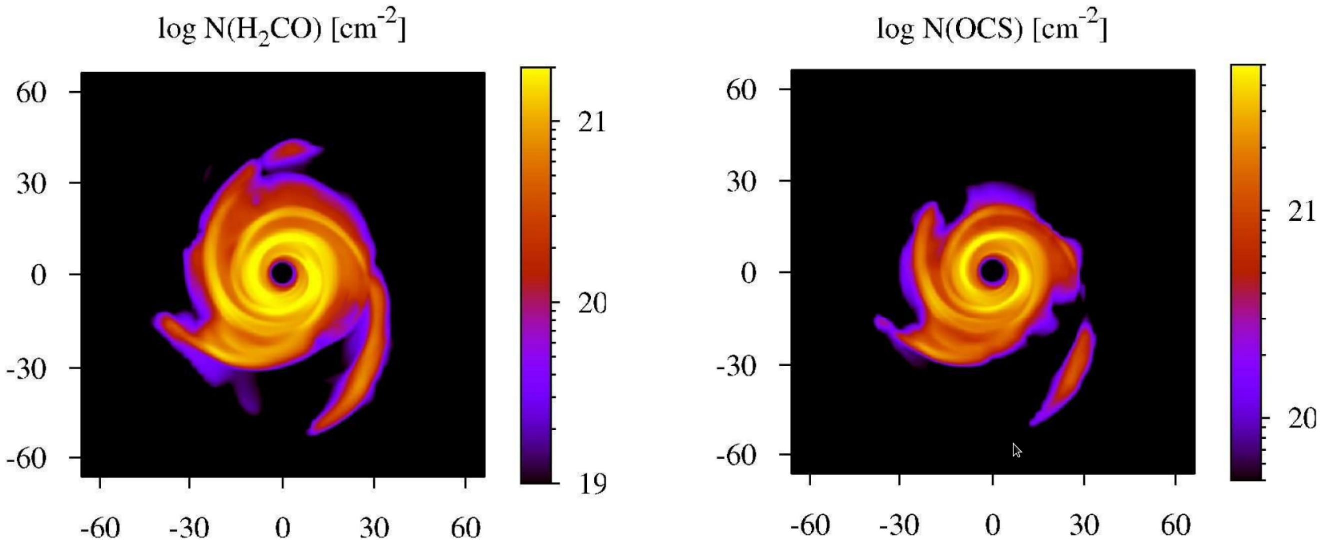

Figure 1: *Column density maps of H_2CO and OCS in a gravitationally unstable protoplanetary disc (adapted from Ilee et al. 2011). The heating in spiral arms in the central ∼100 AUs, allows molecules originally frozen onto dust grains to return in the gas phase and reach abundances large enough to be detected with ALMA. The abscissa and ordinate are in AU, and the colourbar gives the log of the column density of molecules.*

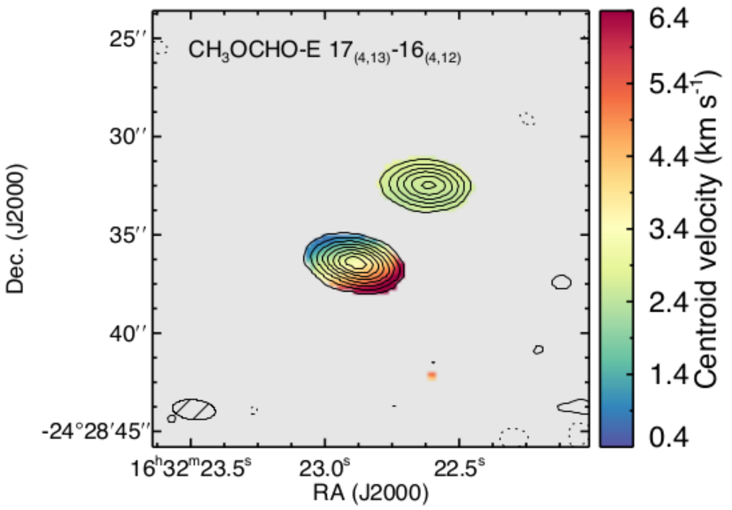

Figure 2: *Intensity-weighted velocity for CH_3OCHO-E (adapted from Pineda et al. 2012). IRAS1629A is in the lower left, IRAS1629B in the upper right. IRAS1629A has been found to be a young protoplanetary disc inclined by about 30-40°, whereas IRAS1629B could be a face-on disc (see text). These are the brightest regions where to test models of gravitationally unstable discs in their early phases of evolution.*

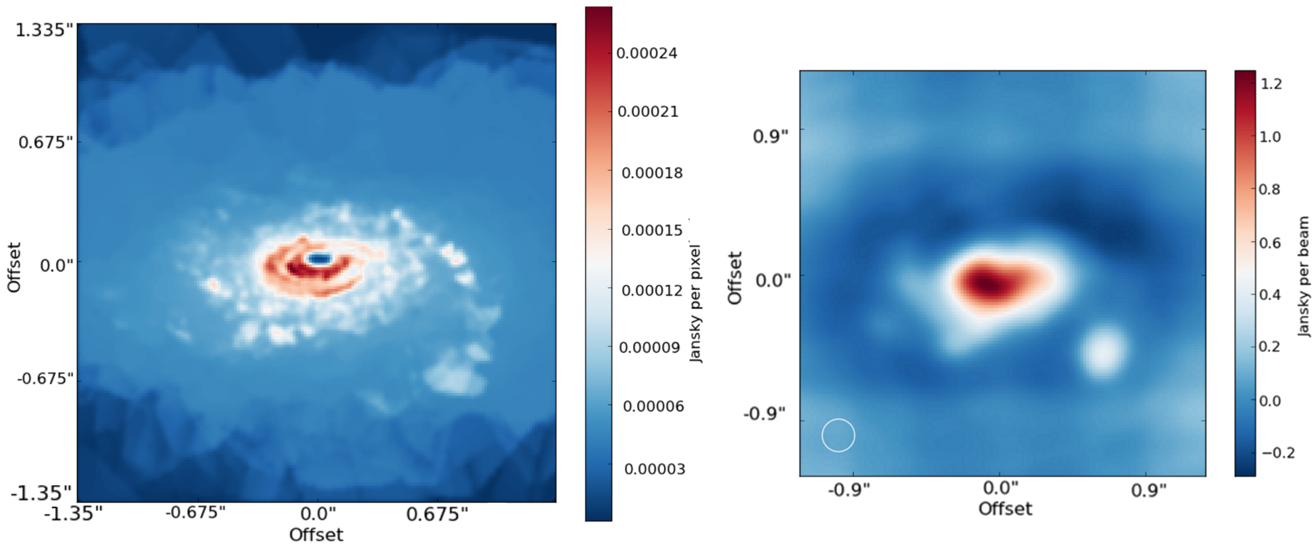

Figure 3: *Our simulated continuum emission of a gravitationally unstable protoplanetary disc inclined at 30° and embedded in a collapsing pre-stellar core (see text for details). Left panel: output image from the radiative transfer (LIME) simulation. Right panel: predicted uncleaned ALMA observations in band 7 (beam size is shown in lower left).*

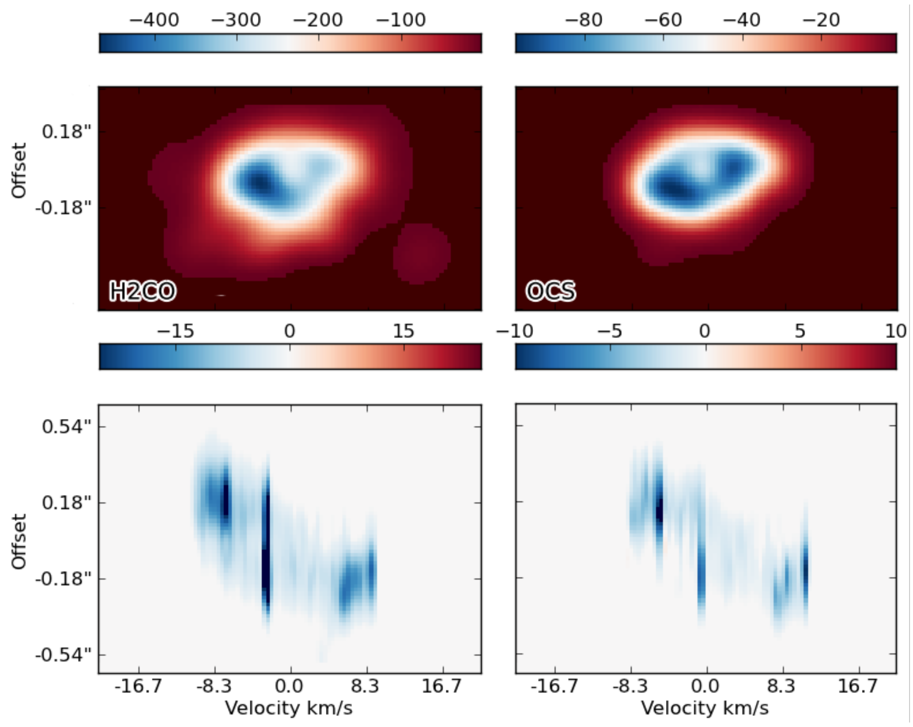

Figure 4: *CASA simulations of continuum-subtracted line absorption, integrated intensity and position-velocity diagrams of $H_2CO(5_{4,2} \rightarrow 4_{4,1})$ and $OCS(28 \rightarrow 29)$ in a disc with spiral density and temperature waves inclined at 30°. The scales are in $K\,km\,s^{-1}$ for the integrated intensity maps and K for the PV diagram.*

Field Setup:

Target(s) max. elevation is low (< 20 degrees)	—
Target(s) max. elevation is high (> 84 degrees)	1
Non-zero proper motion of target(s)	—
Spatial dynamic range > 500 (on basis of peak flux to rms)	—
Spectral dynamic range > 1000 (B3, B6), 500 (B7), 100 (B9)	—
Mosaic pointing separation outside range 0.48 - 0.8 1.2*λ/D	—
Velocity frame is not LSR_K	—
Velocity definition is relativistic	—

Spectral Setup:

Single Polarization selected	—
Linewidth > 90% spectral window width	—
Single spectral window only selected	—

Calibration:

Any user calibration selected	—

Control and Parameters:

Largest scale of interest > max. recoverable scale	—
Extra time selected	—
ACA request and necessity estimator diagreement	—

TA's ID : ProposalID :

2012.1

SG : 1 of 1 IRAS16293 has 1 Target

Description of This Science Goal

Band 7 observations of IRAS16293 A and B

ALMA Band 07 General Properties : 275 - 373 GHz (2SB)

IF GHz	Trx	Tsys	Zenith opacity	1MHz	1mJy@1"
4.0-8.0	75-75K	105-131879K	0.10-6.02	0.93 km/s	0.009-0.016K

HPBW 12m	HPBW 7m	resolution 12m Array	resolution 7m Array
17-22"	28-39"	0.166-0.225"	

Science Goal Control Parameters

Resolution	Largest Structure	Rms	Representative Freq.	Ref. Freq. Width	Extra Time Asked For?	Time Constrained?	User Defined Cal?
0.17"	2.0"	3.14 mJy, 10...	364.311495 GHz	488.281 kHz	no	no	no

Use of 12m Array (32 antennas)

Mode	Time	Map Size	#12m ptgs or hpbw	12m Spacing	Joint?	Data Vol	Data Rate
Synthesis	4.3 h		1		no	626.5 GB	41.7 MB/s

Use of ACA 7m Array (9 antennas) and TP Array

Mode	Time	Map Size	#7m ptgs or hpbw	7m Spacing	Joint?	Data Vol	Combined Data Rate
Synthesis							

Target list for Science Goal 01

Expected Source Properties

Target	Ra,Dec(J2000)	l,b	Motion	V,def,frame --OR--z	Linewidth	Peak Flux	Pol'n	Dyn. Range
1-IRAS16293-2422	16:32:22, -24:28:34		Sidereal	3.0 km/s,lsrk,RADIO	5 km/s	1.000 Jy	0%	318.8

Frequency/correlator/spectral Info

Baseband 0 - setup

Center Freq Rest GHz	Center Freq Sky GHz	Line ID	Pol Products	Eff # Channels per product	Bandwidth	Resolution
364.315141	364.311495	H2CO(many)&OCS 30-29	XX,YY	3840	937.5 MHz, 771.5 km/s	488.28 kHz, 0.402 km/s

Baseband 0 - rms

Frequency (GHz)	Tsys	12m Array Synthesis
364.315141	209.5 K	3.14 mJy, 1 K

Baseband 1 - setup

Center Freq Rest GHz	Center Freq Sky GHz	Line ID	Pol Products	Eff # Channels per product	Bandwidth	Resolution
365.608537	365.604878	Continuum	XX,YY	128	2000.0 MHz, 1640.0 km/s	31250.00 kHz, 25.625 km/s

Baseband 1 - rms

Frequency (GHz)	Tsys	12m Array Synthesis
365.608537	206.8 K	3.1 mJy, 981.1 mK

Baseband 2 - setup

Center Freq Rest GHz	Center Freq Sky GHz	Line ID	Pol Products	Eff # Channels per product	Bandwidth	Resolution
352.288226	352.284700	OCS v=0 29-28	XX,YY	3840	937.5 MHz, 797.8 km/s	488.28 kHz, 0.416 km/s

Baseband 2 - rms

Frequency (GHz)	Tsys	12m Array Synthesis
352.288226	200.3 K	2.68 mJy, 912.6 mK

Baseband 3 - setup

Center Freq Rest GHz	Center Freq Sky GHz	Line ID	Pol Products	Eff # Channels per product	Bandwidth	Resolution
354.505470	354.501922	HCN J=4-3	XX,YY	3840	937.5 MHz, 792.8 km/s	488.28 kHz, 0.413 km/s

Baseband 3 - rms

Frequency (GHz)	Tsys	12m Array Synthesis
354.505470	146.2 K	2.17 mJy, 731 mK