MILLIMETER CONTINUUM MEASUREMENTS OF CIRCUMSTELLAR DUST AROUND VERY YOUNG LOW MASS STARS

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ABSTRACT

We investigate the question of disk formation during the protostar phase. We build on the results of Keene and Masson (1990) whose analysis of 1,1551 showed the millimeter continuum emission comes from both an unresolved circumstellar component i.e. disk and an extended cloud core. We model the dust continuum emission from the cloud core and show it, is important at 1.3 mm but negligible at 2.7 mm. Combining new 2.7 mm Owens Valley Interferometer data of IRAS-Dense cores with data from the literature we conclude that massive disks are also seen towards a number of other sources. However 1.3 mm data from the IRAM 30m telescope for a larger sample shows that massive disks are relatively rare, occurring around perhaps 5% of young embedded stars. This implies that either massive disks occur briefly during the embedded phase or that relatively few young stars form massive disks. At 1.3 mm the median flux of IRAS-Dense corm is nearly the same as T Tauri stars in the sample of Beckwith et al. (1990). We conclude that the typical disk mass during the embedded phase is nearly the same or less than the typical disk mass during the T Tauri phase.

1. Introduction

Continuum measurements at millimeter wavelengths of stellar heated dust have proven to be an important and successful way to detect circumstellar disks around young stellar objects. A number of studios of T Tauri stars (Weintraub, Sandell and Duncan 1989, Adams, Emerson & Fuller 1990, Beckwith et al. 1990) have concluded that 1) circumstellar

disks are common, 2) some disks are massive, meaning the disk mass is comparable with the stellar mass, but that 3) typical disks have masses like 0.01 $M_{\odot}$, the mass inferred for the primitive solar nebula.

It is clearly important to also study circumstellar disk properties around younger, likely protostellar objects in order to understand the formation and evolutionary history of disks, However by their nature protostars arc deeply embedded objects whose extended envelopes contribute to the continuum emission. High spatial resolution measurements by interferometers arc needed to discriminate between the envelope and disk emission.

Due to the difficulty of studying large samples with interferometers the best statistical information comes from single-dish work, Recent studies (e.g. André et al. 1990; André and Montmerle 1993) with moderate resolution (1 1") show that overall, deeply embedded IR sources have nearly the same fluxes as T Tauri stars. This suggests a weak dependence of disk mass with age from 10^5 to 10^6 years.

However high-spatial resolution observations remain kcy to detecting circumstellar disks around embedded sources. Given expected disk sizes on the order of 100 AU (< 1″ in Taurus) it is difficult to actually resolve the disks hut interferometers can provide good upper limits to their sizes. Keene and Masson (19!30) successfully used 2.7 and 1.3 mm interferometer data to distinguish between the envelope and disk emission and convincingly demonstrated the presence of a massive circumstellar disk in 1,1551.

Extending this approach, wc have done extensive theoretical modeling of the expected continuum emission from a collapsing dense cloud core. We then compare the models with both interferometer and single-dish data for a sample of embedded stars. Interested readers are referred to Terebey, Chandler and André (1 993) for a more detailed description of this work,

2. Data

2.1. SOURCE SAMPLE

To select very young sources wc define our sample to be deeply embedded infrared sources that are found near the peaks of dense gas emission in nearby molecular clouds (Myers and Benson 1983; Beichman et al. 1986; Myers et al, 1987; Benson and Myers 1989). The "IRAS- Dense cores" are thought to contain you Jig, embedded low- mass stars with estimated ages of a fcw x 10^5 years. The proximity of the embedded infrared sources to the peaks of the dense gas distribution indicates the stars are very young. Theoretical models suggest the IRAS-Dense c.ores arc protostars surrounded by in falling envelopes of gas and dust (Terebey, Shu and Cassen 1984, hereafter 'TSC; Shu, Adams & Lizano 1987).

2.2. OBSERVATIONS

Wc mapped ten IRAS-Dense cores with the Owens Valley Millimeter Interferometer. The spatial resolution ranged from 3 to 7", corresponding to a linear scale of 300 to 2000 AU. Continuum emission was detected from six of the ten sources at 2.7 mm, and seemed to be spatially unresolved for most sources.

To improve our statistics we obtained fluxes for 25 IRAS-Dense c.ores at the shorter wavelength of 1.3 mm with the IRAM 30m single dish telescope. The ≈ 1 1" beam of the

30m should be sufficient to probe circumstellar structures in nearby star- forming regions. Continuum mission was detected from nearly all the source.s.

2.3. COMPARISON OF IRAS-DENSE CORES WITH T TAURI STARS

For the single-beam measurements we don't know the relative contributions of extended envelope and circumstellar disk to the emission. However the total flux dots provide an upper limit to the amount of mass in a circumstellar disk. With this in mind wc compared the IRAS-Dense corm with the 'J' Tauri sample of Beckwith et al. (1990).

The median flux density of the 25 IRAS-Dense cores is 80 mJy, similar to but somewhat higher than the median flux density of the 'J' Tauri stars. This suggests the circumstellar disk mass does not change substantially between 10^5 and 10^6yr, the rough age span of the IRAS-Dense core to 'J' Tauri phase. 'J)hc 80 mJy flux density corresponds to a circumstellar mass of about 0.02 $M_\odot$. This typical circumstellar mass is somewhat higher than the 0.01$M_\odot$ inferred for the primitive solar nebula, but is still much less than the mass of the young star,

This result has interesting implications for the formation and evolution of disks during the protostellar phase. Angular momentum considerations during the cloud- collapse phase suggest that much of the collapsing gas dots not fall directly onto the star but first falls onto a disk (TSC). Therefore disks arc important because much of the mass that is eventually incorporated into the star, 011 the order of half a solar mass, is first processed through a circumstellar disk, On the other hand the observations show that very fcw protostellar sources have disk masses this large. This means that infalling material dots not ac.cumulate in the disk during most of the protostar phase hut instead is efficiently transported to the central protostar. Whatever the relevant physics turns out to be, the transport of mass and angular momentum in the disk occurs rapidly with respect to the 105 yr formation tilnc.scale even for relatively low- mass disks.

3. Predicted Continuum Emission from the Collapsing Core

Since all the sources in our sample are thought to be embedded within a dense infalling envelope of gas and dust, there will be a contribution to the total continuum flux from this extended component. In order to evaluate the magnitude of the contribution in both our interferometer measurements and the single dish data, we have constructed a model of the expected emission from a collapsing dense cloud core using the TSC collapse models.

3.1. BASIC EQUATIONS

We computed the contribution to the millimeter continuum intensity from thermal dust grains. At millimeter wavelengths the emission from the cloud core is well approximated by low optical depth, so that the emergent intensity profile I as a function of frequency ν is then simply given by,

$$I_\nu(\omega) = \int_{-\infty}^{\infty} B_\nu(T_D)\rho(r)\kappa_\nu \, dl. \tag{1}$$

Here, w is the impact parameter in the plane of the sky, B_ν is the Planck function, T_D is

the dust temperature, ρ is the gas density at radius r from the center of the dense *c.ore,* κ_ν is the: specific gas opacity and l is the line of sight distance through the dense core. If the dust temperature is not too low, the Rayleigh- Jeans regime ($B_\nu \propto T_D$) holds at millimeter wavelengths.

The intensity computation therefore requires three quantities, $\rho(r)$, $T_D(r)$ and κ_ν to be specified. The density profile is provided by the collapse models and in the limit of small radius approaches a power-law with $\rho \propto r^{-3/2}$. *The* dust temperature depends weakly 011 the bolometric luminosity and has a shallow power-law profile (typically $T_D \propto r^{-0.4}$) over the spatial scales of interest. The opacity is the most uncertain quantity in the talc.ulatioll; wc follow the usual practice of extrapolating from far- infrared wavelengths using a power-law with index β between one and two.

4. Results

The model predicts most of the continuum emission at these spatial resolutions arises in the inner, collapsing region of the cloud (hence the name 'infall' envelope). Furthermore, because of the power-law profile of the density, the infall envelope has a characteristic signature that the emission always looks spatially resolved, with size roughly 1.5 times the beam, no matter what the observed beam size.

The mode.1 quantitatively predicts that the continuum emission from the infall envelope scales as $F \propto a_s^3 M^{-0.5} L^{0.2}$ where a_s is the sound speed, M is the c.mitral (star plus disk) mass, and L is the bolometric luminosity. For our sample of about 25 embedded stars the models with M = 0.5 or 1.0 $M_\odot$ can account for much of the observed single-dish emission at 1.3 **mm.** However the emission from a few sources is too strong to be easily explained by the standard parameters and at 2.7 mm the disc repancy extends to all observed sources,

One possible explanation is that our models predict younger sources (having lower central masses) naturally have higher continuum fluxes. However inspection of the 2.7 mm interferometer maps reveals that only a few sources show spatially resolved structure, the characteristic. signature expected of continuum emission from the infall envelope.

For most sources the continuum emission at 2.7 mm appears pointlike. This argues that the excess flux arises in a compact circumstellar disk rather than the infall envelope. This provides evidence that circumstellar disks arc common around IRAS-Dense cores, although they typically are less massive than the disk found around 1,1551 (Keene and Masson 1990).

After throwing out sources from the literature to correct our sample for selection biases wc find that 1/20 or 5% have very strong millimeter continuum fluxes. The statistics arc admittedly poor but the results do agree with other studies that find strong continuum sources are relatively rare (André et al. 1990; André and Montmerle 1993). This implies that either massive disks occur briefly during the protostar phase or that relatively few young stars form massive disks.

Our models suggest that future observations of the dust continuum focusing 0112-3 mm interferometer data will be extremely useful in measuring disk fluxes and disk masses around protostars. It is unfortunate that our poor knowledge of the opacity at millimeter wavelengths limits our ability to infer disk masses, and irksome that the opacity may even

change with time if grains grow rapidly in the protosolar nebula, Despite the difficulties millimeter continuum measurements provide an important way to probe the formation of disks during the early protostar phase.

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