Observing and Characterizing Disks (and Binaries) Around the Youngest Protostars

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L1527: The First 'Confirmed' Class 0 Disk and the Protostar Mass

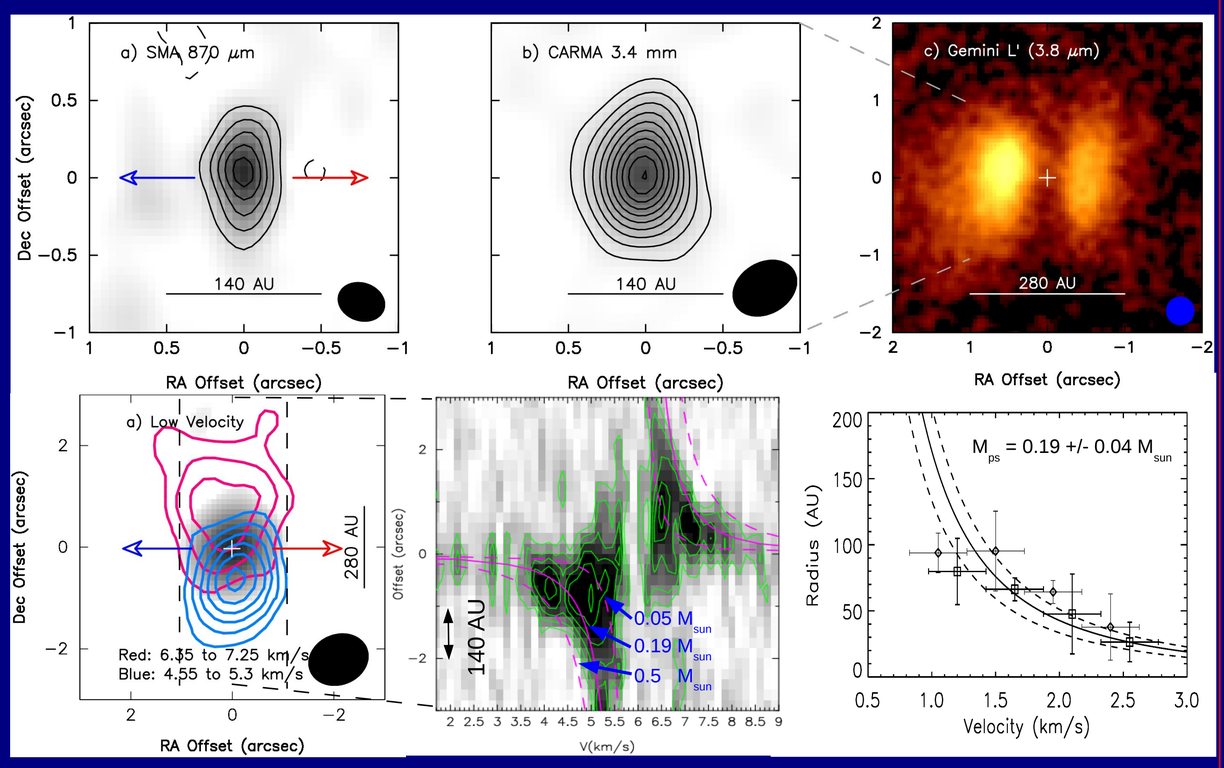


Figure 1: Dust continuum imaging and disk kinematics of L1527. The *top* panels show the SMA and CARMA imaging at 870 um (*left*) and 3.4 mm *(middle),* and the Gemini 3.8 um scattered light image (*right*); contours start at 3σ and the resolution of the data are ~0.3". The *lower* panels show the ^{13}CO (J=2-1) integrated intensity (*left*), the ^{13}CO (J=2-1) position-velocity diagram (*middle*), and the rotation curve (*right*) used to fit the protostar mass. The *solid* curve in the *bottom right* panel is the best-fit protostar mass and +/- 1σ (*dashed*).

- L1527 IRS is a Class 0 protostar in Taurus (d ~ 140 pc), one of the nearest Class 0 sources.
- The edge-on disk recently identified in scattered light and dust continuum (Figure 1; Tobin+2010, Tobin+2012).
- Disk rotation found with the ^{13}CO (J=2-1) line and a protostar mass of 0.19 +/- 0.04 M_{sun} measured (Figure 1).
- Envelope mass is ~ 1 M_{sun}; largest ratio of envelope to protostar mass currently known (Takakuwa+2012).
- Modeling of the millimeter and infrared data find R_{disk} ~ 125 AU, M_{disk} = 0.075 M_{sun}, ρ α $r^{-2.5}$ and H(r) α $r^{1.3}$.
- ALMA Cycle 1 observations are pending to examine the disk structure and kinematics in more detail.

VLA and CARMA Observations of Cepheus Protostars

L1165-SMM1

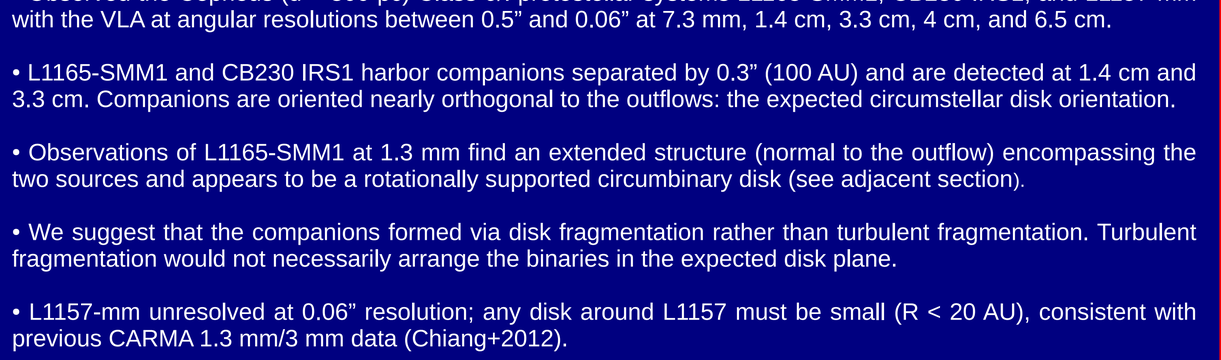


Figure 4: Continuum imaging of L1165-SMM1 at 1.3 mm (*left*) and 7.3 mm (*middle and right*). The CARMA 1.3 mm data at 0.3" resolution show an extended, flattened structure oriented normal to the outflow direction (*left*). The VLA imaging at ~0.25" resolution also show extended structure. The A-array VLA imaging (tapered to 0.1") show that L1165-SMM1 is harboring a companion source separated by ~100 AU (*right*). The lower resolution images appear to trace a circumbinary disk surrounding the two components. The crosses mark the locations of the two sources, arrows denote the outflow directions.

CB230 IRS1

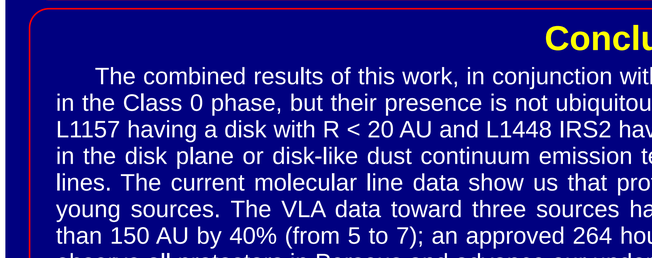


Figure 5: VLA 7.3 mm continuum imaging of CB230 IRS1. Much like L1165-SMM1, CB230 IRS1 is resolved at 0.25" resolution (*left*) and is resolved into two discrete sources at 0.1" resolution (*top right*). The sources are separated by ~0.3" (100 AU) and are near the expected plane of the circumstellar disk.

L1157-mm

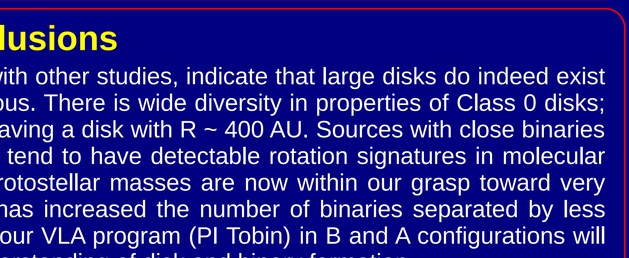


Figure 6: VLA 7.3 mm continuum imaging of L1157-mm. L1157-mm appears unresolved at 0.25" resolution and is still unresolved at the highest resolution (0.06"; 18AU), indicating that the protostellar disk is less than ~20 AU in radius.

- Observed the Cepheus (d ~ 300 pc) Class 0/I protostellar systems L1165-SMM1, CB230 IRS1, and L1157-mm with the VLA at angular resolutions between 0.5" and 0.06" at 7.3 mm, 1.4 cm, 3.3 cm, 4 cm, and 6.5 cm.
- L1165-SMM1 and CB230 IRS1 harbor companions separated by 0.3" (100 AU) and are detected at 1.4 cm and 3.3 cm. Companions are oriented nearly orthogonal to the outflows: the expected circumstellar disk orientation.
- Observations of L1165-SMM1 at 1.3 mm find an extended structure (normal to the outflow) encompassing the two sources and appears to be a rotationally supported circumbinary disk (see adjacent section).
- We suggest that the companions formed via disk fragmentation rather than turbulent fragmentation. Turbulent fragmentation would not necessarily arrange the binaries in the expected disk plane.
- L1157-mm unresolved at 0.06" resolution; any disk around L1157 must be small (R < 20 AU), consistent with previous CARMA 1.3 mm/3 mm data (Chiang+2012).
- Disk mass estimates: M(CB230 IRS1) ~ 0.15 M_{sun}, M(L1165-SMM1) ~ 0.03 M_{sun}, M(L1157-mm) ~ 0.08 M_{sun}

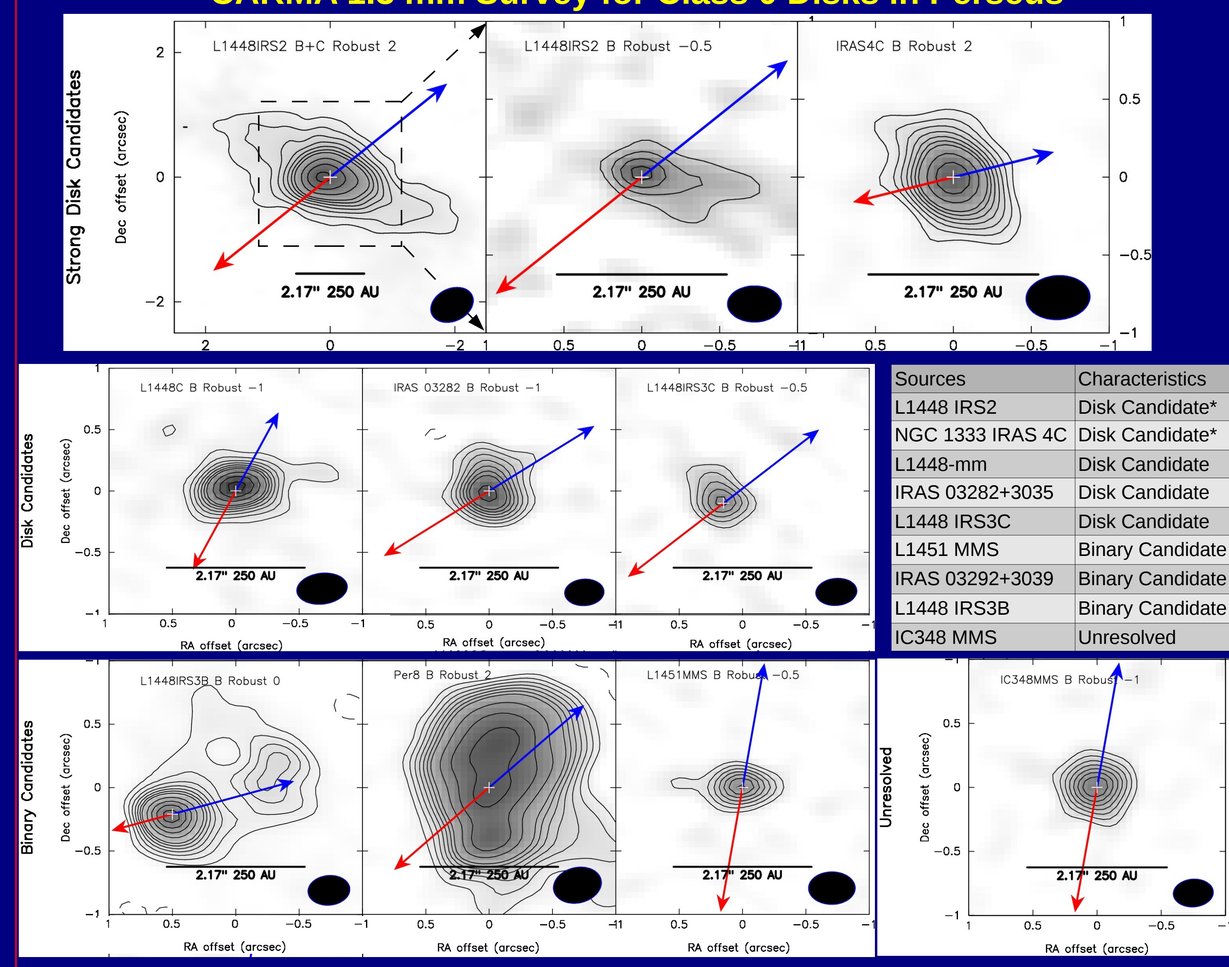
Conclusions

The combined results of this work, in conjunction with other studies, indicate that large disks do indeed exist in the Class 0 phase, but their presence is not ubiquitous. There is wide diversity in properties of Class 0 disks; L1157 having a disk with R < 20 AU and L1448 IRS2 having a disk with R ~ 400 AU. Sources with close binaries in the disk plane or disk-like dust continuum emission tend to have detectable rotation signatures in molecular lines. The current molecular line data show us that protostellar masses are now within our grasp toward very young sources. The VLA data toward three sources has increased the number of binaries separated by less than 150 AU by 40% (from 5 to 7); an approved 264 hour VLA program (PI Tobin) in B and A configurations will observe all protostars in Perseus and advance our understanding of disk and binary formation.

References:

Chiang et al. 2012, *ApJ, 756, 168*
Joos et al. 2012, *A&A*, 554, 17
Krumholz et al. 2013, *ApJL*, 767, 11
Takakuwa et al. 2012, *ApJ*, 754, 52
Tobin et al. 2010, *ApJL*, 722, 12
Tobin et al. 2012, *Nature*, 492, 83
Tobin et al. 2013, *ApJ*, 771, 48

CARMA 1.3 mm Survey for Class 0 Disks in Perseus



Sources	Characteristics
L1448 IRS2	Disk Candidate*
NGC 1333 IRAS 4C	Disk Candidate*
L1448-mm	Disk Candidate
IRAS 03282+3035	Disk Candidate
L1448 IRS3C	Disk Candidate
L1451 MMS	Binary Candidate
IRAS 03292+3039	Binary Candidate
L1448 IRS3B	Binary Candidate
IC348 MMS	Unresolved

Figure 2: CARMA 1.3 mm dust continuum of selected protostars in the Perseus molecular cloud; the resolution in each image is ~0.35" and the 1σ sensitivity is ~1 mJy/beam; contours start at 3σ. The *top* row shows the sources that are well-resolved normal to the outflow direction, consistent with a protostellar disk. The *middle* row shows the sources with extended structure, but not obviously disk-like. The *bottom* row shows the binary candidates and the one unresolved source. Outflow directions are denoted by the blue and red arrows.

L1448 IRS2 Rotation

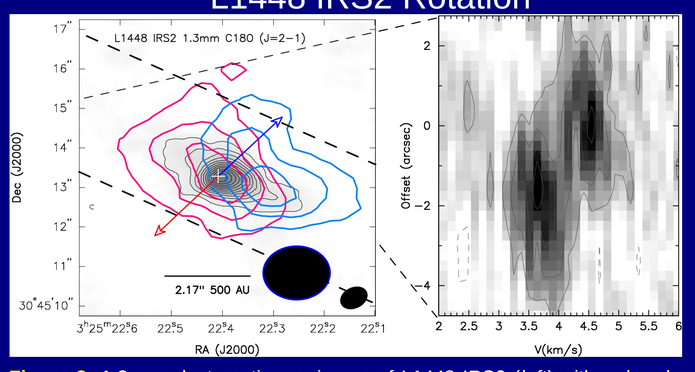


Figure 3: 1.3 mm dust continuum image of L1448 IRS2 (*left)* with red and blue-shifted $C^{18}O$ integrated intensity contours overlaid. The position-velocity diagram for the $C^{18}O$ is shown in the *right* panel; rotation is evident, but the current data lack the sensitivity to probe Keplerian rotation.

- Continuum survey of 9 Class 0 protostars in the Perseus molecular cloud (d~230 pc) with CARMA in B and C configurations.
- Detected two strong disk candidates shown in Figure 2.
- L1448 IRS2 has a rotation signature found in SMA archival data combined with the current CARMA observations (Figure 3).
- Three sources are binary candidates, including the FHSC candidate L1451 MMS.
- Initial results indicate that large (R > 100 AU) disks do exist during the Class 0 phase, but likely in less than 50% of systems; consistent with Krumholz+2013; Joos+2012.

Kinematic Follow-Up of L1165-SMM1, CB230 IRS1, and L1157-mm

L1165-SMM1

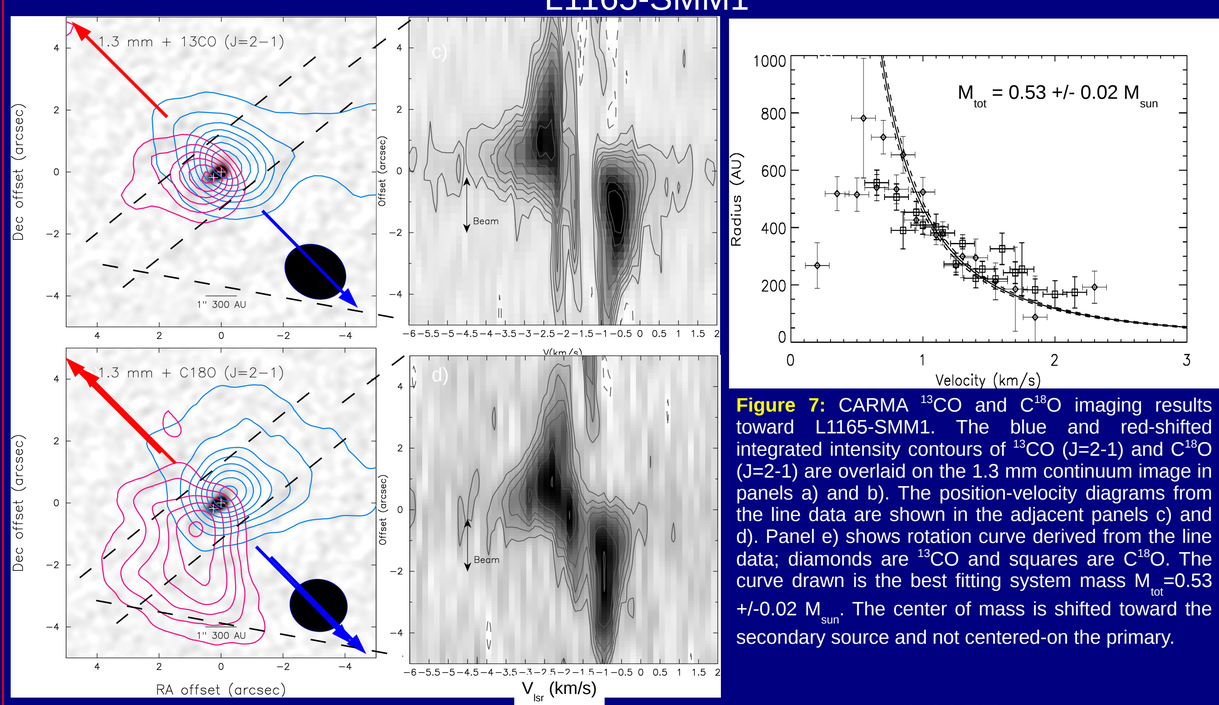
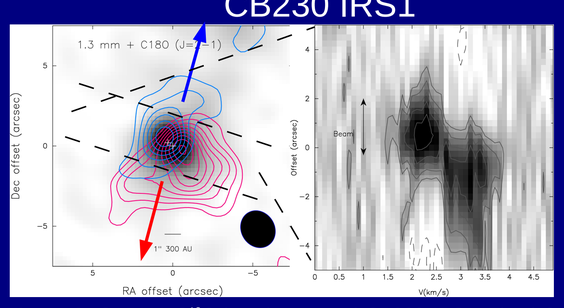


Figure 7: CARMA ^{13}CO and $C^{18}O$ imaging results toward L1165-SMM1. The blue and red-shifted integrated intensity contours of ^{13}CO (J=2-1) and $C^{18}O$ (J=2-1) are overlaid on the 1.3 mm continuum image in panels a) and b). The position-velocity diagrams from the line data are shown in the adjacent panels c) and d). Panel e) shows rotation curve derived from the line data; diamonds are ^{13}CO and squares are $C^{18}O$. The curve drawn is the best fitting system mass M_{tot}=0.53 +/-0.02 M_{sun}. The center of mass is shifted toward the secondary source and not centered-on the primary.

CB230 IRS1



L1157-mm

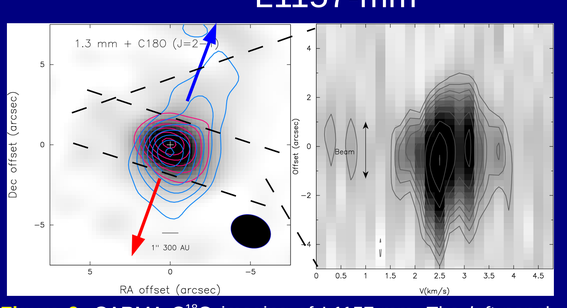


Figure 8: CARMA $C^{18}O$ imaging toward CB230 IRS1. The *left* panel shows the red and blue-shifted $C^{18}O$ (J=2-1) overlaid on the 1.3 mm continuum image, showing a clear rotation-type signature. The position-velocity diagram in the *right* panel shows a velocity shift, but not an obvious Keplerian signature.

Figure 9: CARMA $C^{18}O$ imaging of L1157-mm. The *left* panel shows the red and blue-shifted $C^{18}O$ (J=2-1) overlaid on the 1.3 mm continuum. There is not an obvious rotation signature detected and the position-velocity diagram (*right panel*) shows no rotation signature on ~3" (1000 AU) scales.

- Clear rotation signatures toward L1165-SMM1 (Figure 7) as well as CB230-IRS1 (Figure 8). Indicates that rotation (angular momentum) is playing a role in fragmentation process in these systems.
- L1157 does not show a strong rotation signature (Figure 9); consistent with indications of a very small disk.
- Keplerian rotation found toward L1165-SMM1; calculate a total system mass of M_{tot}=0.53 +/-0.02 M_{sun}. CB230 data do not have enough sensitivity and/or resolution to constrain Keplerian rotation.
- The envelope mass of L1165-SMM1 is ~0.3 M_{sun} and M_{tot} > M_{env}; the envelope to protostar mass ratio falls between L1527 (Class 0) and L1551NE (Class I) (Takakuwa+2012).