On circumstellar disks: *Spitzer* identifies two possible evolutionary paths

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Abstract. Multi-wavelength surveys have vastly improved our understanding of many astrophysical objects, in particular, circumstellar disks. We present our results for the disk population of the young cluster NGC 2264. Our study was based on data obtained with the Infrared Array Camera (IRAC) and the Multiband Imaging Photometer on board the *Spitzer* Space Telescope combined with previously published optical data. We divide the disk population into 3 classes based on their spectral energy distribution shapes: optically thick disks, homologously depleted anemic disks, and radially depleted transition disks. We find that there are two distinct evolutionary paths for disks: a homologous one, where the disk emission decreases uniformly in NIR and mid-infrared wavelengths (anemic disks) and throughout which most sources pass, and a radially differential one where the emission from the inner region of the disk decreases more rapidly than from the outer region (transition disks). Whether a disk evolves in a homologously or radially depleted fashion is still unknown and may depend on the nature of planet formation in the disk.

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1. Introduction

The *Spitzer* Space Telescope (Werner at al., 2004), a spaceborne observatory of unprecedented sensitivity and spatial resolution in the infrared, has brought forth an exciting new era in the study of star formation. In particular, the Multiband Imaging Photometer for *Spitzer* (MIPS; Rieke et al., 2004) has proven excellent at identifying protostars, and the Infrared Array Camera (IRAC; Fazio et al., 2004) has permitted detailed study of jets and circumstellar disks. To better understand protostellar disk evolution it is necessary to study disk populations of clusters to improve statistics on disk frequencies, constrain timescales for disk dispersal and offer insight into how the disk dispersal process occurs. We address herein one particular question: *do dust grains settle onto the mid-plane and grow at the same rate throughout the disk, or does the inner disk evolve at a faster rate?*

NGC 2264 is a young hierarchical cluster (e.g. Lada & Lada, 2003), located 800 pc away in the Monoceros OB1 association, and it has been extensively studied since Walker's (1956) seminal work where he identified its pre-main sequence (PMS) population. We refer the reader to Dahm (2008) for a detailed review of studies conducted on this region. NGC 2264 is considered one of the classical clusters in the field of observational research that has time and again given valuable insights into the star formation process of low mass stars. Indeed, the initial results obtained from *Spitzer* IRAC and MIPS observations led to the discovery of the Spokes cluster (Teixeira et al., 2006), where the nearest neighbor separations between its Class I members still show the fossil signatures of thermal Jeans fragmentation. Within the Spokes cluster a dense microcluster of protostars was also revealed (Young et al., 2006) and follow-up observations with the Submillimeter Array (SMA) (Teixeira, Zapata, & Lada, 2007) found new Class 0 sources whose average separations were also consistent with the Jeans length for the parent molecular core of the microcluster. Initial results on the disk population of NGC 2264 were published by Sung et al. (2009). We hereby add our contribution to the pool of knowledge in this field by presenting our answers to the aforementioned questions based on our study of NGC 2264's disk population.

2. Observations

The IRAC data for NGC 2264 [part of the *Spitzer* Guaranteed Time Observation (GTO) program 37, P.I.: G. Fazio] were acquired in two epochs comprising of two dithers at each epoch. The observations were carried out in the IRAC high dynamic range (HDR) mode, consisting of two consecutive exposures of 0.4 s and 10.4 s integration times at each dither position. The total mosaicked area covered in all four IRAC bands (3.6 μm, 4.5 μm, 5.8 μm, and

$8\,\mu$m) is approximately $0.5° \times 0.9°$, centered at (α, δ)(J2000)=($06^{\mathrm{h}}40^{\mathrm{m}}54.53^{\mathrm{s}}$, $+09°36'53.3''$). The data reduction, resampling ($1/\sqrt{2}$ of the original IRAC scale), and calibration are explained in Teixeira et al. (2006). The source extractor SExtractor software (Bertin & Arnouts, 1996) was used to generate a list of point sources for each wavelength. Aperture photometry was performed on these detected sources using the Image Reduction and Analysis Facility (IRAF) routine APPHOT, with an aperture radius of 2 resampled IRAC pixels, and a sky annulus of inner and outer radii of 2 and 6 resampled IRAC pixels, respectively. The zero point magnitudes used for the IRAC passbands of effective wavelengths $3.6\,\mu$m, $4.5\,\mu$m, $5.8\,\mu$m, and $8\,\mu$m were 17.83, 17.34, 16.75, and 15.93 mag., respectively.

The MIPS observations were carried out using the scan map mode (GTO program 58, P.I.: G. Rieke). Fourteen scan legs of $0.75°$ length and $160''$ offsets were taken at medium speed. The full map was centered at (α, δ)(J2000)= ($6^{\mathrm{h}}40^{\mathrm{m}}55^{\mathrm{s}}$, $+9°37'08''$) with a position angle of $179°$. A total integration time of $80\,$s per point was obtained in the $24\,\mu$m band. Although $70\,\mu$m and $160\,\mu$m were also obtained, we do not make use of these data for this paper. We obtained a calibrated mosaic of the region by using the MIPS Data Analysis Tool (DAT; Gordon et al., 2005). Photometry was then performed on the mosaic using IRAF DAOPHOT and IDL routines. We used a zero point of $7.3\,$Jy for the $24\,\mu$m magnitude scale.

3.   Results

3.1   Disk identification

To begin identifying and characterizing the disk population of NGC 2264 we make use of a tool defined by Lada et al. (2006) in their study of the young cluster IC 348; they measured the slope of the spectral energy distribution, for each source, between $3.6\,\mu$m and $8\,\mu$m. We used this same measure, α_{IRAC}, to classify the evolutionary status of sources with respect to their circumstellar material. The sources were classified according to the α_{IRAC} empirical scheme shown in Table 1.

Table 1. Source classification scheme using α_{IRAC}.

Class I (C I) sources	$\alpha_{\mathrm{IRAC}} \geq 0.5$
Flat spectrum (FS) sources	$0.5 > \alpha_{\mathrm{IRAC}} \geq -0.5$
Sources with thick disks (TD)	$-0.5 > \alpha_{\mathrm{IRAC}} \geq -1.8$
Sources with anemic disks (AD)	$-1.8 > \alpha_{\mathrm{IRAC}} \geq -2.56$
Sources with naked photospheres (NP)	$\alpha_{\mathrm{IRAC}} \leq -2.56$

For sources detected in all four IRAC bands, we find that the majority (996) have naked photospheres - these comprise of diskless PMS sources of NGC 2264

as well as foreground and background field stars. We find 372 sources that have circumstellar material, of which 271 sources have thick disks and 116 sources have anemic disks. We remind the reader that the IRAC wavelength range is sensitive to emission arising from the inner part of a circumstellar disk (T $\geq$ 500 K). We identified sources with no IRAC excess emission, yet these sources did show MIPS 24 μm excess emission. We interpret these sources as having colder disks with inner holes and classify them as candidate "transition" disks, following the term adopted by the larger astronomical community.

3.2 Disk accretion

To investigate disk accretion we consider a subsample of Hα emitting sources (Dahm et al., 2005) from our sample of sources that are detected in all four IRAC bands; this subsample consists of 172 sources with measured Hα equivalent widths, W(Hα).
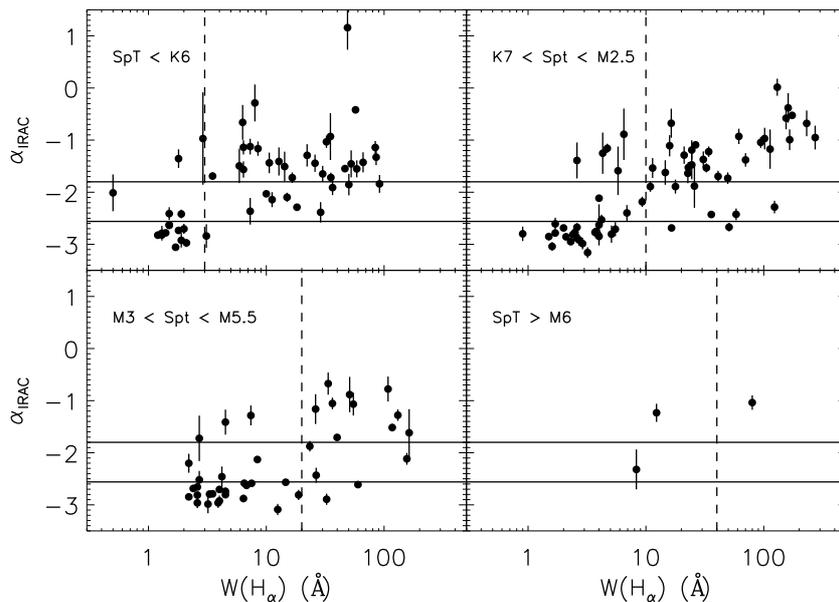
Figure 1. Comparison of the Hα equivalent widths, W(Hα), with α_{IRAC} for sources of different spectral types (SpT). The horizontal lines mark the separation between diskless sources and sources with either thick or anemic disks (see Table 1), while the vertical dashed lines separate accreting and non-accreting sources.

Figure 1 shows how W(Hα) varies for young stars of different α_{IRAC} values; the figure is composed of four panels corresponding to stars of four spectral type groups. The W(Hα) limit used to classify a source as accreting or non-accreting

is a function of spectral type (White & Basri, 2003). These different limits are represented by vertical dashed lines in Fig. 1. Sources located on the right of these lines, according to their spectral types, are considered to be accreting.

There are several sources with thick disks that do *not* appear to be accreting, implying they have *passive* thick disks. Figure 1 also shows the existence of sources with passive anemic disks and diskless sources that are non-accreting – these are expected to exist if the gas and dust removal in the disk occur at approximately the same rate. The diagram also shows that the majority (85%) of the sources with thick disks appear to be accreting; these results are consistent with what Lada et al. (2006) found in the young cluster IC 348. A particularly interesting region of the diagram corresponds to that occupied by *accreting diskless sources.*

We found eighteen accreting sources with anemic IRAC disks and five accreting sources with no IRAC inner disk. Of the accreting sources with anemic IRAC disks, six of them have $24 \, \mu$m detections that indicate the existence of outer thick disks, and fifteen of them have X-ray emission (Flaccomio et al., 2006). Regarding the sources with no inner disk, all five of them are X-ray emitting sources. They possess $24 \, \mu$m emission characteristic of a thick outer disk. These five sources therefore have inner holes that are cleared of dust (hence the lack of emission at wavelengths $\leq 8 \, \mu$m) but not cleared of gas as they are still accreting: they are candidate transition disk sources.

4.   Discussion

The sources with anemic and transition disks are clearly more evolved ($< 50\%$ of them are accreting) than sources with thick disks (85% are accreting). We propose that the anemic disk phase and the transition disk phase are two distinct evolutionary paths that a source with a thick disk may take. An anemic disk is one that is homologously depleted throughout its radius - the disk flattens out uniformly. The transition disk, on the other hand, evolves inside out, clearing its inner region at a faster rate. Since there are many more anemic disks in NGC 2264 than transition disks, it seems that the anemic disk evolutionary path is the one that most disks follow.

There are currently three possible scenarios that could account for the formation of holes within a protoplanetary disk, or a transition disk: the first scenario describes disk hole formation (i) through photoevaporation and viscous disk evolution processes. Alexander et al. (2006) modeled disk evolution combining both viscous evolution and photoevaporation of the disk. Their results suggest that all evolving disks pass through a short inner disk hole phase; they furthermore predict that transition disk sources should account for about $10 \, \%$ of the disked sources in a given cluster. The second possibility for disk hole

formation is (ii) via planet formation (Alexander & Armitage, 2007). Quillen et al. (2004) argue that the inner hole of $10\,\mathrm{AU}$ in the disk of Coku Tau/4 could have been created by a $0.1\,\mathrm{M_{Jupiter}}$ planet within $1\,\mathrm{Myr}$. Stronger observational evidence for this scenario is given by Setiawan et al. (2008), who found a planet ($9.8\,\mathrm{M_{Jupiter}}$, orbiting at $0.04\,\mathrm{AU}$) in TW Hya's transition disk using the radial velocity technique. Finally, a disk hole can also be explained by (iii) grain growth (Flaherty & Muzerolle, 2008). Dullemond & Dominik (2005) model the evolution of protoplanetary disks and predict that grain growth and dust settling occurs more rapidly in the inner region of the disk than in the outer regions.

The fraction of transition disks for NGC 2264 is $\sim$10%. According to Butler et al. (2006), $\sim$12% of FGKM stars observed host giant planets within 30 AU. These two numbers are similar and it is tempting and plausible (Setiawan et al., 2008) to suggest that giant planet formation is indeed occurring within the herein identified transition disks of NGC 2264. On the other hand, as previously mentioned, Alexander et al. (2006) propose that 10% of disks go through an inner hole disk phase during their evolution. Interestingly, Sicilia-Aguilar et al. (2006) also found that 10% of the disked sources in the young cluster Trumpler 37 are sources with transition disks.

A number of cutting-edge observational facilities are coming online within the next couple of years (such as ALMA) or are planned for the next decade (20-40 m diameter optical/near-infrared telescopes) and will be able to directly test the giant planet formation scenario.

References

Alexander R. D., Clarke C. J., & Pringle J. E., 2006, MNRAS, 369, 229
Alexander R. D., & Armitage P. J., 2007, MNRAS, 375, 500
Bertin E., & Arnouts S., 1996, A&AS, 117, 39
Butler R. P., Wright J. T., Marcy G. W., et al., 2006, ApJ, 646, 505
Dahm S. E., & Simon T., 2005, AJ, 129, 829
Dahm S. E., 2008, Handbook of Star Forming Regions, Volume I, 966
Dullemond C. P., & Dominik C., 2005, A&A, 434, 971
Fazio G. G., Hora J. L., Allen L. E., et al., 2004, ApJS, 154, 10
Flaccomio E., Micela G., & Sciortino S., 2006, A&A, 455, 903
Flaherty K. M., & Muzerolle J., 2008, AJ, 135, 966
Főrész G., Hartmann L. W., Szentgyorgyi A. H., et al., 2006, ApJ, 648, 1090
Gordon K. D., Rieke G. H., Engelbracht C. W., et al., 2005, PASP, 117, 503
Lada C. J., & Lada E. A., 2003, ARA&A, 41, 57
Lada C. J., Muench A. A., Luhman K. L., et al., 2006, AJ, 131, 1574
Quillen A. C., Blackman E. G., Frank A., & Varnière P., 2004, ApJL, 612, L137
Rieke G. H., Young E. T., Engelbracht C. W., et al., 2004, ApJ, 154, 25
Setiawan J., Henning Th., Launhardt R., et al., 2008, Nature, 451, 38
Sicilia-Aguilar A., Hartmann L. W., Főrész G., et al., 2006, AJ, 132, 2135

Sung H., Stauffer J. R., & Bessell M. S., 2009, AJ, 138, 1116
Teixeira P. S., Lada C. J., Young E. T., et al., 2006, ApJL, 636, L45
Teixeira P. S., Zapata L. A., & Lada C. J., 2007, ApJL, 667, L179
Young E. T., Teixeira P. S., Lada C. J., et al., 2006, ApJ, 642, 972
Walker M. F., 1956, ApJS, 2,365
Werner M. W., Roellig T. L., Low F. J., et al., 2004, ApJS, 154, 1
White R. J., & Basri G., 2003, ApJ, 582, 1109