VLA AND CARMA OBSERVATIONS OF PROTOSTARS IN THE CEPHEUS CLOUDS: SUB-ARCSECOND PROTO-BINARY FORMATION VIA DISK FRAGMENTATION

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ABSTRACT

We present observations of three Class 0/I protostars (L1157-mm, CB230 IRS1, and L1165-SMM1) using the Karl G. Jansky Very Large Array (VLA) and observations of two (L1165-SMM1 and CB230 IRS1) with the Combined Array for Research in Millimeter-wave Astronomy (CARMA). The VLA observations were taken at wavelengths of $\lambda = 7.3$ mm, 1.4 cm, 3.3 cm, 4.0 cm, and 6.5 cm with a best resolution of $\sim 0.06$ (18 AU) at 7.3 mm. The L1165-SMM1 CARMA observations were taken at $\lambda = 1.3$ mm with a best resolution of $\sim 0.3$ (100 AU) and the CB230 IRS1 observations were taken at $\lambda = 3.4$ mm with a best resolution of $\sim 3''$ (900 AU). We find that L1165-SMM1 and CB230 IRS1 have probable binary companions at separations of $\sim 0.3$ (100 AU) from detections of secondary peaks at multiple wavelengths. The position angles of these companions are nearly orthogonal to the direction of the observed bipolar outflows, consistent with the expected protostellar disk orientations. We suggest that these companions may have formed from disk fragmentation; turbulent fragmentation would not preferentially arrange the binary companions to be orthogonal to the outflow direction. For L1165-SMM1, both the 7.3 mm and 1.3 mm emission show evidence of a large ($R > 100$ AU) disk. For the L1165-SMM1 primary protostar and the CB230 IRS1 secondary protostar, the 7.3 mm emission is resolved into structures consistent with $\sim 20$ AU radius disks. For the other protostars, including L1157-mm, the emission is unresolved, suggesting disks with radii $<20$ AU.

Key words: ISM: individual objects (CB230, L1165, L1157) – protoplanetary disks – stars: formation

Online-only material: color figures

1. INTRODUCTION

Binary or multiple systems comprise at least half of all solar-type stars and the physical separation of companions ranges from $\sim 10000$ AU to $< \sim 0.01$ AU. The formation mechanism for multiple systems is still debated (e.g., Tohline 2002), but seems to occur during the protostellar phase when there is still a significant mass reservoir available. Thus, in order to test binary formation mechanisms, observations of very young sources that have not undergone significant evolution are the most ideal. The earliest recognized phase of protostellar evolution is the Class 0 phase (André et al. 1993); Class 0 sources are characterized by a large, dense envelope surrounding the protostar(s). The Class I phase follows the Class 0 phase, where the protostar is still embedded in its envelope but the envelope has become less massive due to a combination of infall and/or outflow dissipation (e.g., Arce & Sargent 2006).

Rotationally supported disks10 were once thought to form as a simple consequence of angular momentum conservation during the collapse of the protostellar envelope (e.g., Ulrich 1976; Cassen & Moosman 1981; Terebey et al. 1984). The angular momentum causes the infalling material to subsequently fall onto the disk and the disk can grow as higher angular momentum material falls in and becomes rotationally supported at progressively larger radii (Yorke & Bodenheimer 1999). The accretion to the protostar is then mediated by the circumstellar disk. Angular momentum is also thought to contribute to the formation of multiple systems by causing infalling material to form a rotationally flattened region in the inner envelope, significantly larger than a disk, where density perturbations would cause multiple collapse centers (Burkert & Bodenheimer 1993; Boss 1995; Tohline 2002).

This simple picture of disk and binary formation breaks down in collapse models that consider magnetic braking (Mouschovias 1979; Basu & Mouschovias 1994). Ideal magnetohydrodynamic (MHD) simulations and analytic models showed that even when gravity is dominant over the magnetic field in the starless phase, magnetic braking can slow the rotation during the collapse phase and prevent the formation of rotationally supported disks (Allen et al. 2003; Galli et al. 2006; Mellon & Li 2008, 2009). The slowed rotation on $\sim 1000$ AU scales would also prevent binary formation from rotation-induced envelope fragmentation (i.e., Burkert & Bodenheimer 1993; Boss 1995). Moreover, given that disk formation is suppressed, the fragmentation of these disks to form close binaries is also more difficult (Hennebelle & Teyssier 2008) than in the non-magnetic case (e.g., Vorobyov 2010; Stamatellos & Whitworth 2009). Later models considering dissipative, non-ideal MHD effects

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10 Note that the term “disk” used in the text implicitly refers to a rotationally supported or Keplerian disk, whether or not it has been kinematically verified.
do enable the formation of initially very small disks (Dapp & Basu 2010) and the misalignment of magnetic fields with respect to the rotation axis of a system may also enable disk formation in the absence of strong dissipative effects (Joos et al. 2012; Li et al. 2013).

Observationally, there had been little direct evidence for resolved disks toward Class 0 sources (Chiang et al. 2008, 2012; Maury et al. 2010) until a rotationally supported disk, 125 AU in radius, was discovered around the Class 0 protostar L1527 (Tobin et al. 2012). $^{13}$CO ($J = 2 \rightarrow 1$) emission confirmed rotational support and enabled a measurement of protostellar mass ($\sim 0.2 M_{\odot}$). There was also the recent detection of a possible Keplerian disk around the prototype Class 0 system VLA1623 (Murillo & Lai 2013). Only a few disks have been resolved at millimeter wavelengths around Class I sources (e.g., Rodríguez et al. 1998; Launhardt & Sargent 2001; Brinch et al. 2007; Lommen et al. 2008; Jørgensen et al. 2009; Takakuwa et al. 2012; Haro et al. 2013), but the results do point to large disks being prevalent in the Class I phase (Eisner 2012).

The multiplicity of protostars is better characterized than their disk properties thus far. Connelley et al. (2008) carried out a multiplicity survey of Class I protostars in the near-infrared (NIR; 1.6 $\mu$m, 2.15 $\mu$m, and 3.7 $\mu$m) with spatial resolutions as fine as $\sim 70$ AU (0$''$33). They found a rather flat separation distribution between 100 AU and 1000 AU, with increasing multiplicity on 5000 AU scales. At separations $< 500$ AU, an expected scale for disk formation, the authors found 35 multiple protostars. However, the infrared observations are biased against protostars that are deeply embedded in their natal envelopes, as most Class 0 and Class 0/1 protostars are. Only interferometric observations in the millimeter and centimeter can characterize multiplicity in the early stages of protostellar evolution. Work by Looney et al. (2000) showed that multiple systems are prevalent on spatial scales of $\gtrsim 1000$ AU in the Class 0 and I phases. Chen et al. (2013) recently found that Class 0 protostars might have a higher multiplicity fraction than Class I protostars. There have only been a few studies with high enough resolution to probe multiplicity on scales $< 500$ AU in the millimeter; Maury et al. (2010) had suggested a lack of Class 0 binary systems between 150 AU and 550 AU based on their data combined with Looney et al. (2000), arguing that fragmentation and disk formation were suppressed by magnetic fields. Another study by Enoch et al. (2011) in the Serpens star-forming region only detected one source out of nine with evidence of multiplicity on scales smaller than 415 AU. However, Chen et al. (2013) found evidence for seven systems to be multiple with separations $< 500$ AU and Reipurth et al. (2002, 2004) observed 21 systems and found seven to be multiple systems with four separated by $< 500$ AU.

The results on scales $< 150$ AU are quite sparse; there are currently only five Class 0 or Class I systems known to be multiples or at least candidate multiples with such close separations from millimeter and centimeter observations: L1551 NE (Reipurth et al. 2002), L1551 IRS5 (Looney et al. 1997; Rodríguez et al. 1998), IRAS 16293-2422A (Pech et al. 2010), HH211 (Lee et al. 2009), and VLA1623 (Murillo & Lai 2013). Connelley et al. (2008) found 13 multiple Class I protostars with binary separations $< 150$ AU in the infrared. Thus far, it is unclear if the small numbers at radio wavelengths reflect a true paucity or simply a lack of observations with high enough resolution (or high-resolution observations with low sensitivity). A paucity of binaries on scales $< 150$ AU could indicate that binaries typically form with larger separations ($\sim \text{few} \times 1000$ AU) and migrate to smaller radii. Offner et al. (2010) proposed such a scenario where turbulent fragmentation caused binary systems to form and they subsequently migrated.

The conflicting and sparse results on binaries and disks in the early phases of protostellar evolution can be attributed to small sample sizes and low spatial resolution. The maximum angular resolution of sub/millimeter interferometers has been previously limited to $\sim 0''/2$, corresponding to a spatial resolution of $\sim 45$ AU at the 230 pc distance of the Perseus molecular cloud; however, few protostars have been observed at these highest resolutions needed to characterize close binary protostars and disks. Spatial resolutions better than 50 AU are necessary in order to determine when (what evolutionary stage) and where binary protostars form and by what mechanism; 50 AU is roughly the peak of the binary separation distribution for solar-type field stars (Raghavan et al. 2010). It is difficult to determine the fragmentation mechanism on an individual basis; however, the characteristics of the systems may indicate that one mechanism is more likely than another. Moreover, with the small sample of known proto-binaries separated by $< 150$ AU, even small additions are important.

The NRAO Karl G. Jansky Very Large Array (VLA) opens a new window on the study of protostars with its order-of-magnitude increase in the sensitivity in the 7 mm band and currently unprecedented resolution of $\sim 0''/6$. We have observed three Class 0/I protostars (L1157-mm, CB230, and L1165-SMM1) in the Cepheus Flare region ($d \sim 300$ pc; e.g., Kirk et al. 2009), attempting to characterize their disk properties and multiplicity. Complementary data were taken with the Combined Array for Research in Millimeter-wave Astronomy (CARMA) for L1165-SMM1 and CB230 IRS1, with corresponding CARMA data taken from the literature for L1157-mm (Chiang et al. 2012). Since all these targets are at declinations $> 59^\circ$, they cannot be observed by the nearly complete Atacama Large Millimeter/Submillimeter Array and these VLA observations provide the most detailed view of their small-scale structure for the foreseeable future. Despite the small sample of protostars, the high-fidelity data set enables us to shed new light on the properties of disks and multiplicity in young protostellar objects.

This paper is organized as follows: the sample, observations, and data reduction are detailed in Section 2, the basic observational results are given in Section 3, the results are discussed in Section 4, and we present our conclusions in Section 5.

2. THE SAMPLE, OBSERVATIONS, DATA REDUCTION, AND ANALYSIS

We observed the protostars CB230 IRS1, L1165-SMM1, and L1157-mm with the VLA in A, B, and C configurations at $\lambda = 7.3$ mm, 1.4 cm, 3.3 cm, 4.0 cm, and 6.5 cm; the source properties and coordinates are given in Table 1. We also obtained observations from CARMA for L1165-SMM1 at 1.3 mm in B and C configurations and CB230 IRS1 at 3.4 mm in C configuration.

2.1. Sources

The three selected protostars are all isolated and located in the Cepheus Flare region. L1157-mm is found within one of several denser regions within a larger ring-like molecular cloud (Kirk et al. 2009) and L1165-SMM1 and CB230 IRS1 reside within discrete dark clouds. Despite the small sample, the sources span a range of luminosities and bolometric temperatures. Class 0
Class I protostars are typically distinguished using the ratio of submillimeter luminosity ($L_{\text{submm}}$) to bolometric luminosity ($L_{\text{bol}}$) and/or bolometric temperature ($T_{\text{bol}}$). The bolometric temperature is defined as the temperature of a blackbody with the same average frequency as the observed data. For a protostar to be a Class 0 source, it must have either $T_{\text{bol}} < 70$ K or $L_{\text{submm}}/L_{\text{bol}} > 0.005$ (Chen et al. 1995; Andre et al. 1993); however, protostars can fulfill the $L_{\text{submm}}/L_{\text{bol}}$ criterion, but not necessarily the $T_{\text{bol}}$ criterion, and we refer to these sources as Class 0/I sources.

L1157-mm (IRAS 20386+6751) is a Class 0 source with $T_{\text{bol}} = 40$ K and $L_{\text{submm}}/L_{\text{bol}} = 0.018$ and it has the lowest luminosity of the sample with $L_{\text{bol}} \sim 4.3 L_{\odot}$. The envelope surrounding L1157-mm is also found to have a flattened, filamentary structure that is extended perpendicular to the outflow direction (Looney et al. 2007). Observations of the outflow indicate that the protostar is viewed with a near edge-on orientation (Guthe et al. 1996). L1157-mm was studied extensively with CARMA, aiming to detect emission from its disk (Chiang et al. 2012); however, the source remained unresolved at a resolution of 0.3 (90 AU) at 1.3 mm and 3.4 mm. Models of the dust emission without an unresolved disk component are a modestly better fit to the data than those with a disk, suggesting that any disk around L1157-mm has very little overall mass; model-dependent mass estimates range from 0.004 $M_{\odot}$ to 0.024 $M_{\odot}$.

The protostar L1165-SMM1 (IRAS 22051+5848, HH 354 IRS) was first examined in the submillimeter by Visser et al. (2002) with 850 $\mu$m dust continuum maps and outflow maps; Reipurth et al. (1997) had previously noted the Herbig–Haro object near this source. There is also a bright infrared source (IRAS 22051+5849) 89" (~0.13 pc) away from L1165-SMM1, but it is not detected in the submillimeter maps by Visser et al. (2002). The Spitzer c2d survey identified this source as a candidate young stellar object and it has a spectral index consistent with a Class II source (Evans et al. 2009). We classify L1165-SMM1 as a Class 0/I source given that $L_{\text{submm}}/L_{\text{bol}} = 0.012$ and $T_{\text{bol}} \sim 78$ K; this classification makes use of new Herschel photometry that samples the protostellar spectral energy distribution (SED) between 100 $\mu$m and 500 $\mu$m (see Appendix).

The difference between the new and previous $T_{\text{bol}}$ determinations for L1165-SMM1 is due to the inclusion of NIR fluxes in the calculation of $T_{\text{bol}}$ and a well-sampledSED out to the millimeter from Herschel. We note that inclination effects can lead to elevated values of $T_{\text{bol}}$, causing Class 0 sources to be classified as Class I sources. This is due to NIR to mid-infrared (MIR) scattered light emission escaping through the outflow cavities (Jørgensen et al. 2009; Launhardt et al. 2013) and the frequency-weighted nature of $T_{\text{bol}}$ makes it very sensitive to the level of short-wavelength flux. $L_{\text{submm}}/L_{\text{bol}}$ is also affected by inclination, but less than $T_{\text{bol}}$ since it is the integral of the flux density rather than a frequency-weighted average wavelength.

The protostar CB230 IRS1 (L1177, IRAS 21169+6804) resides within an isolated globule identified by Clemens & Barvains (1988). NIR imaging previously detected a companion separated from IRS1 by ~10" (3000 AU) to the east (Yun 1996); we refer to this companion as IRS2. IRS2 has been detected at wavelengths between 1.2 $\mu$m and 24 $\mu$m (Massi et al. 2008), but is undetected in Herschel data at 100 $\mu$m (Launhardt et al. 2013), SCUBA at 450 $\mu$m (Launhardt et al. 2010), and OVRO 1.3 mm and 3.4 mm data (Launhardt et al. 2001; Launhardt et al. 2001b). CB230 IRS1 is also classified as a Class 0/I source with $L_{\text{submm}}/L_{\text{bol}} = 0.037$ and $T_{\text{bol}} = 189$ K (Launhardt et al. 2013).

Both L1165-SMM1 and CB230 IRS1 are found to be FU Ori-like objects from CO and water absorption in their NIR spectra (Reipurth & Aspin 1997; Greene et al. 2008; Massi et al. 2008). The distances to all the sources are uncertain given their association with the Cepheus Flare, but are estimated to be between 250 pc and 440 pc (Viotti 1996; Straizys et al. 1992; Kun 1998; Kun et al. 2008); we have adopted a distance of 300 pc as we have in previous studies (Tobin et al. 2010b, 2011). The selected protostars all have rather filamentary envelopes in dust extinction at 8 $\mu$m (Tobin et al. 2010b) and have strong emission in the dense gas tracers NH$_3$ and N$_2$H$^+$. All the protostars have velocity gradients normal to the outflow direction that may be indicative of rotation or infalling flows along the envelope; L1165 and CB230 IRS1 have gradients that are $\geq 2$ times larger than the gradient in L1157-mm (Tobin et al. 2011).

### 2.2. VLA Observations

The observations were taken in the standard full-polarization continuum mode with 2 GHz of total bandwidth covered by 16 sub-bands that have a bandwidth of 128 MHz. Each sub-band is further divided into 64 channels, each having a width of 2 MHz. Details of the observations are listed in Table 2. The observations in C configuration were taken between 2012 February and March. Each track was shared between the three target sources, with alternating observations on a target source for 4 minutes.
An additional C-array observation was taken in 2013 July at 4.0 cm and 3.3 cm to complement the shorter wavelength data. The observations at 4.0 cm observed the calibrator J2148+6107 for 1 minute and then each source for ~12 minutes. In the 4.0/6.5 cm observations, the two 1 GHz basebands were separated by 1.8 GHz with central wavelengths of 6.5 cm and 4.0 cm in order to measure a spectral index from the 4.0/6.5 data alone. The observations in B configuration were carried out in 3 hr scheduling blocks for each source in 2012 June. The protostars were observed at λ = 7.3 mm, 1.4 cm, and 3.3 cm during the same track. The observations were taken in a fast switching mode to compensate for rapid atmospheric phase fluctuations, observing the source for 1 minute and the gain calibrator for 30 s. The lack of a strong calibrator less than 10° away from any of the protostars reduced the observing efficiency to ~25% due to slew times. The A configuration observations were taken in 1 hr blocks over many dates between 2012 October and 2012 December (Table 2). The observations at 7.3 mm, 1.4 cm, and 3.3 cm were taken in separate observing blocks to maximize probability of scheduling; the 1.4 cm and 3.3 cm data could be observed during more marginal weather than the 7.3 mm data. The same gain calibrators were used for both A and B configurations and either 3C48 or 3C286 was used for flux density calibration. For all configurations, we did an interferometric pointing scan at 3.3 cm on the primary calibrator every hour for the 7.3 mm and 1.4 cm observations, as pointing errors become apparent on this timescale; pointing is not necessary at 3.3, 4.0, or 6.5 cm.

Each data set was reduced using the Common Astronomy Software Application (CASA). The raw visibility data were downloaded from the VLA archive as CASA measurement sets. We first inspected the amplitudes and phases in each data set and flagged uncalibrateable data, characterized by low amplitudes, amplitude jumps, phase jumps, and/or periods of high phase decorrelation. The amplitudes across all spectral windows were also inspected for issues such as radio frequency interference. Following the data editing, we used the setjy task with the appropriate clean component model to set the absolute flux density scale of the flux density calibrators identified in Table 2. We then checked for updated antenna positions and coordinates, as pointing errors become apparent on this timescale; pointing is not necessary at 3.3, 4.0, or 6.5 cm.

Notes. We observed in fast-switching mode for the B and A configuration data and due to non-optimal calibrator separations, our on-source efficiency was generally 20%–25%; our efficiency was ~50% in C configuration. The B and C configuration data were from the VLA project 12A-082 and the A configuration data were from 12B-211.

a Incorrect coordinates were used for CB230 IRS1 and the source was at the edge of the primary beam; these data are not used in the analysis.
b Scans for the flux calibrator were missing from this observation and the flux density from the February 19 track was assumed.
c This track had very high phase variance; however, we were able to use the calibrator data to determine the flux density for application to the February 12 track.
d Problems with pointing caused the first 2 hr of the data to be unusable.

### Table 2

| Sources          | Config. | Date (UT) | Track Length (hr) | Central Frequency(s) (GHz) | Gain Calibrator/Flux Density (Name, Jy) | Flux Calibrator |
|------------------|---------|-----------|-------------------|---------------------------|----------------------------------------|---------------|
| L1157            | C-array | 1996 Feb 26 | 1.25              | 4.86, 8.46                | 2016+1614, 3.1, 2.9                     | 3C48          |
| L1165, L1157, CB230 | C-array | 2012 Feb 12 | 4                 | 41                        | J2022+6136, 1.6                        | 3C48b         |
| L1165, L1157, CB230 | C-array | 2012 Feb 19 | 1.5               | 41                        | J2022+6136, 1.6                        | 3C48          |
| L1165, L1157, CB230 | C-array | 2012 Mar 12 | 1.5               | 41                        | J2022+6136, 1.35                       | 3C48          |
| CB230d           | B-array | 2012 Jun 4  | 3                 | 9, 21, 41                 | J2009+7229, 0.75, 0.65, 0.74            | 3C48          |
| L1157            | B-array | 2012 Jun 7  | 3                 | 9, 21, 41                 | J2009+6244, 0.7, 0.56, 0.51             | 3C48          |
| L1165            | B-array | 2012 Jun 11 | 3                 | 9, 21, 41                 | J2022+6136, 3.0, 1.9, 1.1               | 3C48          |
| L1157            | A-array | 2012 Oct 7  | 1                 | 9                         | J2006+6244, 0.47                        | 3C286         |
| CB230            | A-array | 2012 Oct 11 | 1                 | 9                         | J2009+7229, 0.77                        | 3C286         |
| L1165            | A-array | 2012 Oct 11 | 1                 | 9                         | J2009+6244, 0.47                        | 3C48          |
| CB230            | A-array | 2012 Nov 2  | 1                 | 9                         | J2009+7229, 0.82                        | 3C48          |
| L1165            | A-array | 2012 Oct 3  | 1                 | 9                         | J2006+6244, 1.96                        | 3C48          |
| L1165            | A-array | 2012 Oct 8  | 1                 | 9                         | J2006+6244, 1.96                        | 3C48          |
| L1165            | A-array | 2012 Oct 9  | 1                 | 9                         | J2006+6244, 0.47                        | 3C48          |
| L1165            | A-array | 2012 Nov 2  | 1                 | 9                         | J2006+6244, 0.74                        | 3C48          |
| L1165            | A-array | 2012 Dec 7  | 1                 | 9                         | J2006+6244, 0.74                        | 3C48          |
| L1165            | A-array | 2012 Oct 13 | 1                 | 9                         | J2006+6244, 0.86                        | 3C48          |
| L1165            | A-array | 2012 Oct 15 | 1                 | 9                         | J2006+6244, 0.91                        | 3C48          |
| L1165            | A-array | 2012 Oct 15 | 1                 | 9                         | J2006+6244, 0.91                        | 3C48          |
| L1165            | A-array | 2012 Nov 3  | 1                 | 9                         | J2006+6244, 0.51                        | 3C48          |
| L1157            | A-array | 2012 Nov 9  | 1                 | 9                         | J2006+6244, 0.44                        | 3C48          |
| L1157            | A-array | 2012 Nov 14 | 1                 | 9                         | J2006+6244, 0.42                        | 3C48          |
| L1157            | A-array | 2012 Nov 20 | 1                 | 9                         | J2006+6244, 0.42                        | 3C48          |
| L1157            | A-array | 2012 Nov 20 | 1                 | 9                         | J2006+6244, 0.42                        | 3C48          |
| CB230            | A-array | 2012 Nov 28 | 1                 | 9                         | J2006+6244, 0.42                        | 3C48          |
| CB230            | A-array | 2012 Nov 30 | 1                 | 9                         | J2006+6244, 0.7                          | 3C286         |
| CB230            | A-array | 2012 Dec 2  | 1                 | 9                         | J2006+6244, 0.7                          | 3C48          |
| CB230            | A-array | 2012 Dec 5  | 1                 | 9                         | J2006+6244, 0.7                          | 3C48          |
| CB230            | A-array | 2012 Dec 5  | 1                 | 9                         | J2006+6244, 0.7                          | 3C48          |
| CB230, L1165     | C-array | 2013 Jul 7  | 1.75              | 4.5, 7.4                  | J2014+6107, 1.2                         | 3C48          |

Notes. We observed in fast-switching mode for the B and A configuration data and due to non-optimal calibrator separations, our on-source efficiency was generally 20%–25%; our efficiency was ~50% in C configuration. The B and C configuration data were from the VLA project 12A-082 and the A configuration data were from 12B-211.

a Incorrect coordinates were used for CB230 IRS1 and the source was at the edge of the primary beam; these data are not used in the analysis.
b Scans for the flux calibrator were missing from this observation and the flux density from the February 19 track was assumed.
c This track had very high phase variance; however, we were able to use the calibrator data to determine the flux density for application to the February 12 track.
d Problems with pointing caused the first 2 hr of the data to be unusable.

11 http://casa.nrao.edu
generated a gain table to correct the phases using the `gen-Cal` task. The atmospheric opacity was determined from the weather station data via the `plotWeather` task and the opacity in each spectral window was used as input in all subsequent amplitude calibration tasks. We then performed first-pass gain calibration for amplitude and phase on the flux calibrator and primary amplitude gain calibrators using the `gaincal` task. When 3C48 was used as the flux calibrator, we only considered baselines with \( uv \) distances less than 1000 k\( \lambda \), since the source is resolved out on longer baselines. We then used the `fluxscale` task to determine the flux of the primary gain calibrators at each observed wavelength. The `setjy` task was then used to set the measured fluxes of the gain calibrators. The absolute calibration uncertainty is expected to be 10% and we only quote statistical uncertainties hereafter.

We next calibrated the bandpass solution using the `bandpass` task and we used the primary gain calibrator to determine the bandpass solution. Therefore, it was necessary to calculate a gain solution on 10 s timescales to compensate for the rapid phase variations over the course of the track, prior to calculating the bandpass solution. After bandpass calibration, we performed a final gain calibration for amplitude and phase using the `gainCal` task over the entire length of each calibrator scan. The calibration tables from the bandpass and gain calibrations were then applied to the data using the `applyCal` task. Following the application of the calibration data, we verified that the calibrations were properly applied by examining the phase and amplitudes of the data versus time and flagged obviously bad data consisting of, but not limited to, phase jumps, high phase variance, and low amplitudes. We then applied corrected baseline solutions when needed by using the `uvedit` task. After these initial calibrations, we inspected the phase and amplitudes of the calibrated data. We verified that then applied to the data using the `fluxCal` task. Following these particular protostars. The 1.4 cm and 3.3 cm data have corresponding angular resolutions of \( \sim 0.3 \) (\( \sim 90 \) AU); the exact resolutions depend on the value of the robust parameter and any applied tapering. The 4.0 cm and 6.5 cm data had resolutions of \( \sim 4'' \) and \( 7'' \), respectively. In the case of the 7.3 mm and 1.4 cm data, we generally applied tapering and used a robust parameter of 2, which is equivalent to natural weighting. For the 3.3 cm data, we used robust values of 0.5 and 1 for L1165-SMM1 and CB230 IRS1, respectively, to achieve higher resolution.

2.3. CARMA Observations

L1165-SMM1 was observed by CARMA in C and B configurations at 1.3 mm in 2012 December and 2013 January; the details are given in Table 3. The B-array data were taken during exceptionally good weather, as indicated by the low opacity at 225 GHz. The local oscillator frequency was 225.05 GHz and six correlator windows were configured to have 500 MHz bandwidths for continuum observations, yielding a total continuum bandwidth of 6 GHz (dual-side band) and the remaining two windows were configured to have 31 MHz bandwidth and 0.13 km s\(^{-1}\) channels. These two windows were set to observe \( ^{12}\)CO, \( ^{13}\)CO, and \( ^{18}\)O (\( J = 2 \rightarrow 1 \)), with \( ^{12}\)CO and \( ^{18}\)O being observed in the same spectral window in opposite side bands. The data were taken in a standard observing loop, science target observations bracketed by gain calibrator observations. The C configuration data observed the calibrator 3C418 for 3 minutes and then the source for 9 minutes; the first B configuration track observed 3C418 for 2 minutes and then L1165-SMM1 for 9 minutes. The second B configuration track observed 3C418 for 2 minutes, L1165-SMM1 for 8 minutes, and then a test point source 2148+611 for 1 minute.

CB230 IRS1 was observed by CARMA in C configuration at 3.4 mm in 2013 January and May. The local oscillator frequency was 90.9 GHz and one 500 MHz window was configured for continuum observation, yielding 1 GHz of continuum bandwidth (dual-side band). Spectral lines were observed in the remaining windows, but these data will not be considered here. The data were taken in a standard observing loop, science target observations bracketed by gain calibrator observations. The calibrator (1927+734) was observed for 90 minutes and then the target source for 90 minutes. The first B configuration track observed 3C418 for 2 minutes, L1165-SMM1 for 8 minutes, and then a test point source 2148+611 for 1 minute.

The data were reduced with the MIRIAD software package (Sault et al. 1995). We first split out the noise source observations and then applied corrected baseline solutions when needed using the `uvedit` task. Following this, we applied calibrations for transmission line length changes due to thermal expansion using the `lineCal` task. After these initial calibrations, we inspected the phase and amplitudes of the data versus time and flagged obviously bad data consisting of, but not limited to, phase jumps, high phase variance, and low amplitudes. We then applied bandpass corrections determined with the `fluxCal` task, using...
the noise source to correct the 31 MHz bands and a bright quasar for the 500 MHz bands. Following these calibrations, we determined the flux density of the primary gain calibrator using the absolute flux calibrators listed in Table 3 with the bootflux task. The flux calibration uncertainty is estimated to be 10%–20% and we only quote statistical uncertainties hereafter.

We then calibrated the complex gain and phases on the wide-band continuum data using the mfcal task and transferred these solutions to the 31 MHz bands. We then ran mfcal on the 31 MHz windows to correct for phase offsets between the 500 MHz and 31 MHz bands.

The data were imaged by first inverting the visibility data to construct the dirty map with the invert task. The dirty map was CLEANed with the mossdi task and the clean components are then convolved with the clean beam and added back to the residuals using the restor task to output the final clean map.

The image fidelity in B array was verified by imaging the faint secondary calibrator taken in the second B-array track and finding an unresolved point-source. While we did not observe a secondary calibrator in the first track, the science target structure was consistent between the first and second track, indicating that the conditions were similarly good.

2.4. Ancillary Infrared Data

NIR and MIR data are also included in this paper for CB230 to illustrate the larger-scale structure of CB230 IRS1. The Ks-band NIR imaging of CB230 IRS1 was taken with the 2.4 m Hiltner telescope of the MDM Observatory at Kitt Peak on 2008 June 12. The data were taken in a five-point dither pattern and off-source sky frames were observed every 6 minutes. The data were reduced using standard methods for NIR data reduction in IRAF. We refer the reader to Tobin et al. (2008) for more details of the observations and reduction procedure.

The Spitzer IRAC and MIPS photometry were published in Massi et al. (2008), but they did not show any Spitzer images in their work. We previously published the 3.6 μm image in Tobin et al. (2010b) and the reduction procedure can be found there; the MIPS 24 μm image is taken directly from the Spitzer archive.

3. RESULTS

The VLA imaging toward the protostars L1165-SMM1, L1157-mm, and CB230 IRS1 has enabled us to examine their circumstellar structure in detail previously unattainable with the old VLA system and at resolutions currently unmatched by a millimeter interferometer. The emission at 7.3 mm is expected to be dominated by thermal dust emission with a contribution of optically thin, free–free emission from the protostellar jets (Anglada1995; Anglada et al. 1998; Shirley et al. 2007); the 1.4 cm emission is expected to have roughly equal contributions from dust emission and free–free emission and the 3.3 cm, 4.0 cm, and 6.5 cm data are expected to be dominated by free–free emission.

3.1. L1165-SMM1

The 7.3 mm data for L1165-SMM1 are shown in Figure 1; the left panel shows the larger-scale (~150 AU) emission with the visibilities tapered at 500 kλ yielding ~0′′.3 resolution. The emission on 0′.3 scales is clearly asymmetric with an extension toward the southeast. The 2000 kλ tapered image, with a resolution of ~0′′.1, is shown in the middle panel of Figure 1 and the source is resolved into an apparent binary system at the higher resolution, with a separation of 0′.3 (~100 AU). Both sources are clear detections, but the secondary is about 3 times fainter than the primary at 7.3 mm. The primary also appears marginally resolved in the central panel of Figure 1 and the companion is unresolved. Finally, the highest resolution image with A-array data only is shown in the right panel of Figure 1. This image shows that the primary source is resolved, appearing disk-like (~60 AU diameter) and extended perpendicular to the outflow; both sources appear fainter due to more emission being resolved out in the A-array only data.

The centimeter-wave emission (1.4 cm and 3.3 cm) is shown in Figure 2. The 1.4 cm image shows that both sources are point-like and distinct from each other at this wavelength. At 3.3 cm, the primary source is well detected, but the secondary is only a 3.5σ detection and blended with the primary. The detection of the secondary source at both 1.4 cm and 3.3 cm wavelengths is
evidence that it is a bona fide protostar, given the large contribution from free–free emission at these wavelengths requires some source of ionization. Moreover, since the secondary is located normal to the outflow direction of the primary, it is unlikely that an outflow shock could be causing a false secondary in dust continuum and/or free–free emission. We examined the position of the young stellar object (IRAS 22051+5849) located 89° north in the 3.3 cm, 4.0 cm, and 6.5 cm images and did not find evidence of emission. We do not show the 4.0 cm or 6.5 cm data for the sake of brevity, but list the flux densities in Table 4.

Follow-up observations of dust continuum emission at 1.3 mm were obtained with CARMA with ~0.3′ resolution. The 1.3 mm data are shown in Figure 3 and trace an extended, flattened structure oriented perpendicular to the outflow, possibly a circumbinary disk. The disk structure appears to be surrounding the two protostars and it appears to be more extended southeast in the 1.3 mm data than at 7.3 mm. There is also an extension toward the northwest in the 1.3 mm data not seen at 7.3 mm. We also found that when the 1.3 mm data were imaged with the robust parameter set to −2, increasing the resolution of our deconvolved image (with increased noise), the two sources are still blended and there is extended structure associated with the primary (Figure 3, top-right panel). Gaussian fitting enabled the sources to be separated; the flux density of the secondary is a factor of ~5 less than the primary, a larger ratio than at 7.3 mm. The integrated flux densities measured with CARMA and the VLA are given in Table 4, as well as Gaussian fits to the image data.

In order to better determine the properties of the circumbinary structure around L1165-SMM1, it is necessary to decompose its emission from that which is more closely associated with the two protostars. We used the positions of the two sources from the VLA 7.3 mm map as a prior to fit the flux densities of the sources in the 1.3 mm robust = −2 map. Point sources rather than Gaussians were used in this case because our goal is to separate the extended structure from the compact structure. We performed this step on the robust = −2 map because it has less extended structure and better isolates the emission from the individual sources. Next, we used the positions and fitted flux densities (48.1 mJy and 13.7 mJy) to construct a model image of the two blended point sources at the resolution of the robust = 1 map (Figure 3, bottom left). We then subtracted the model from the data and the residual image is shown in the bottom-right panel of Figure 3; the flux density in the residual image is 20.5 ± 3 mJy. The residual image shows that the robust = 1 map cannot be reproduced by two blended point sources, having what appears to be a more extended circumbinary structure. We note that this structure is slightly offset to the northeast from the primary source; however, this could be due to projection effects because L1165-SMM1 is not viewed edge-on. While this analysis was done in the image plane, we also performed the same analysis in the uv plane by subtracting point sources with the uvmodel task and obtained a similar result.

We do find evidence for rotation on the scale of the circumbinary disk structure in 13CO (J = 2 → 1) emission. Figure 4 shows the 13CO channel maps and the emission is consistent with rotation on the scale of the disk. However, the signal-to-noise of the data is not good enough to attempt a mass measurement or verify a Keplerian velocity profile. The 12CO (J = 2 → 1) line was also detected in our CARMA observations; the integrated redshifted and blueshifted CO emission is shown in Figure 5. The blueshifted and redshifted sides of these outflows are consistent with the outflow observations by Visser et al. (2002). While not well resolved, the blueshifted emission is centered toward the primary source and the redshifted emission is centered near the secondary source. The centroid shift between the blueshifted and redshifted 12CO emission could have a number of causes: rotation of the disk, rotation of the outflow, or two outflows originating from either source. The offset in the blueshifted and redshifted 12CO emission appears similar to that of CB26. The characteristics of CB26 could be explained as outflow rotation via the outflow being coupled to the rotating disk; however, a misaligned outflow from a binary companion was also suggested as a possibility (Launhardt et al. 2009).

3.2. CB230 IRS1

The 7.3 mm data for CB230 IRS1 are shown in Figure 6 with the combined A, B, and C configuration images shown with tapering at 500 kλ and 2000 kλ in the left and middle panels; the A-array only data are shown in the right panel. A second source, separated from the main protostar by 0.3 (100 AU), is detected in the two highest resolution images. The sources

Figure 2. L1165-SMM1 images at 1.4 cm and 3.3 cm. Both sources are clearly detected at centimeter wavelengths, indicative of free–free emission from the thermal jets of each source. The centroids of the secondary are slightly offset at each wavelength, which may result from the free–free emission not being centered at the dust continuum peak at 7.3 mm and blending with the primary in the 3.3 cm image. Contours start at ±3σ and increase at 2σ intervals in the 1.4 cm image, where σ = 12.8 μJy beam−1. In the 3.3 cm image, the contours are [2, 3, 5, 7, 9, ...] × σ, where σ = 9.6 μJy beam−1.

(A color version of this figure is available in the online journal.)
Table 4
L1165-SMM1 Measurements

| Wavelength (mm) | Configuration(s) | Integrated Flux (mJy) | Peak Flux (mJy) | Aperture (") | Gaussian Size (") | Gaussian P.A. (°) | Deconvolved Size (") | Deconvolved P.A. (°) | Robust | Taper (kl) | Beam (") | Beam P.A. (°) |
|----------------|------------------|-----------------------|----------------|--------------|-------------------|-------------------|---------------------|---------------------|-------|----------|-----------|-------------|
| 1.3            | BC               | 82.3 ± 3              | 52.8 ± 1       | 0.9 × 0.9    | 0.551 × 0.331    | −55.1             | 0.40 × 0.12         | −48.4               | 1     | none     | 0.39 × 0.30 | −72.0       |
| 1.3            | B                | 69.9 ± 11             | 44.5 ± 3       | 0.9 × 0.9    | 0.443 × 0.266    | −55.5             | 0.35 × 0.12         | −0.1                | −2    | none     | 0.28 × 0.23 | −80.9       |
| 3.4            | CD               | 13.3 ± 0.8            | 10.3 ± 0.3     | 10 × 10      | 3.89 × 2.93      | −85.6             | 1.81 × 0.990        | 85.6                | 2     | none     | 3.45 × 2.74 | −81.0       |
| 7.3            | A                | 0.9 ± 0.1             | 0.34 ± 0.03    | 0.4 × 0.25   | ...               | ...               | ...                 | ...                 | 2     | none     | 0.072 × 0.075 | −32.2       |
| 7.3            | ABC              | 1.4 ± 0.1             | 0.45 ± 0.02    | 0.4 × 0.25   | ...               | ...               | ...                 | ...                 | 2     | none     | 0.089 × 0.074 | −30.2       |
| 7.3            | ABC              | 1.7 ± 0.2             | 0.51 ± 0.02    | 0.4 × 0.25   | ...               | ...               | ...                 | ...                 | 2     | 2000     | 0.13 × 0.11 | −12.0       |
| 7.3            | ABC              | 1.4 ± 0.1             | 0.71 ± 0.03    | 0.9 × 0.9    | 0.46 ± 0.31      | 135.9             | 0.35 × 0.12         | 134.3               | 2     | 500      | 0.30 × 0.29 | −22.2       |
| 14             | AB               | 0.35 ± 0.02           | 0.21 ± 0.01    | 0.9 × 0.9    | ...               | ...               | ...                 | ...                 | 2     | 1000     | 0.19 × 0.16 | 13.7        |
| 33             | AB               | 0.25 ± 0.01           | 0.09 ± 0.01    | 0.9 × 0.9    | ...               | ...               | ...                 | ...                 | 0.5   | none     | 0.28 × 0.20 | 30.3        |
| 40             | C                | 0.17 ± 0.02           | 0.14 ± 0.01    | 6 × 6        | ...               | ...               | ...                 | ...                 | 1     | none     | 3.7 × 2.7    | 1.2         |
| 65             | C                | 0.13 ± 0.03           | 0.11 ± 0.01    | 10 × 10      | ...               | ...               | ...                 | ...                 | 1     | none     | 6.0 × 4.5   | −178.6      |

**Primary**

| Wavelength (mm) | Configuration(s) | Integrated Flux (mJy) | Peak Flux (mJy) | Aperture (") | Gaussian fit | Gaussian fit parameters for the sake of brevity. |
|-----------------|------------------|-----------------------|----------------|--------------|--------------|-------------------------------------------------|
| 1.3             | BC               | 59.8 ± 3              | 44.6 ± 2       | Gaussian fit | 0.342 × 0.245 | 135.0 ± 3.5                                     |
| 7.3             | A                | 0.45 ± 0.2            | 0.34 ± 0.03    | 0.25 × 0.25  | 0.13 × 0.063  | 120.0                                           |
| 7.3             | ABC              | 1.0 ± 0.05            | 0.45 ± 0.02    | 0.25 × 0.25  | 0.15 × 0.096  | 125.5                                           |
| 7.3             | ABC              | 0.76 ± 0.05           | 0.51 ± 0.02    | 0.25 × 0.25  | 0.18 × 0.13   | 140.0                                           |
| 14              | AB               | 0.23 ± 0.03           | 0.18 ± 0.01    | 0.25 × 0.25  | 0.21 ± 0.19   | 156.2                                           |
| 33              | AB               | 0.10 ± 0.01           | 0.09 ± 0.01    | 0.3 × 0.3    | 0.33 ± 0.22   | 41.5                                            |

**Secondary**

| Wavelength (mm) | Configuration(s) | Integrated Flux (mJy) | Peak Flux (mJy) | Aperture (") | Gaussian fit | Gaussian fit parameters for the sake of brevity. |
|-----------------|------------------|-----------------------|----------------|--------------|--------------|-------------------------------------------------|
| 1.3             | BC               | 11.8 ± 3              | 11.2 ± 2       | Gaussian fit | 0.298 × 0.221 | 173 ± 15                                        |
| 7.3             | A                | 0.17 ± 0.06           | 0.12 ± 0.03    | 0.25 × 0.25  | ...          | ...                                             |
| 7.3             | ABC              | 0.34 ± 0.04           | 0.17 ± 0.02    | 0.25 × 0.25  | 0.17 × 0.14   | 127.5                                           |
| 7.3             | ABC              | 0.34 ± 0.05           | 0.19 ± 0.02    | 0.25 × 0.25  | 0.22 ± 0.184  | 151.1                                           |
| 14              | AB               | 0.01 ± 0.02           | 0.069 ± 0.01   | 0.25 × 0.25  | 0.28 ± 0.21   | 40.1                                            |
| 33              | AB               | 0.03 ± 0.02           | 0.036 ± 0.01   | 0.25 × 0.25  | 0.32 × 0.235  | 38.5                                            |

**Notes.** Uncertainties on the integrated and peak flux densities are from the flux measurements in the specified apertures, unless “Gaussian fit” is listed in the Aperture column. We do not give uncertainties on the Gaussian fit parameters for the sake of brevity.


Figure 3. L1165-SMM1 images at 1.3 mm showing an extended structure normal to the outflow direction and surrounding the two sources. The top-left panel is the combined B and C configuration image, showing more extended structure than the 7.3 mm image with 500 kλ tapering (Figure 1), with a robust weighting of 1. The top-right panel shows the B configuration image with a robust weighting of −2, yielding higher resolution and less extended emission. This image finds a strong continuum source peaked near the 7.3 mm peak of the primary protostar with a weaker extension toward the position of the secondary. The bottom-left panel is a model image of the two blended point sources with the same resolution as the top-left image. The bottom-right panel is the residual of the top-left image after subtraction of the model image. The contours plotted in the top-left, bottom-left, and bottom-right panels (robust = 1 images) are $-3, 3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 35, 40, 50, 60, 70 \times \sigma$, where $\sigma = 0.69$ mJy beam$^{-1}$. The top-right panel (robust = −2 image) contours are $-3, 3, 4, 5, 6, 9, 12, 15 \times \sigma$, where $\sigma = 2.9$ mJy beam$^{-1}$.

(A color version of this figure is available in the online journal.)

are marginally resolved at 0".27 resolution (500 kλ tapering) and resolved into two sources in the higher resolution data. The primary source appears unresolved in the high-resolution images; Gaussian fits to the images, listed in Table 5, indicate that the source is only marginally more extended than the beam. The secondary, however, appears to be resolved in both the A-array only and 2000 kλ tapered images and it has a diameter of $\sim$60 AU and may be indicative of a compact circumstellar disk around the source.

Both sources are also detected at 1.4 cm and 3.3 cm, as shown in Figure 7. The 3.3 cm detection toward the secondary is marginal ($\sim$3.5σ); however, the 3.3 cm emission appears extended toward the secondary, possibly related to the outflow activity in the source. Moreover, at 1.4 cm the primary appears resolved in the direction of the outflow axis. The presence of 3.3 cm emission located at the secondary source is an indication that there is an outflow driving source, energetic enough to produce the ionization required to have detectable free–free emission. The flux densities measured from the VLA data are given in Table 5 along with Gaussian fitting of the sources. The CARMA data had lower resolution than the other data sets, $\sim$2", but they provided a shorter wavelength data point. We do not show the 3.4 mm, 4.0 cm, and 6.5 cm data for the sake of brevity, but the flux densities are given in Table 5.

We noted in Section 2 that CB230 IRS1 has an infrared companion (CB230 IRS2) separated from the main protostar by 10" ($\sim$3000 AU), making CB230 IRS1 a triple system. NIR and MIR images of CB230 IRS1 and IRS2 are shown in Figure 8. We examined the location of the wide tertiary source for emission at all observed wavelengths and did not detect it; this source is well within the VLA and CARMA primary beams at 7.3 mm and 3.4 mm (65" and 72", respectively). Therefore, the tertiary source does not appear to have substantial dust emission or free–free emission, consistent with non-detections at 1.3 mm and 3 mm (Launhardt et al. 2001, 2010; Launhardt 2001); the 3σ upper limits are given in Table 5.
### Table 5

**CB230 IRS1 Measurements**

| Wavelength (mm) | Configuration(s) | Integrated Flux (mJy) | Peak Flux (mJy) | Aperture (″) | Gaussian Size (″) | Gaussian P.A. (°) | Deconvolved Size (″) | Deconvolved P.A. (°) | Robust (kλ) | Taper | Beam (″) | Beam P.A. (°) |
|-----------------|------------------|------------------------|-----------------|--------------|------------------|-------------------|---------------------|---------------------|-------------|-------|---------|--------------|
| 3.4             | C                | 13.3 ± 0.8             | 10.3 ± 0.3      | 10 × 10      | 3.89 ± 2.93     | 1.81 ± 0.990      | 85.6                | ±3.4                 | 2           | none  | 3.45    | ±2.74        |
| 7.3             | A                | 1.5 ± 0.2              | 0.42 ± 0.02     | 0.4 × 0.25   | ...             | ...               | ...                 | ...                 | 2           | none  | 0.068   | ±0.051       |
| 7.3             | ABC              | 1.8 ± 0.1              | 0.46 ± 0.02     | 0.4 × 0.25   | ...             | ...               | ...                 | ...                 | 2           | none  | 0.073   | ±0.055       |
| 7.3             | ABC              | 1.5 ± 0.1              | 0.58 ± 0.03     | 0.4 × 0.25   | ...             | ...               | ...                 | ...                 | 2           | none  | 0.097   | ±0.086       |
| 7.3             | ABC              | 1.5 ± 0.1              | 0.79 ± 0.04     | 0.9 × 0.9    | 0.55 ± 0.29     | 0.48 ± 0.14       | 56.6                | ±10.3                | 2           | 500   | 0.27    | ×0.25        |
| 14              | AB               | 0.34 ± 0.03            | 0.17 ± 0.01     | 0.9 × 0.9    | ...             | ...               | ...                 | ...                 | 2           | 1000  | 0.18    | ×0.17        |
| 33              | AB               | 0.1 ± 0.02             | 0.053 ± 0.01    | 0.5 × 0.5    | ...             | ...               | ...                 | ...                 | 1           | none  | 0.27    | ×0.24        |
| 40              | C                | 0.098 ± 0.02           | 0.071 ± 0.01    | 6 × 6        | ...             | ...               | ...                 | ...                 | 1           | none  | 4.1     | ×2.7         |
| 65              | C                | 0.064 ± 0.02           | 0.064 ± 0.01    | 8 × 8        | ...             | ...               | ...                 | ...                 | 1           | none  | 6.6     | ×4.5         |

### Primary

| Wavelength (mm) | Configuration(s) | Integrated Flux (mJy) | Peak Flux (mJy) | Aperture (″) | Gaussian Size (″) | Gaussian P.A. (°) | Deconvolved Size (″) | Deconvolved P.A. (°) | Robust (kλ) | Taper | Beam (″) | Beam P.A. (°) |
|-----------------|------------------|------------------------|-----------------|--------------|------------------|-------------------|---------------------|---------------------|-------------|-------|---------|--------------|
| 7.3             | A                | 0.94 ± 0.1             | 0.42 ± 0.02     | 0.25 × 0.25  | 0.09 ± 0.076    | 3.4               | 0.064 × 0.047       | 335.0               | 2           | none  | 0.068   | ×0.051       |
| 7.3             | ABC              | 1.1 ± 0.1              | 0.46 ± 0.02     | 0.25 × 0.25  | 0.10 ± 0.086    | 179.3             | 0.074 × 0.061       | 31                  | 2           | none  | 0.073   | ×0.055       |
| 7.3             | ABC              | 0.95 ± 0.1             | 0.58 ± 0.03     | 0.25 × 0.25  | 0.12 ± 0.11     | 180.0             | 0.075 × 0.07       | 19                  | 2           | 2000  | 0.097   | ×0.086       |
| 14              | AB               | 0.26 ± 0.03            | 0.18 ± 0.01     | 0.25 × 0.25  | 0.24 ± 0.20     | 172.9             | 0.16 × 0.10       | 173.6               | 2           | 1000  | 0.18    | ×0.17        |
| 33              | AB               | 0.054 ± 0.003          | 0.053 ± 0.005   | 0.25 × 0.25  | 0.28 ± 0.25     | 165.5             | ...                 | ...                 | 1           | none  | 0.27    | ×0.24        |

### Secondary

| Wavelength (mm) | Configuration(s) | Integrated Flux (mJy) | Peak Flux (mJy) | Aperture (″) | Gaussian Size (″) | Gaussian P.A. (°) | Deconvolved Size (″) | Deconvolved P.A. (°) | Robust (kλ) | Taper | Beam (″) | Beam P.A. (°) |
|-----------------|------------------|------------------------|-----------------|--------------|------------------|-------------------|---------------------|---------------------|-------------|-------|---------|--------------|
| 7.3             | A                | 0.46 ± 0.1             | 0.20 ± 0.02     | 0.25 × 0.25  | 0.13 ± 0.07     | 67.0              | 0.12 ± 0.02        | 67                  | 2           | none  | 0.068   | ×0.051       |
| 7.3             | ABC              | 0.63 ± 0.1             | 0.22 ± 0.02     | 0.25 × 0.25  | 0.13 ± 0.08     | 68.4              | 0.12 ± 0.04       | 68.5                | 2           | none  | 0.073   | ×0.055       |
| 7.3             | ABC              | 0.52 ± 0.1             | 0.27 ± 0.03     | 0.25 × 0.25  | 0.14 ± 0.10     | 66.0              | 0.12 ± 0.03       | 68.7                | 2           | 2000  | 0.097   | ×0.086       |
| 14              | AB               | 0.092 ± 0.02           | 0.074 ± 0.01    | 0.25 × 0.25  | 0.36 ± 0.19     | 61.2              | 0.31 ± 0.11       | 61.6                | 2           | 1000  | 0.18    | ×0.17        |
| 33              | AB               | 0.0093 ± 0.008         | 0.018 ± 0.005   | 0.25 × 0.25  | ...             | ...               | ...                 | ...                 | 1.0         | none  | 0.27    | ×0.24        |

### CB230 IRS2

| Wavelength (mm) | Configuration(s) | Integrated Flux (mJy) | Peak Flux (mJy) | Aperture (″) | Gaussian Size (″) | Gaussian P.A. (°) | Deconvolved Size (″) | Deconvolved P.A. (°) | Robust (kλ) | Taper | Beam (″) | Beam P.A. (°) |
|-----------------|------------------|------------------------|-----------------|--------------|------------------|-------------------|---------------------|---------------------|-------------|-------|---------|--------------|
| 3.4             | C                | <1.0                   |                 |              |                  |                   |                     |                     |             |       |         |              |
| 7.3             | ABC              | <0.08                  |                 |              |                  |                   |                     |                     |             |       |         |              |
| 14              | AB               | <0.04                  |                 |              |                  |                   |                     |                     |             |       |         |              |
| 33              | AB               | <0.02                  |                 |              |                  |                   |                     |                     |             |       |         |              |
| 40              | AB               | <0.02                  |                 |              |                  |                   |                     |                     |             |       |         |              |
| 65              | AB               | <0.04                  |                 |              |                  |                   |                     |                     |             |       |         |              |

**Notes.** Uncertainties on the integrated and peak flux densities are from the flux measurements in the specified apertures, unless “Gaussian fit” is listed in the Aperture column. We do not give uncertainties on the Gaussian fit parameters for the sake of brevity.
### Table 6
L1157-mm Measurements

| Wavelength (mm) | Configuration(s) | Integrated Flux (mJy) | Peak Flux (mJy) | Aperture (") | Gaussian Size (") | Gaussian P.A. (°) | Deconvolved Size (") | Deconvolved P.A. (°) | Robust | Taper (kλ) | Beam (") | Beam P.A. (°) |
|----------------|-------------------|-----------------------|-----------------|--------------|-------------------|------------------|----------------------|----------------------|--------|-----------|---------|-------------|
|                |                   | Total                 |                 | 181 ± 30     | 98.5 ± 1.0       | 1 x 1            | 0.509 x 0.37        | 0.35 x 0.20          | 70.6   | none      | 0.37 x 0.33 | −83.2       |
| 1.3            | B                 | 3.4                   | 9.0 ± 1.0       | 6.8 ± 0.3    | 1 x 1            | 0.48 x 0.40      | 75.0                 | 0.33 x 0.171        | 59.9   | none      | 0.39 x 0.33 | −61.4       |
| 3.4            | A                 | 7.3                   | 1.7 ± 0.1       | 0.49 ± 0.02  | 0.3 x 0.3        | 0.11 x 0.11      | 130.0                | 0.093 x 0.083       | 80     | none      | 0.070 x 0.052| −23.2       |
| 7.3            | A                 | 7.3                   | 2.2 ± 0.1       | 0.71 ± 0.02  | 0.3 x 0.3        | 0.12 x 0.12      | 78.0                 | 0.11 x 0.082        | 72.0   | none      | 0.073 x 0.055| −21.0       |
| 7.3            | ABC               | 7.3                   | 2.2 ± 0.1       | 1.0 ± 0.02   | 0.3 x 0.3        | 0.15 x 0.15      | 8.4                  | 0.11 x 0.10         | 56     | 2000      | 0.11 x 0.095| −13.2       |
| 7.3            | ABC               | 7.3                   | 2.4 ± 0.1       | 1.7 ± 0.03   | 0.5 x 0.5        | 0.35 x 0.33      | 11.3                 | 0.20 x 0.18         | 31     | 500       | 0.29 x 0.28 | 0.7         |
| 14             | AB                | 33                    | 0.54 ± 0.07     | 0.31 ± 0.01  | 0.5 x 0.5        | 0.21 x 0.14      | 134.1                | 0.12 x 0.069        | 134.3  | 1000      | 0.18 x 0.17 | −12.7       |
| 33             | AB                | 36                    | 0.24 ± 0.02     | 0.21 ± 0.01  | 0.5 x 0.5        | 0.36 x 0.25      | 35.33                | ...                  | 2       | none      | 0.36 x 0.23 | 40.6        |
| 36             | C                 | 62                    | 0.21 ± 0.07     | 0.21 ± 0.02  | 10 x 10          | 3.3 x 2.5        | 164.6                | ...                  | 2       | none      | 3.5 x 2.5  | −37.3       |
| 62             | C                 |                       | 0.18 ± 0.05     | 0.19 ± 0.03  | 10 x 10          | 5.7 x 4.8        | 130.7                | ...                  | 2       | none      | 6.6 x 4.6  | −54.9       |

**Notes.** Uncertainties on the integrated and peak flux densities are from the flux measurements in the specified apertures, unless “Gaussian fit” is listed in the Aperture column. We do not give uncertainties on the Gaussian fit parameters for the sake of brevity.
3.3. L1157-mm

Unlike L1165-SMM1 and CB230 IRS1, L1157-mm appears to be a single source; only one continuum peak is observed in the 7.3 mm image shown in Figure 9, as well as the 1.4 cm and 3.3 cm data in Figure 10. There is a hint of the source being marginally resolved perpendicular to the outflow in the A-array-only image shown in Figure 9. Gaussian fitting to the image data (Table 6) indicates that the source is marginally resolved in the highest resolution 7.3 mm data and the deconvolved position angle is perpendicular to the outflow. The marginally extended emission is suggestive of a small disk ($R < 15$ AU), but by no means definitive. The lack of significant resolved structure on small scales is consistent with the source having point-like structure at $\sim 0''.3$ resolution at 1.3 mm and 3.4 mm (Chiang et al. 2012). The 1.4 cm data appear to be resolved, as evidenced by the peak flux differing from the integrated flux, while the 3.3 cm data are consistent with a point source. This could be indicative of the 1.4 cm data having a marginally extended free–free component, as often found by Reipurth et al. (2002, 2004).

3.4. Millimeter–Centimeter Spectra

Between 1.3 mm and 3.3 cm, the broadband spectra of many protostellar objects transition from being dominated by thermal dust emission to being dominated by free–free emission from the thermal jets driven by the protostars and disks (Anglada 1995; Anglada et al. 1998; Shirley et al. 2007). Emission at 7.3 mm lies in the part of the spectrum where there may be significant contributions from both dust and free–free emission. In order to interpret the 7.3 mm emission in terms of dust emission alone, we must subtract the potential contribution from free–free emission.

The spectra of the three sources are plotted in Figure 11 from 1.3 mm to 6.5 cm. The individual flux measurements for the companion sources to L1165-SMM1 and CB230 IRS1 are shown, as well as the total flux density. We have attempted to reasonably match the resolutions of the data from different wavelengths such that we are measuring dust emission from...
Figure 6. CB230 IRS1 images at 7.3 mm. The sources appear marginally resolved in the lower resolution image with 500 kλ tapering and are quite distinct in the two higher resolution images shown in the middle and right panels. The primary source appears unresolved; however, the companion source appears extended roughly perpendicular to the outflow direction. Contours start at ±3σ and increase in 2σ intervals for all images, where σ = 41.3 μJy beam⁻¹, 27.5 μJy beam⁻¹, and 25.8 μJy beam⁻¹ for the 500 kλ tapered image, the 2000 kλ tapered image, and the A-array-only image, respectively.

(A color version of this figure is available in the online journal.)

Figure 7. CB230 IRS1 images at 1.4 cm (left) and 3.3 cm (right). The two sources are resolved at 1.4 cm; the extended feature between them may simply result from the sources being blended. At 3.6 cm, the secondary has a marginal peak above the 3σ level, but is surrounded by extended emission at the 2σ level. Contours start at ±3σ and increase at 2σ intervals in the 1.4 cm image, where σ = 11.5 μJy beam⁻¹. In the 3.3 cm image, the contours are ±[2, 3, 5, 7, 9, ...] × σ, where σ = 5.3 μJy beam⁻¹. We start at ±2 sigma in the 3.3 cm image to better show the extension of emission at this wavelength.

(A color version of this figure is available in the online journal.)

Figure 8. Images of CB230 IRS1 and IRS2 at 2.15 μm (left), 4.5 μm (middle), and 24 μm (right). The positions of the two close binary sources detected by the VLA are the blended crosses near the center of the image and the tertiary source is 10′′ east. The scattered light emission of the tertiary is clearly seen at the two shorter wavelengths and the source is weakly detected at 24 μm, blended with the point-spread function of the main protostars.

(A color version of this figure is available in the online journal.)

the same spatial scales; however, the highest resolution data at wavelengths shortward of 7.3 mm have resolutions between 0.3 (at best) and ~2′′ (at worst) for these sources. Wavelengths longer than 1.4 cm are dominated by unresolved free–free emission, therefore resolution does not matter as much, except that the multiple sources are not as well resolved.

We fit the full spectra simultaneously, assuming that the data can be described by two spectral slopes, one representing the
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Figure 9. L1157-mm images at 7.3 mm. The images are shown with tapering at 500 kλ (left), 2000 kλ (middle), and A-array-only untapered (right). The tapered images show indications of a low-level extended structure that might be related to warm dust in the outflow cavity, as seen at shorter wavelengths (Tobin et al. 2013; Stephens et al. 2013). There is no evidence of a companion or resolved structure toward the intensity peak in the two tapered images, but the A-array-only image shows a possible indication of resolved structure, consistent with the expected axis of the disk. The contours in all images start at ±3σ and increase in 3σ intervals for all images, where σ = 38.5 beam−1 μJy, 24.2 μJy beam−1, and 18.9 μJy beam−1 for the 500 kλ tapered image, the 2000 kλ tapered image, and the A-array-only image, respectively.

(A color version of this figure is available in the online journal.)

Figure 10. L1157-mm images at 1.4 cm (left) and 3.3 cm (right). The source is marginally resolved at 1.4 cm, but it is compact and does not show obvious indications of a disk-like structure. The contours in all images start at ±3σ and increase in 3σ intervals for each image, where σ1.4c m = 12.1 μJy beam−1 and σ3.3c m = 6.3 μJy beam−1.

(A color version of this figure is available in the online journal.)

Table 7

| Source  | Free–Free Slope  | F0 (Free–Free) (mJy) | Thermal Slope | F0 (Thermal) (mJy) |
|---------|------------------|---------------------|---------------|-------------------|
| CB230   | −0.71 ± 0.42     | 1.2 ± 2.0           | −3.3 ± 0.38   | 890 ± 450         |
| L1157   | −0.35 ± 0.42     | 0.77 ± 1.2          | −2.6 ± 0.25   | 270 ± 80          |
| L1165   | −0.013 ± 0.33    | 0.15 ± 0.26         | −2.45 ± 0.13  | 160 ± 20          |

Notes. The spectral slopes are defined by the convention $F_{\lambda} = F_0(\lambda/1 \text{ mm})^\alpha$, where α is the spectral slope. The thermal and free–free spectral indices are derived from simultaneous fitting of the two components.

3.5. Mass Estimates

The masses of the material surrounding each protostar can be estimated by assuming that the dust emission is isothermal and optically thin, using the formula

$$M = \frac{D^2 F_\lambda}{\kappa_0 \left( \frac{\lambda}{850 \mu m} \right)^{-\beta} B_\lambda(T_{\text{dust}})},$$

where $D$ is the distance to the source, $F_\lambda$ is the flux density at frequency $\lambda$, $\kappa_0$ is the dust opacity at 850 μm, $B_\lambda(T_{\text{dust}})$ is the blackbody spectrum at temperature $T_{\text{dust}}$, and $\beta$ is the spectral index of the dust.

thermal dust emission and the other representing the free–free emission. The fits are made using the least-squares fitting routine mpfit (Markwardt 2009); the total fluxes at all the wavelengths are plotted in Figure 11. In the fitting procedure, the free–free slope is constrained to be between $\lambda^{-1.0}$ and $\lambda^{1.0}$, while the thermal slope is assumed to be between $\lambda^{-1.0}$ and $\lambda^{-4.5}$. Note that this fit is for the total flux density of a source, given that the shorter wavelength data do not resolve the proto-binnaries. The sources have a range of thermal and free–free spectral slopes that are given in Table 7. CB230 has a steep spectral slope, while L1165 has a shallow spectral slope; the spectral slopes in the centimeter are consistent with previous measurements toward protostars (Shirley et al. 2007). We note that there is significant uncertainty in the spectral slopes given the degeneracies between the thermal and free–free components; moreover, there may be variability in the free–free emission (e.g., Shirley et al. 2007) and that would further add to the uncertainty.

The spectral slope of the free–free emission enables us to subtract its contribution from the 7.3 mm data to determine the flux density only due to dust emission. This enables us to estimate the mass of the emitting material with some assumptions. Free–free emission at 7.3 mm comprises ~10% of the total in L1165-SMM1, ~19% in CB230 IRS1, and ~18% in L1157-mm; the values are relative to the flux densities measured in the 500 kλ tapered images. A lingering issue is that we do not know the free–free spectral slopes of the companion sources since we can only measure the spectral index of the total flux. Therefore, we have assumed that the spectral slope of the total flux is applicable to the primary and secondary sources.
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Figure 11. Millimeter to centimeter spectra of L1165-SMM1, CB230 IRS1, and L1157-mm. There is a clear free–free (dashed line) and dust emission (dotted line) component to each spectrum. About 70%–90% of the emission at 7.3 mm is expected to be from dust continuum (see Section 3.4). The contributions from free–free emission and dust are about equal at 1.4 cm and the free–free dominates at 3.3 cm.

\[ B_\lambda = \frac{2 \pi k T}{c^2} \lambda^3 \]

is the Planck function. We have assumed that \( T_{\text{dust}} = 30 \text{ K} \), \( \kappa_{850} = 0.035 \text{ cm}^2 \text{ g}^{-1} \) (dust+gas opacity, assuming a dust-to-gas ratio of 100), and \( D = 300 \text{ pc} \), basing our assumptions on previous works (Beckwith et al. 1990; Andrews & Williams 2005; Tobin et al. 2012). The dust opacity spectral index \( \beta \) is estimated from the fit to the spectrum thermal slope (Table 7), under the assumption that \( F_\lambda \propto \lambda^{-2(1+\beta)} \). Note that the dust opacity we have assumed is larger than typically assumed for protostars (e.g., Ossenkopf & Henning 1994) and more typical of the Class II sources (e.g., Andrews & Williams 2005; Andrews et al. 2009); however, a larger opacity may be correct given the indications of grain growth in the protostellar phase (Kwon et al. 2009; Tobin et al. 2013). With this opacity, we can more directly compare our results with those of more evolved disks, but we may be systematically underestimating the dust masses if the dust opacities are indeed lower.

The derived masses are in the range 0.01–0.2 \( M_\odot \), comparable with the masses found for Class II disks (e.g., Andrews et al. 2010). The mass estimates for each source and their components are listed in Table 8, along with the assumed \( \beta \). The mass estimates agree reasonably well at the different wavelengths for all sources; differences likely reflect a combination of uncertainties in absolute flux calibration, variations in dust opacities, sensitivity to different spatial scales, etc. Note that these mass estimates are temperature dependent and larger characteristic temperatures would yield lower mass estimates. Moreover, these sources certainly have temperatures gradients that cannot be accounted for in this simple analysis.

4. DISCUSSION

Two protostars out of our sample of three are found to have a previously unknown companion source separated by 0′3 (~100 AU). The presence of these companions raises questions. How did these companions form and did they form in situ or have their separations evolved significantly via dynamical evolution?

| Source          | Wavelength (mm) | \( \beta \) | Mass \((M_\odot)\) | Free–Free Emission Fraction |
|-----------------|-----------------|-------------|-------------------|---------------------------|
| CB230 IRS1 A+B  | 3.4             | 1.3 ± 0.38  | 0.13 ± 0.008      | 0.038                      |
| CB230 IRS1 A+B  | 7.3             | " "        | 0.16 ± 0.01       | 0.19                      |
| CB230 IRS1 A+B  | 14              | " "        | 0.18 ± 0.02       | 0.53                      |
| CB230 IRS1 A    | 7.3             | " "        | 0.054 ± 0.004     | 0.18                      |
| CB230 IRS1 A    | 14              | " "        | 0.075 ± 0.008     | 0.40                      |
| CB230 IRS1 B    | 7.3             | " "        | 0.034 ± 0.005     | 0.052                     |
| CB230 IRS1 B    | 14              | " "        | 0.036 ± 0.008     | 0.18                      |
| L1165-SMM1 A+B  | 1.3             | 0.45 ± 0.13 | 0.027 ± 0.001     | 0.002                     |
| L1165-SMM1 A+B  | 7.3             | " "        | 0.027 ± 0.002     | 0.10                      |
| L1165-SMM1 A+B  | 14              | " "        | 0.022 ± 0.003     | 0.41                      |
| L1165-SMM1 A    | 7.3             | " "        | 0.020 ± 0.001     | 0.002                     |
| L1165-SMM1 A    | 14              | " "        | 0.014 ± 0.0009    | 0.15                      |
| L1165-SMM1 A    | 14              | " "        | 0.012 ± 0.0015    | 0.50                      |
| L1165-SMM1 B    | 1.3             | " "        | 0.0038 ± 0.0008   | 0.003                     |
| L1165-SMM1 B    | 7.3             | " "        | 0.0065 ± 0.001    | 0.10                      |
| L1165-SMM1 B    | 14              | " "        | 0.0067 ± 0.002    | 0.33                      |
| L1157-mm        | 1.3             | 0.6 ± 0.25  | 0.063 ± 0.01      | 0.004                     |
| L1157-mm        | 3.4             | " "        | 0.034 ± 0.004     | 0.06                      |
| L1157-mm        | 7.3             | " "        | 0.058 ± 0.002     | 0.16                      |
| L1157-mm        | 14              | " "        | 0.026 ± 0.004     | 0.65                      |

Notes. The calculated masses all assume a dust-to-gas mass ratio of 1:100 and a dust temperature of 30 K. The flux densities used for the total masses at 7.3 mm are derived from the images tapered to 500 k\( \lambda \). The uncertainties on the masses are statistical only; the 1.3 mm and 3.4 mm measurements carry an absolute calibration accuracy of 10%–20% and the 7.3 mm data have a calibration accuracy of ~10%. Note that there are additional systematic uncertainties from the fits to the spectral slopes that have not been accounted for.
4.1. Constraining the Probable Binary Formation Mechanism

There are three likely mechanisms for the formation of binary/multiple protostellar systems. The first is fragmentation induced by the rotating collapse of the infalling envelope (e.g., Burkert & Bodenheimer 1993; Boss 1995; Tohline 2002; Sterzik et al. 2003). In this scenario, a rotating, spherical envelope has a mild azimuthal density perturbation and simulations show that the density perturbation becomes enhanced during collapse. The rotation causes the formation of a large, flattened, and asymmetric density structure from which two density peaks form with ~1000 AU separations. While these simulations are simplistic and have rather high initial rotation rates, envelopes have been observed to be even more asymmetric than assumed in these simulations (Tobin et al. 2010b; Launhardt et al. 2013). Therefore, this mechanism could form both wide (~1000 AU) and close (<500 AU) binary systems, depending on the angular momentum of the infalling gas. The wide binary systems could then further evolve to smaller separations via dynamical friction. If the infalling matter had high angular momentum, the binary separations might widen rather than shrink (Zhao & Li 2013).

The second mechanism is turbulent fragmentation. Offner et al. (2010) found that protostars forming in global molecular cloud simulations typically had initial separations of a few thousand AU and fragmentation on the scale of the disk could be suppressed by radiative heating. These protostars could then migrate toward smaller separations via dynamical friction and the accretion of low angular momentum gas. The dynamical evolution could shrink the separations of systems from ~2000 AU to ~200 AU on timescales as short as ~10 kyr. Thus, even on the short timescale of protostellar collapse, binaries could migrate to small separations rapidly enough that it would be unclear if they formed in place or if they had migrated.

The third formation mechanism is direct fragmentation of the rotationally supported circumstellar disk via gravitational instability (e.g., Kratter et al. 2010; Vorobyov 2010; Zhu et al. 2012). This is similar to the fragmentation of the rotating, asymmetric envelope, but is happening within the rotationally supported circumstellar disks, whereas the flattened envelope was not supported by its rotation. In this scenario, a large, massive disk (\(M_d \sim \text{few} \times 0.1 M_\odot\)) forms due to the angular momentum of the infalling envelope. The self-gravity of the disk enables fragmentation to happen at large radii, forming the binary components in place and migration of the fragments could take place within the disk. The fragments would also all be in the equatorial plane of the system and would share a common angular momentum vector. This is also the case for rotational fragmentation of a common infalling envelope. However, there is no expectation for protostars formed via turbulent fragmentation to share the same orbital plane/ angular momentum vector as their companions.

We suggest that the likely fragmentation mechanism for CB230 IRS1 and L1165-SMM1 is direct fragmentation of their circumstellar disks. The principal evidence for this is the apparent circumbinary disk around the two protostars in L1165-SMM1 and the fact that the secondary sources in both CB230 IRS1 and L1165-SMM1 are both located nearly orthogonal to the outflow direction. This is expected if they formed in a disk and the outflow is launched perpendicular to the equatorial plane of the disk. While we did not detect evidence of a circumbinary disk around CB230 IRS1, its presence or lack thereof cannot be ruled out with the data in hand. The case for a circumbinary disk around L1165-SMM1 is reasonably strong given that the emission is not simply comprised of two blended point sources, as shown by our image decomposition in Figure 3. Moreover, the total flux is 10 mJy lower in the robust = −2 image than in the robust = 1 image, indicative of extended structure being filtered out at higher resolution. Lastly, there is an indication of rotation on the scale of the circumbinary disk from the 13CO (\(J = 2 \rightarrow 1\)) channel maps in Figure 4. We note that rotationally supported circumbinary disks have been observed toward GG Tau ((Guilloteau et al. 1999) and L1551 NE (Takakuwa et al. 2012); therefore, it is conceivable that the disk around L1165-SMM1 is rotationally supported. While the masses of material surrounding L1165-SMM1 and CB230 IRS1 inferred from dust emission are not large, it is important to remember that much of the mass that was present prior to fragmentation has likely already been incorporated into the protostellar objects and we are simply observing the leftovers.

We concede that even with the evidence presented, we cannot concretely rule out envelope rotational fragmentation or turbulent fragmentation with subsequent migration, although these processes seem unlikely for the following reasons. Rotational fragmentation of the envelope is probably unlikely since the envelope would have high angular momentum and this would keep the sources from migrating toward smaller separations until the envelope had dissipated (Zhao & Li 2013). The extended emission observed in single-dish bolometer maps shows that the two binary sources are still embedded in their natal envelopes (Visser et al. 2002; Launhardt et al. 2010). Turbulent fragmentation is also probably not likely since migrating companions would not have preferential alignment with the expected disk plane; however, we cannot absolutely rule out chance alignment with the disk plane for a sample of two.

We note that both CB230 IRS1 and L1165-SMM1 were observed to have large velocity gradients (~11 km s\(^{-1}\) pc\(^{-1}\)) perpendicular to the outflow directions in their respective envelopes, relative to the full samples presented in Tobin et al. (2011) and Chen et al. (2007). L1157-mm has a smaller velocity gradient (3.5–6.2 km s\(^{-1}\) pc\(^{-1}\)) and is found to be single. Under the assumption that the velocity gradients trace pure rotation and that the central protostellar masses were 0.5 M_\odot, the centrifugal radii of the material at 2000 AU were ~100 AU, ~150 AU, and ~50 AU for L1165-SMM1, CB230 IRS1, and L1157-mm, respectively (Tobin et al. 2012). These values agree reasonably well with the scale of the binaries observed in L1165-SMM1 and CB230 IRS1, as well as the size of the circumbinary disk structure in L1165-SMM1. Moreover, another close binary candidate HH211 (Lee et al. 2009) was also found to have a large velocity gradient normal to the outflow (Tanner & Arce 2011; Tobin et al. 2011). While we questioned the interpretation of velocity gradients as pure rotation in Tobin et al. (2011, 2012), the coincidence of binary/multiple systems where there are large velocity gradients is suggestive of a relationship between the two, but better statistics are needed.

Our results, taken with previous studies, increase the number of mm/cm-wave proto-binary systems with separations <150 AU to seven, the other systems being L1551 NE, L1551 IRS5, IRAS 16293-2422A, HH211, and VLA1623; L1527 had been previously suggested to be a 25 AU binary (Loinard et al. 2002) but recent VLA follow-up has ruled this out (Melis et al. 2013, in preparation). Maury et al. (2010) had suggested that there was a lack of binary systems within the specific separation range of 150 AU < R < 550 AU. While this range is quite specific, there are definitely systems with separations smaller
than this lower limit and our detections are near the lower end of this limit. Zhao & Li (2013) had suggested that a prevalence of binary systems at radii \( \lesssim 100 \) AU might result from accreting material that has been magnetically braked and could explain the results of Maury et al. (2010). On the other hand, a large archival study by Chen et al. (2013) finds systems with a variety of separations and within the region where Maury et al. (2010) suggested a deficit. Our results, combined with the other studies, indicate that the result from Maury et al. (2010) may have simply resulted from small-number statistics.

We note that there is uncertainty in the distance to the sources in this work; however, all distance work thus far (Kun 1998; Kun et al. 2009; Straizys et al. 1992) does not point to the sources being a factor of two closer, but the sources could be a factor of \( \sim 1.75 \) more distant. This uncertainty does not strongly affect any conclusions in this work since the size of resolved structure increases linearly with distance and masses would increase with the square of the distance. Thus, the separation of the companions is at most 200 AU, still within an expected scale for circumstellar disks to form.

### 4.2. Disk Sizes

The VLA and CARMA observations of L1165-SMM1 have revealed a possible \( \sim 200 \) AU diameter circumstellar disk with a total mass of \( \sim 0.03 \, M_\odot \); the mass of just the circumstellar component from image decomposition is \( \sim 0.007 \, M_\odot \). The higher resolution VLA observations also show an apparent \( \sim 40 \) AU diameter disk-like structure surrounding the primary source. These structures are strong, circumstantial evidence for the presence of a rotationally supported disk around this Class 0/I protostar. There is evidence of rotation in the \( ^{13}\text{CO} \) data shown in Figure 4, as well as \( \text{HCO}^+ (J = 1 \rightarrow 0) \) observations that detect high-velocity (\( \sim 3 \, \text{km s}^{-1} \)) blueshifted and redshifted emission located in the plane of the disk (Tobin et al. 2011, 2012). In CB230 IRS1, we observe the presence of a resolved structure \( \sim 40 \) AU in diameter surrounding the secondary source, but the primary appears unresolved, indicating a circumprimary disk size of less than 30 AU in diameter. We lack complementary observations at shorter wavelengths that might detect a circumbinary disk, if present. L1157-mm does not have strong indications of a disk-like structure at 7.3 mm, consistent with its lack of resolved disk structure at 1.3 mm and 3.4 mm (Chiang et al. 2012); therefore, any disk in L1157 likely has \( R < 15 \) AU.

A source of uncertainty in the lack of disk detections is whether or not the 7.3 mm data are simply “missing” the larger disks due to insufficient sensitivity. Studies of Class II disks show that the 8 mm dust continuum emission from T-Tauri disks can be more spatially compact than the emission at shorter wavelengths, indicating that the longest wavelengths are only tracing the innermost regions of the disks where the grains have grown to larger sizes (Pérez et al. 2012). This has been interpreted to be consistent with radial drift of large dust grains toward small radii (Weidenschilling 1977). Models including radial drift and grain growth during protostellar collapse and disk formation demonstrate that this process could be happening in the protostellar phase as well (Birnstiel et al. 2010). Moreover, evidence for grain growth is also seen in the envelopes before the material even reaches the disk (Kwon et al. 2009).

For L1165-SMM1, the 7.3 mm emission observed on similar spatial scales as the 1.3 mm emission is not as extended, but this may simply be due to our sensitivity limits. The Class 0 protostar L1527 harbors a \( \sim 125 \) AU diameter rotationally supported disk (Tobin et al. 2012) and was found to have a 40 AU diameter disk-like structure detected at 7 mm with the old VLA system (Loinard et al. 2002). Follow-up VLA observations of L1527 at 7 mm detect the disk out to \( \sim 60 \) AU (Melis et al. 2013, in preparation). Thus, observations at \( \lambda = 7 \) mm may systematically underestimate the sizes of protostellar disks. The resolved structures are best regarded as lower limits to the disk size and indicate that observations at shorter wavelengths may detect yet larger structures, as was the case for L1527 and L1165-SMM1, given that L1157-mm lacks resolved structure at shorter wavelengths and in the VLA data we can confidently conclude that its disk is small. On the other hand, CB230 IRS1 may have a larger circumbinary disk that we do not detect at 7.3 mm, given its similarities to L1165-SMM1.

Since our sample was quite small and not all are bona fide Class 0 protostars, we cannot draw broad conclusions about the sizes of disks in Class 0 sources. However, given the youth of L1165-SMM1, it appears to have formed a large disk by the time it transitioned to the Class I phase. The compact circumprimary disk likely formed at the same time as the larger circumbinary disk. Moreover, if the companion source formed via disk fragmentation, the disk would have had to be more massive in the past given the currently low mass of the circumstellar structure.

Recently, a few other Class 0 protostars have been found to harbor disks: L1527 in Taurus (Tobin et al. 2010a, 2012) with a confirmed Keplerian disk, HH211 with a disk-like structure and possible rotation (Lee et al. 2009), VLA 1623 A with a resolved structure and possible Keplerian rotation (Murillo & Lai 2013), and finally IRAS 16293-2422B with what appears to be a face-on, optically thick disk with \( R \sim 25 \) AU (Zapata et al. 2013). Maury et al. (2010) had a sample of 5 sources that they concluded did not show evidence of disks or binaries, but we now know that L1527 does have a disk, so their disk-less sample is reduced to four. Combining the results from these studies, four systems have evidence of large (\( R > 100 \) AU) disks that formed during the Class 0 phase and six systems do not have evidence of large disks. Therefore, the rather strong conclusion by Maury et al. (2010) that large (\( R > 100 \) AU) disk formation is suppressed by magnetic fields during the Class 0 phase does not seem to be supported by more recent results. Rather, it appears that there may be a wide diversity in the sizes of Class 0 disks, likely reflecting a variety of initial formation conditions. Note that we have left CB230 IRS1 out of these numbers since we do not know if there is an undetected circumstellar disk present.

### 4.3. A Disrupted Triple System in CB230?

We noted in Section 3.2 that there is an infrared-detected tertiary component (CB230 IRS2) separated from the main protostar (CB230 IRS1) by \( \sim 10'' \) (3000 AU). This source was not detected at millimeter or centimeter wavelengths, indicating that the dust mass from this source must be \( <0.005 \, M_\odot \) (3σ upper limit using assumptions from Section 3.5) and that any free–free emission from this source must be very weak, indicating that the source is not driving a strong thermal jet. This leads us to examine its relationship with the protostellar system more closely. The tertiary is a highly reddened source, not detected in the optical, with strong infrared excess emission at 24 μm (Massi et al. 2008); it is resolved in the NIR and there is some diffuse scattered light emission around the source (Figure 8). Moreover, Launhardt (2001) found indications of two outflows in \(^{13}\text{CO} \) observations, while not detecting the tertiary in...
continuum emission (Launhardt 2001; Launhardt et al. 2010). Moreover, recent \(^{12}\text{CO} (J = 2 \rightarrow 1)\) observations also find strong evidence for an outflow orthogonal to the outflow from the main source (Segura-Cox et al., in preparation).

The NIR to MIR emission can be explained by a combination of direct stellar light, scattered light, and warm dust emission from an inner disk. Infrared excess emission from the inner disk can be produced with disk masses \(<0.001M_\odot\) (Robitaille et al. 2007; Espaillat et al. 2010). Thus, all evidence points to the tertiary being young and in close association with CB230 IRS1. Unlike other proto-binaries at large separations (e.g., NGC 1333 IRS 2, L1448 IRS3, BHR71), it does not show the typical signs of extreme youth like IRS1. There is little evidence of it accreting from the large infalling envelope; there is no increased line width or velocity structure related to the wide companion in \(N_2H^+\) or ammonia (Chen et al. 2007; Tobin et al. 2011) and the far-infrared emission is not extended toward its location (Launhardt et al. 2013).

Given its close association with the CB230 IRS1 and its lack of Class 0/I protostellar properties, we suggest that the tertiary source may have formed in closer proximity to the compact binary system, perhaps in a disk, and that it was ejected in a three-body interaction (Reipurth 2000; Reipurth & Clarke 2001). Simulations of disk fragmentation in protostellar systems have shown such ejections of low-mass members via interactions with the primary source and other disk fragments (Basu & Vorobyov 2012). Such an interaction could leave the tertiary with very little circumstellar material (Reipurth 2000), consistent with the lack of detectable millimeter-wave emission. If the tertiary source was kicked out with a velocity of \(~1\ \text{km s}^{-1}\) (Basu & Vorobyov 2012), it could have reached its present position in \(~15\ \text{klyr}, \text{well within the expected ~500 kyr evolutionary timescales of the system as a whole (Evans et al. 2009). Furthermore, the location of the tertiary is approximately orthogonal to the outflow, in the same plane as the compact secondaries and the expected disk plane. However, the outflow indicates that the current angular momentum vector of the tertiary may be perpendicular to that of the primary. This hypothesis of the tertiary source being an ejected member could be tested with high-resolution NIR spectra of the primary and secondary sources, enabling the relative radial velocities of the sources to be examined. However, it is uncertain if sufficiently accurate velocities could be measured toward these sources, given that the NIR emission is dominated by scattered light and Covey et al. (2006) were only able to obtain precisions of \(~2\ \text{km s}^{-1}\) for Class I protostars.

5. CONCLUSIONS

We have presented a VLA and CARMA study of three Class 0/I protostellar systems in the Cepheus clouds: L1157-mm, L1165-SMM1, and CB230 IRS1. The VLA observations were taken in A, B, and C configurations at 7.3 mm, 1.4 cm, 3.3 cm, 4.0 cm, and 6.5 cm, providing the highest resolution view of these systems at any wavelength. The CARMA observations in B and C arrays toward L1165-SMM1 have also provided the highest resolution view of the system at 1.3 mm. The results presented have enabled us to expand our knowledge of the disk and binary star formation process by probing scales \(<100\ \text{AU}\) with a \(3\sigma\) mass sensitivity of 0.005 \(M_\odot\), an order of magnitude more sensitive than the typical mass of a T-Tauri disk (Andrews et al. 2009). Moreover, the sizes of the resolved structures from the VLA and CARMA observations provide lower limits on disk sizes during the early stages of protostellar evolution.

We find that two (L1165-SMM1 and CB230 IRS1) out of three observed systems have an apparent companion separated by \(0.3\ \text{(~100 AU)}\). The companions are well detected and resolved from the primary at 7.3 mm and 1.4 cm; they are weakly detected at 3.3 cm and somewhat blended with the primary components. The 1.3 mm imaging of L1165-SMM1 yields an extended disk structure surrounding the two components and possibly two outflows. Our results point to a disk fragmentation origin of L1165-SMM1 and CB230 IRS1, given their close proximity and alignment with the expected orbital plane of the disk in these systems; this interpretation is stronger for L1165-SMM1 given the extended disk centered on the primary protostar, as observed at 1.3 mm. CB230 IRS1 does have a third member of its system, detected in the NIR and MIR and its direction from the primary source is perpendicular to the outflow; we do not detect emission from this source between 3.4 mm and 6.5 cm. We suggest that it may have been ejected via a three-body interaction.

Despite the high sensitivity of our VLA observations, we did not detect direct evidence of large \((~100\ \text{AU})\) disk structures surrounding any of the sources at 7.3 mm. The extended 7.3 mm emission toward L1165-SMM1 is not obviously disk-like and the CARMA 1.3 mm data gave a more firm detection of a probable circumbinary disk. The primary source in L1165-SMM1 does have resolved structure, consistent with a small disk \((~40\ \text{AU}\ \text{in diameter})\); the secondary source in L1165-SMM1 appears unresolved. The primary source in CB230 IRS1 appears unresolved and the secondary source appears to have a resolved structure \(~40\ \text{AU}\ \text{in diameter}\). Finally, L1157-mm does not show strong evidence for a resolved disk, indicating that the disk is at most 15 AU in radius.

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Figure 12. L1165 *Herschel* maps at 100 μm, 160 μm, 250 μm, 350 μm, and 500 μm. L1165-SMM1 is the bright source marked with a white cross in each map.

**Facilities:** VLA, CARMA, Hiltner, Spitzer

**APPENDIX A**

**L1165-SMM1 PHOTOMETRY**

We have collected relevant photometry for L1165-SMM1 and constructed the SED between 2.15 μm and 850 μm. Note that we do not include the interferometer data in this analysis since they may resolve out emission from the envelope; moreover, the flux densities are low enough that they do not significantly contribute to the bolometric luminosity or temperature calculations. The 850 μm data for L1165-SMM1 are from Visser et al. (2002), the 25 μm, 60 μm, and 100 μm points are from IRAS (Neugebauer et al. 1984), and the 12 μm and 22 μm data are from the WISE survey (Wright et al. 2010); the additional data are described in the following subsections.

**A.1. Near-infrared Data**

The *Ks*-band data were taken at the MDM observatory on 2008 June 23 and the data were reduced using standard methods for NIR imaging. The details of the reduction and observational methods can be found in Tobin et al. (2008, 2010b).

**A.2. Spitzer Data**

The *Spitzer* observations and reduction for L1165-SMM1 were presented in Tobin et al. (2010b). The IRAC data cover four NIR/MIR bands: 3.6 μm, 4.5 μm, 5.8 μm, and 8.0 μm. We performed photometry on the IRAC data in 10000 AU apertures (33.′′3) and applied the extended source aperture corrections.14 The MIPS data at 24 μm and 70 μm are taken from the Cores-to-Disks Legacy program data delivery and photometry were taken in aperture radii outside the first Airy ring and the requisite aperture corrections were applied.15

**A.3. Herschel Data**

The L1165 dark cloud was observed with the *Herschel* PACS and SPIRE photometers on 2011 May 5 and 2011 July 11; the observation IDs are 1342223967, 1342223968, and 1342219969. The PACS and SPIRE maps were generated using the Scanamorphos software, version 20 with the Galactic option. The SPIRE level 1 data were processed directly by Scanamorphos and the PACS data were converted to Scanamorphos format using the convertL1Scanam procedure in HIPE, version 10. These reductions made use of PACS calibration, version 45 and SPIRE calibration, version 10.1. The maps of the five *Herschel* bands are shown in Figure 12. The PACS photometry were taken in 12′′ apertures at 70 μm and 100 μm and a 22′′ aperture at 160 μm as recommended by the PACS calibration documentation.16 SPIRE photometry were taken in 22′′, 30′′, and 42′′ radii in the 250 μm, 350 μm, and 500 μm bands, respectively, with the requisite aperture corrections for extended sources and color corrections applied.17 The uncertainty in the absolute flux scale for SPIRE and PACS is estimated to be ~5%. The SED plot for L1165-SMM1 is shown in Figure 13.

14 http://irs.ipac.caltech.edu/data/SPITZER/docs/mips/mipsinstrumenthandbook/30/

15 http://irs.ipac.caltech.edu/data/SPITZER/docs/mips/mipsinstrumenthandbook/home/

16 http://herschel.esac.esa.int/twiki/bin/view/Public/PacsCalibrationWeb

17 http://herschel.esac.esa.int/hcss-doc-9.0/load/spire_drg/html/ch05s07.html
where $S_\nu$ is the observed flux density at a given frequency and then the bolometric temperature is given by

$$T_{\text{bol}} = 1.25 \times \langle \nu \rangle \text{ K Hz}^{-1}.$$  \hspace{1cm} (C2)

Chen et al. (1995) then defined approximate Class boundaries at $T_{\text{bol}} \sim 70$ K for Class 0 to Class I, $T_{\text{bol}} \sim 650$ K for Class I to Class II, and $T_{\text{bol}} \sim 2800$ K for Class II to Class III.

To calculate the integrals in Equation (C1), we use the trapezoidal integration routine $tsum$ found in the IDL Astronomy Library (Landsman 1993). We calculate $T_{\text{bol}} = 40$ K, $L_{\text{bol}} = 4.3 L_\odot$, and $L_{\text{submm}}/L_{\text{bol}} = 0.018$ for L1157; for L1165, $T_{\text{bol}} = 78$ K, $L_{\text{bol}} = 15.6 L_\odot$, and $L_{\text{submm}}/L_{\text{bol}} = 0.012$.

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APPENDIX B

L1157 PHOTOMETRY

We have also collected the relevant photometry to construct a full SED of L1157. The Spitzer IRAC and MIPS data are from Kirk et al. (2009) and the 450 μm and 850 μm data are from Young et al. (2006). We also include 60 μm, 100 μm, 160 μm, and 200 μm data from the Infrared Space Observatory (Froebrich 2005). The SED plots for L1157-mm are shown in Figure 13.

APPENDIX C

BOLOMETRIC TEMPERATURE

The bolometric temperature is a standard observational diagnostic for young stellar objects to determine their observational class, complementing the spectral index and submillimeter luminosity diagnostics. The bolometric temperature is defined as the temperature of a blackbody having the same average frequency. Myers & Ladd (1993) calculate the average frequency

$$\langle \nu \rangle = \frac{\int \nu S_\nu d\nu}{\int S_\nu d\nu},$$  \hspace{1cm} (C1)
