A SPITZER c2d LEGACY SURVEY TO IDENTIFY AND CHARACTERIZE DISKS WITH INNER DUST HOLES

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Abstract

Understanding how disks dissipate is essential to studies of planet formation. However, identifying exactly how dust and gas dissipates is complicated due to difficulty in finding objects clearly in the transition of losing their surrounding material. We use Spitzer IRS spectra to examine 35 photometrically-selected candidate cold disks (disks with large inner dust holes). The infrared spectra are supplemented with optical spectra to determine stellar and accretion properties and 1.3mm photometry to measure disk masses. Based on detailed SED modeling, we identify 15 new cold disks. The remaining 20 objects have IRS spectra that are consistent with disks without holes, disks that are observed close to edge-on, or stars with background emission. Based on these results, we determine reliable criteria for identifying disks with inner holes from Spitzer photometry and examine criteria already in the literature. Applying these criteria to the c2d surveyed star-forming regions gives a frequency of such objects of at least 4\% and most likely of order 12% of the YSO population identified by Spitzer.

We also examine the properties of these new cold disks in combination with cold disks from the literature. Hole sizes in this sample are generally smaller than for previously discovered disks and reflect a distribution in better agreement with exoplanet orbit radii. We find correlations between hole size and both disk and stellar masses. Silicate features, including crystalline features, are present in the overwhelming majority of the sample although 10 micron feature strength above the continuum declines for holes with radii larger than ~7 AU. In contrast, PAHs are only detected in 2 out of 15 sources. Only a quarter of the cold disk sample shows no signs of accretion, making it unlikely that photoevaporation is the dominant hole forming process in most cases.

The data: The Cores to Disks (c2d) Spitzer Legacy program

The 'Cores to Disks' (c2d) Spitzer Legacy Program (Evans et al. 2009) observed five large, nearby young molecular clouds with IRAC and MIPS and produced a large and homogeneous magnitude- limited sample of 1024 Young Stellar Objects, out of which 773 are Class II or III objects (Evans et al. 2009).

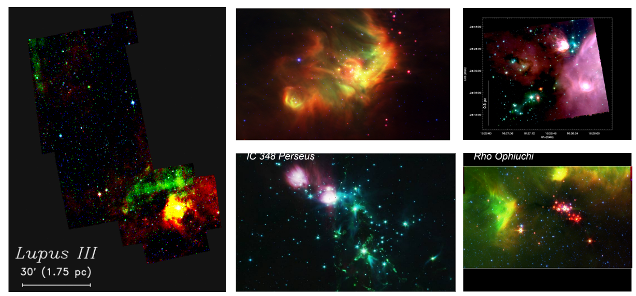

Figure 1 Left: Color composite images of some of the c2d-observed star-forming clouds using IRAC 2 (4.5 μm) in blue, IRAC 4 (8.8 μm) in green and MIPS 1 (24 μm) in red (except NGC 1333, with IRAC1, IRAC2 and IRAC4). The coverage of the c2d mosaics greatly extends the area of the well-known star-forming cluster above. These observations produced a magnitude-limited sample of 1024 so-called c2d YSOs (Evans et al. 2009).

Selection criteria, IRS spectra, SEDs and results

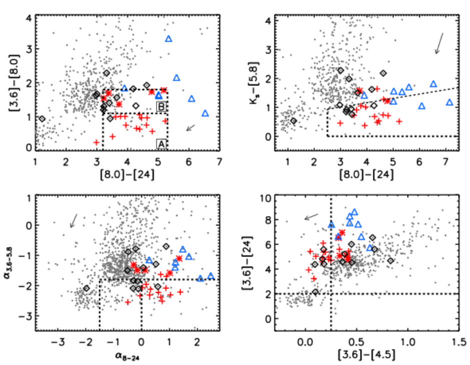

Fig. 15.— Selection criteria. Red stars and crosses are the spectroscopically confirmed cold disks, black diamonds are disks without holes and blue triangles are edge-on disks. The grey crosses are all the sources in c2d YSO catalog (Evans et al. 2009). (top left) Our selection criteria. Regions A and B define the two selection criteria for identifying cold disks in photometric sample, the first one, represented with red crosses, selects "clean" inner holes and the second one, represented with red stars, identifies cold disks with near-IR excess. (top right) Selection criteria from Fang et al. (2009). (bottom left) Selection criteria from Muzerolle et al. (2010). (bottom right) Selection criteria from Cieza et al. (2010) with transitional disks according to their definitions in the upper left quadrant. Arrows show the effect of correcting for an extinction of A_V=10.

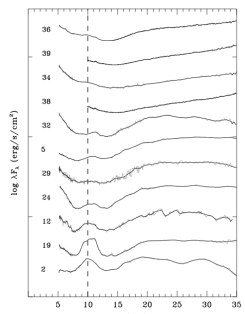

Figure 4. IRS spectra of the accreting cold disks in the sample ordered from bottom to top with increasing inner hole radii. The thick and gray lines are the binned and original spectra, respectively, and the numbers give their identifications in Table 1.

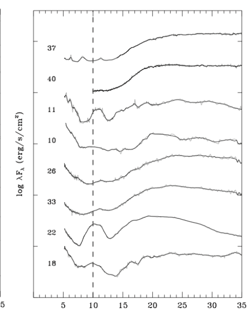

Figure 5. IRS spectra of the non-accreting or non-classified cold disks ordered from bottom to top with increasing inner hole radii. The thick and gray lines are the binned and original spectra, respectively, and the numbers give their identifications in Table 1.

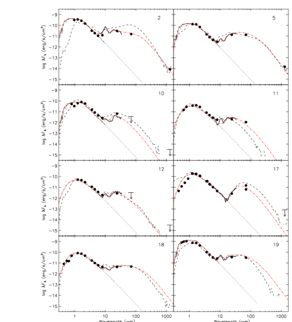

Figure 7. SEDs of the disks with holes in the sample. Points are dereddened fluxes from IRAC, MIPS, and IRAM. The thick solid line is the IRS spectrum, the dotted line is the stellar photospheric model, the red dash-dotted line is the best-fit RADMC disk model, and the thin black dashed line is the Robitaille model fit. The numbers give their identifications in Table 1.

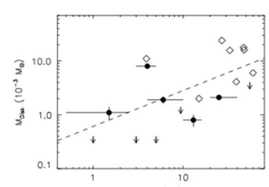

Figure 16. Correlation between hole size and disk mass. Dots and upper limits represent sources with millimeter fluxes from this work, while the diamonds are the cold disks with millimeter-measured disk masses from Kim et al. (2009) and Brown et al. (2007). To minimize systematic differences, disk masses for sources from Kim et al. (2009) have been recalculated using the 1.3 mm fluxes in Andrews & Williams (2005) and the conversion in Section 4.1. The correlation has a Pearson's correlation coefficient of 0.6 and is statistically significant on the 99% level including the upper limits and 90% level with only the detected sources. The systematically lower disk masses in this survey might explain the generally smaller hole sizes than previously published transitional disks.

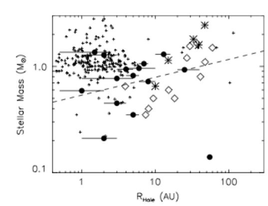

Figure 17. Relationship between the size of the inner disk hole and the mass of the central star. Solid circles represent our sample, while stars and diamonds are transitional disks from Brown et al. (2007) and Kim et al. (2009), respectively. The dotted line is the best linear fit to the data. The small crosses mark the semimajor axis of all exoplanets in the http://exoplanet.eu database as of 2009 December, compared to the mass of their parent stars.

Discussion and Conclusions

- Optical spectra, 2MASS and Spitzer photometry, millimeter continuum observations and Spitzer/IRS 5 to 35 μm spectra of a sample of 35 cold disk candidates selected from c2d photometry are presented and analyzed.
- Out of 35 objects in the initial sample, SED modeling identifies 15 as disks with inner holes, which we call ``cold disks'', following the c2d convention (Brown et al. 2007). Of the remaining sources, 10 could be modelled without holes, 8 are edge-on disks and 2 have SEDs strongly contaminated by cloud material.
- The color cuts 0.0<[3.6]-[8.0]<1.1 and 3.2<[8.0]-[24]<5.3 identify most cold disks from this sample (~ 80%), in particular those with the cleanest inner holes. Extension of the [3.6]-[8.0] color cut to 1.8 recovers some objects with small near-IR excesses and large holes, but contains contamination from disks without holes. Out of the large c2d YSO sample, between ~ 12\% of the disks are estimated to be cold disks based on these selection criteria.
- We evaluated the criteria of Fang et al. (2009), Muzerolle et al. (2010) and Cieza et al. (2010) and suggest improvements based on our spectroscopic study.
- The cold disks presented here have small hole sizes, generally less than 10 AU. This distribution is more in agreement with exoplanet orbit radii than the large hole sizes of most cold disks in the literature.
- A large fraction (75%) of the cold disks are accreting, suggesting that gas is flowing through the dust depleted hole. This large fraction of accreting disks is not in agreement with the dominant hole origin being photoevaporation.
- The sizes of the inner holes scale linearly with the stellar mass and disk mass although with a large spread.
- The 10 μm silicate features in the sample show substantial grain growth. The 10 μm silicate emission feature strength with respect to continuum decreases drastically for inner holes larger than ~7 AU. Some (33-60%) of the cold disks show long wavelength crystalline features indicating that mixing from the inner regions where crystallization occurs to outside the inner hole region must be efficient. Only 2 source (~ 13%) show PAH emission.

Acknowledgements

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