Tying the Geometrical Traits of Massive Young Stellar Objects and Their Disks to a Potential Evolutionary Sequence Using Infrared Observations

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Abstract

Young massive stars influence their surroundings from local to galactic scales, but the observational challenges associated with their distance and embedded nature has, until the recent decade, made high-resolution studies of these objects difficult. In particular, comparative analyses of massive young stellar object (MYSO) disks are currently lacking and our understanding of their evolution is limited. Here, we combine the results of two studies with the aim to attribute geometrical features to an evolutionary sequence for a sample of seven MYSOs. The time evolution is based on near-infrared spectral features, while the geometry is determined from a multi-size-scale study of MYSOs. We find that MYSO disks with determined geometrical substructure turn out to be also spectroscopically more evolved. This implies that disk evolution and dispersal occur within MYSOs similarly to low-mass young stellar object (YSO) disk evolution, despite their faster formation timescales.

Unified Astronomy Thesaurus concepts: Star formation (1569); Massive stars (732); Circumstellar disks (235); Infrared astronomy (786); Interferometry (808); Observational astronomy (1145)

1. Introduction

Massive stars ($\geq 8M_{\odot}$) are some of the most influential objects within the Universe, affecting their own local environments and the galaxy as a whole. Through their winds and outflows, they mold molecular clouds (Krumholz et al. 2014), affect further star formation, and shape galactic superwinds (Leitherer 1994). When they end their lives through supernovae events, they synthesize the heaviest elements in the universe and distribute them throughout the interstellar medium, enriching the material of future stellar systems like our own. Additionally, when they end their lives, they are the only stars to create black holes and, as such, are the progenitors of gravitational wave sources (Abbott et al. 2016). Despite their importance, the formation process of massive stars is not well understood as they are distant, deeply embedded, and rare (Motte et al. 2018). One phase of evolution, which is of particular interest to study, is the so-called massive young stellar object (MYSO)—an infrared-bright object whose spectral energy distributions (SEDs) peak in the far-infrared and have a total luminosity of around $10^{5} L_{\odot}$. The nature of MYSOs, in particular at scales of hundreds of au, have remained elusive. Interferometric observations, in general, provide higher resolution views of massive forming stars than those obtained through other observing techniques, reaching scales of $\sim 0''01$. This allows interferometry to probe the innermost regions of MYSOs involved in the accretion process. In the infrared, such interferometric studies have revealed the presence of disks around MYSOs (e.g., Kraus et al. 2010, 8 au spatial resolution) and the presence of close binary systems (e.g., Kounia et al. 2019 at $\sim 30$ au). In the submillimeter, the Atacama Large Millimeter/submillimeter Array (ALMA) has provided new insights to the environments of MYSOs at $\sim 200$ au scales (e.g., Maud et al. 2018). Using continuum measurements and molecular studies, structures such as warps (Sanna et al. 2019; Jiménez-Serra et al. 2020), spirals (Johnston et al. 2020), and rings (Maud et al. 2019) have been detected in MYSO disks. The presence of such disks is of great significance as disk accretion is a potential way that MYSOs accrete mass. As for low-mass stars, disk accretion is the main avenue of mass transfer from the wider environment to the star. For low-mass stars, large interferometric surveys of disks have been performed, allowing detailed investigations of their composition and the processes occurring within them (e.g., DSHARP; Andrews et al. 2018). These types of surveys combined with previous works, which defined evolutionary classes of low-mass disks based on their spectral SED emission (Shu 1977; Barsony 1994), have allowed different disk features to be attributed to different ages of protostellar disks. Younger disks show evidence of accretion features in their SEDs and their minimum dust radius is often dictated by dust sublimation alone (Beltrán & de Wit 2016). On the other hand, inner clearing is observed in so-called “transition disks” (Cieza et al. 2010)—one elder form of disk. Other structures such as spirals and rings in disks are typically observed in elder sources, save for a few examples (e.g., Sheehan & Eisner 2018). Studying such features is critical in determining the physical processes occurring within the disk, such as those related to planet formation, dust amalgamation, or the formation of companions. Such a classification of the evolution of MYSO disks has, thus far, not been feasible.

In Frost et al. (2021), we used an approach that used multiple data sets that trace 10 mas scales, 100 mas scales, and SEDs to characterize the geometry of a sample of eight MYSOs, but with no information on their age. Independently, Cooper (2013) and Cooper et al. (2013) studied a sample of nearly 130 MYSOs using their near-infrared color and near-infrared spectra. In doing so, they noticed different spectral lines in the redder, more embedded, and therefore younger sources to the elder bluer sources. From this, they developed a classification scheme associated with evolutionary phase. In this paper, we combine the results and methods of these two studies to attribute the geometrical characteristics of MYSOs (and specifically their disks) to a potential evolutionary
sequence for the first time. In the next subsections, we introduce the methods and results of Frost et al. (2021) and Cooper (2013) for ease of interpreting the results of this paper. In Section 2, we present the evolutionary classification of the sources from Frost et al. (2021), use their geometrical features to compare them to previous star formation models, and estimate numerical ages for the sources. In Section 3, we discuss our results before concluding.

1.1. Work Thus Far I—Characterizing the Geometry of MYSOs at Multiple Scales

The most detailed interferometric studies of MYSOs tend to focus on single MYSOs. Such individual studies are not homogeneous, as they use different methods and types of analysis. Boley et al. (2013) presented a survey of 20 MYSOs with the now-decommissioned VLTI MID-infrared Interferometer (MIDI) instrument, fitting geometric models to 10.6 μm data, providing the first glimpse of mid-infrared structure at 100 au scales around MYSOs and attributing this to disk and outflow emission. Some studies have investigated MYSOs using their SEDs, which provide information on the whole source, but with no direct spatial information. In Liu et al. (2019), the model grid of Zhang & Tan (2018) was used to fit SEDs to a number of MYSOs. However, the interpretation of SED data can be difficult particularly given the strong dependencies on parameters such as viewing angle (e.g., Whitney et al. 2003; Robitaille 2017) and the embedded nature of MYSOs, meaning that disk emission is not easily distinguished from stellar/envelope emission as can be done for low-mass stars. de Wit et al. (2009) and Wheelwright et al. (2012) fit Q-band image profiles and SEDs using 2D radiative transfer (RT) models, therefore linking the information of an SED to a high ∼0.7 resolution data set but lacking the sensitivity to small spatial scales that interferometry could provide. Frost et al. (2019) and Frost et al. (2021) combined all these observables using a detailed methodology that combines the N-band (∼7–13 μm) interferometric data from Boley et al. (2013) (required to probe the smallest 0.001 spatial scales) with near-diffraction-limited imaging in the Q-band (19.5–24.5 μm) from Frost et al. (2021) and de Wit et al. (2009) and SEDs. SEDs were compiled using the online database of the Red MSX Source (rms) survey and the literature, including fluxes from instruments such as 2MASS, WISE, GLIMPSE, Herschel/PACS, ATLASGAL, SCUBA, and more (see Frost et al. 2021 for a complete list) covering near-infrared to millimeter wavelengths. These observables were fit with synthetic observations from RT models using the 3D dust RT code HOCHUNK-3D (Whitney et al. 2013). This code simulates the protostellar environment through the combination of different geometrical components; a central source defined by its mass, temperature, and radius, two disk components (a “large grains” disk and a “small grains” disk each with their own determinable scale-heights, minimum radii, and maximum radii) that contribute to one overall disk mass, a surrounding envelope component, and bipolar outflow cavities. The models from the RT code were fit to the three observables simultaneously. Synthetic images at 1 μm intervals were generated in the N-band and post-processed to produce visibilities at each wavelength to be compared to those observed (Frost et al. 2019). Similarly Q-band synthetic images were generated by the code, convolved to match the observations, and had radial profiles extracted from them to allow comparison to diffraction-limited ∼20 μm images. In doing so, the characteristics of a sample of MYSOs were obtained at multiple scales and the combination of high-resolution data sets allowed the distinction between disk emission and other components.

In Frost et al. (2021) we applied this methodology on a sample of eight MYSOs, the largest sample to be analyzed in such a way. The sources were selected randomly based on the availability of both archival interferometric N-band data (MIDI; Boley et al. 2013) and the additional presence of Q-band imaging data (de Wit et al. 2009; Frost et al. 2021). When fitting the Q- and N-band data sets simultaneously, the cavity wall geometry was constrained at two scales. With this in place, it was found that one could not satisfy the N-band and Q-band data simultaneously without including disks in the models (see Figure 8, Frost et al. 2019). The simulated N-band emission is affected most by the presence of a disk, with the N-band visibilities being higher in a disk and envelope model than in an envelope-only model due to the presence of a compact object. The geometry of the disk is also significant, with the simulated visibilities being particularly sensitive to the disk inner radius and scale height, and with the disk outer radius and total mass being less well constrained. For one source (NGC 2264 IRS1), which is close to face-on, the mass was better constrained as the disk data was the best fit with a mass-dependent spiral structure. The SED provides additional information on the wider cooler environment out to millimeter wavelengths. With these three observables combined, a multiscale picture of the MYSOs is obtained and a wide parameter space encompassing the disks, cavities, and envelopes of the sources can be investigated.

In Frost et al. (2021) we concluded that, in agreement with previous works, the geometry of these MYSOs consisted of dusty envelopes of natal material that are rotating and infalling (following the solution of Ulrich 1976). Within these envelopes, bipolar outflow cavities are present and carved out of the natal material by outflows, which are ubiquitously observed around MYSOs. Importantly, disks are present at scales of ∼100 au, which could therefore be involved in the accretion process. All sources in the sample are relatively similar at large scales, with envelope radii of the order 104 au from the fitted models. Similarly, the envelope infall rates of the sample were all ∼10−4 M⊙ yr−1 except for one source (S255 IRS3) that is known to be episodically accreting (Caratti o Garatti 2017), and for which the data used were from an accretion lull for the source. A range of opening angles (measured from the polar axis) and cavity densities were seen across the sample with minima and maxima of 12° and 40° and ∼10−19 g cm−3 and ∼10−21 g cm−3, respectively. The best-fit models of the disks in each source vary considerably, some are flat (scale height ∼0.1) while others are flared (scale height ≥0.4). Finally, it was found that adding substructure to the disks in the models improved the fits to the observational data. Most commonly, this substructure takes the form of cleared inner regions, where the minimum dust radius is greater than the sublimation radius of the central source. The best-fit model for one source (NGC 2264 IRS1) incorporates a spiral/gap structure within its flared disk.

1.2. Work Thus Far II—Spectral Variance in MYSOs

Cooper (2013) and Cooper et al. (2013) examined the near-infrared spectra of over 100 MYSOs from the rms survey.
Various emission signatures were observed throughout the objects, allowing them to be categorized into three main types. The emission lines that allowed this were H$_2$, Br$\gamma$, Br10, and fluorescent Fe II (hereafter fl-Fe II).

Based on the presence of these lines, the MYSOs were grouped into different evolutionary “types”. Each of these types is classed as a different evolutionary phase. Type I MYSOs display strong H$_2$ (2.1218 $\mu$m) emission lines, which are attributed to shocks from the collision of high-velocity ejections with ambient material (Marston et al. 2004). Type I sources do not display any other lines and are categorized as the youngest sources. Type II sources display H$_2$ and Br$\gamma$ emissions, with the latter arising due to the increasing central temperature and luminosity of the central protostar (Cooper 2013). Br10 emission is weak or absent, and there is also a lack of fl-Fe II emission as the star is not yet evolved enough to produce the ionizing photons that cause its emission (Cooper 2013). Type III display weak or absent H$_2$ emission, strong Br$\gamma$ emission, and a presence of Br10 and fl-Fe II emissions. As the MYSO evolves through the Type II and Type III stages, the amount of H$_2$ emission decreases, perhaps because the outflow itself is weakening, the amount of circumstellar material is depleting due to dispersal, and/or because the molecules of H$_2$ are being dissociated as the protostar gets hotter. The increase in temperature also induces (Type II) and increases (Type III) the Br$\gamma$ emission. By the time an MYSO is at Type III, either the outflow is too weak or there is not enough material to form shocks of H$_2$. Past this point ionization would be prevalent enough to create a H II region.

Mid-infrared color–color cuts can be used as crude estimators of age and have allowed MYSOs to be distinguished from other evolutionary stages of massive star formation (Lumsden et al. 2013). Within the sample of Cooper (2013), the Type III sources were found to be bluer than the Type I sources, indicating that Type I is the youngest and that the sources may have evolved through the Type II stage to the Type III stage. Additionally, He I emission, which is a common signature of main-sequence wind activity, is not found in the Type I sources (Cooper 2013). Some presence in Type II sources is observed and He I emission is most prevalent in the spectra of the Type III sources, thereby implying that the Type III are closest to the main sequence and the most evolved.

For the sources of Frost et al. (2021) we compiled a catalog of all spectra required to categorize them according to the outline above. Spectra for six of the eight sources from Frost et al. (2021) are available from previous works on the rms survey MYSOs (Cooper et al. 2013; Pomohaci 2017 and Cooper 2013). In addition, a spectra of M8EIR was obtained from Porter et al. (1998) and a 2 $\mu$m spectra for IRAS 17216-3801 obtained from Kraus et al. (2017) were sufficient to provide a reasonable characterization according to Cooper (2013). Therefore, in total, the sample analyzed in this paper consists of seven sources. The sources are listed in Table 1.

2. New Results

We present the classifications of the sources in Table 2. Most of the sources were straightforward to classify. We classify S255 IRS3 as a Type I source, in agreement with the previous classification by Cooper (2013). This implies that it is the least evolved source in the sample. G305.20 + 0.21 and W33A are both classified as Type II sources. NGC 2264 IRS1 and M8EIR are classified as Type III sources. While the available spectra for IRAS 17216-3801 did not cover the Br series, an absence of H$_2$ emission, and the strength of the Br$\gamma$ line suggests that this is a Type III source, and we discuss the source as such. One source, AFGL 2136, was more complex to classify. AFGL 2136 could be interpreted as either a Type II or Type III source, which presents discussion. Its spectrum displays a lack of H$_2$, implying it is an older Type III object but Br$\gamma$ is only weakly observed, implying instead that it is a younger Type II object. Emission lines like Br$\gamma$ and H$_2$ could appear weak if the source has a high dust column density, which would increase the amount of continuum emission making the lines look fainter and could be the source of this confusion. The continuum emission of AFGL 2136 is high but its column density was not directly measured in our work. AFGL 2136 could be classified as either a Type II or Type III according to the classifications as it lacks H$_2$ emission and only shows weak Br$\gamma$ emission. Indriolo et al. (2020) and Barr et al. (2020) studied AFGL 2136 spectroscopically with VLT+CRIRES, SOFIA+EXES, and Gemini North+TExES spectra. They found that the weak Br$\gamma$ emission has to be limited to a very small emitting region in the inner disk based on the presence of spatially unresolved H30$\alpha$ emission, and also noted that the close to edge-on inclination of the source could lead to the weak appearance of the Br$\gamma$ line. The presence of the H30$\alpha$ recombination line also implies the presence of ionization, and therefore, UV photons, which again implies the central protostar is more evolved and that AFGL 2136 is closer to a Type III than a Type II source.

2.1. Comparison with Previous 3D Radiation-hydrodynamical Simulations

Following the determination of a potential evolutionary phase for each of the MYSOs, we additionally considered the work of Offner et al. (2011). These authors investigate how protostellar outflows change for YSOs with 3D radiation-hydrodynamic simulation. In the simulations, a turbulent steady state was achieved and the gravitational energy was comparable to the turbulent energy in the box at $t = 0$ (Offner et al. 2009). Energy is injected into the simulation and after the initial driving phase the turbulence decays on a dynamical timescale, initiating a global collapse. Protostars are added to

| Name       | R.A. (J2000) (h:m:s) | Decl. (J2000) (d:m:s) | log ($L/L_\odot$) | Distance (kpc) |
|------------|---------------------|-----------------------|-------------------|----------------|
| G305.20 + 0.21 | 13:11:10.45         | −62:34:38.6           | 4.7$^\dagger$    | 4.0$^\dagger$  |
| W33A       | 18:14:39.00         | −17:52:03             | 4.5$^{14}$       | 2.4$^{14}$     |
| NGC 2264 IRS1 | 06:41:10.15        | +09:29:33.6           | 3.6$^{14}$       | 0.7$^{14}$     |
| S255 IRS3  | 06:12:54.02         | +17:59:23.60          | 4.7$^{14}$       | 1.8$^{14}$     |
| IRAS 17216-3801 | 17:25:06.51     | −38:04:00.4           | 4.8$^{14}$       | 3.1$^{14}$     |
| M8EIR      | 18:04:53.18         | −24:26:41.4           | 3.8$^{14}$       | 1.3$^{14}$     |
| AFGL 2136  | 18:22:26.38         | −13:30:12.0           | 5$^{1}$          | 2.2$^{14}$     |
In This Table We Present the Types of Sources We Derive for the MYSOs of Our Sample and the Ages We Derive by Comparing Our Cavity Sizes to the Work of Offner et al. (2011)

| Name          | R_{min} (au) | θ_{cav} (°) | Cavity Density (g cm^{-3}) | Type | H_2 Flux | Br_γ Flux | Br 10 Flux | β-Fe II Flux | Age (log yr) |
|---------------|--------------|-------------|-----------------------------|------|----------|-----------|-----------|--------------|--------------|
| S255 IRS3     | 12 (=R_{sub}) | 20          | 6 \times 10^{-19}          | I    | (1.20 \pm 0.06) \times 10^{-17} | <1.2 \times 10^{-17} | <2.5 \times 10^{-18} | <2.1 \times 10^{-18} | 3.1           |
| W33A          | 18 (=R_{sub}) | 20          | 1 \times 10^{-19}          | II   | (8.7 \pm 0.1) \times 10^{-18} | (2.1 \pm 0.2) \times 10^{-17} | ...         | ...          | 3.1           |
| G305.20 + 0.21| 60 (=3.5R_{sub}) | 12°        | 1 \times 10^{-19}          | II   | (4.2 \pm 0.003) \times 10^{-17} | (1.1 \pm 0.002) \times 10^{-17} | ...         | ...          | ...           |
| AFGL 2136     | 125 (=4R_{sub}) | 22.5       | 3 \times 10^{-19}          | II/III | ... | (2.9 \pm 0.1) \times 10^{-17} | ...         | ...          | 3.5           |
| NGC 2264 IRS1 | 4 (=R_{sub})  | 25          | 8 \times 10^{-21}          | III  | <7.0 \times 10^{-16} | (9.9 \pm 0.3) \times 10^{-16} | (4.0 \pm 0.3) \times 10^{-16} | (1.8 \pm 0.3) \times 10^{-16} | 3.8           |
| IRAS 17216-3801 | 100 (=3R_{sub}) | 40          | 9 \times 10^{-21}          | III  | ... | ... | ... | ... | 5.0           |
| M8EIR         | 30 (=1.5R_{sub}) | 25          | 8 \times 10^{-21}          | III  | ... | 1 | 0.37 | 0.06 | 3.8           |

Note. θ_{cav} is the cavity opening angle. The units of the line fluxes are W m^{-2} μm^{-1}. For clarity, we also include the emission line information from Cooper (2013), Pomohaci (2017), Porter et al. (1998), and Cooper et al. (2013) used in the classification process, and some relevant geometric information from our previous work, Frost et al. (2021), which we discuss in Section 4. The cavity opening angle of G305 is starred as this source has a secondary dusty source within its outflow cavity, which likely affected the fitting process. As a result, we do not calculate an age for this source. A full discussion can be found in Frost et al. (2019). The spectral information for M8EIR comes from Porter et al. (1998), where the line strength is presented relative to the flux of the Br_γ, so these ratios are reiterated for that source. No line data are included for IRAS 17216-3801 as the emission lines were present in the differential phases and visibilities of the spectrinterferometric data of Kraus et al. (2017). The nondetection of H_2 for AFGL 2136 is discussed in Section 2.
this initial space that then generate outflows characterized by their ejection efficiency, velocity, and momentum distribution. Using these models, Offner et al. (2011) find that the cavity opening angles of the YSOs increase with age. Similar results have been found in works such as Beuther & Shepherd (2005) and Vaidya et al. (2011).

Given that the cavity opening angle was a parameter that could affect both the $N$- and $Q$-band simulated high-resolution data sets throughout our previous work in Frost et al. (2021), it was of interest to see what ages Offner et al. (2011) would associate with the final geometries derived in Frost et al. (2021) and to see how these compared to the evolutionary types derived for the sources in this paper. For this reason, we reiterate some relevant characteristics from Frost et al. (2021) in Table 2. It must be noted that in Frost et al. (2021) and here what we refer to as the “cavity opening angle” is the cavity “half angle” in Offner et al. (2011). Henceforth we continue to use “cavity opening angle” for consistency with our previous work. The cavity opening angle of S255 IRS3 is one of the smaller of the sample at $20^\circ$. This corresponds to a protostellar age of $\sim10^3$ yr according to the modeling of Offner et al. (2011). W33A also has a $20^\circ$ cavity putting it at the younger end of the evolutionary track of Offner et al. (2011). The cavity opening angle for G305 is the smallest of the sample, but this value may be affected by a secondary dusty object detected in the cavity by Liu et al. (2019; see Frost et al. 2019 for further discussion). As a result we do not calculate an age for this source. AFGL 2136 can, as previously discussed, be considered either a Type II or Type III source and its cavity opening angle lies between those determined for W33A (Type II) and the Type III sources. The cavity opening angles for the Type III sources are also the larger of the sample, and according to Offner et al. (2011) they range in age between $\sim10^3$–$10^4$ yr old. Therefore, this comparison provides independent support of the classification using the types based on the near-infrared spectra, with the elder types having the largest ages, though given our low-number statistics further investigation is required.

### 3. Notable Trends and Discussion

The majority of the Type III sources have lower densities in their cavities ($\sim10^{-21}$ g cm$^{-3}$, Frost et al. 2021). They show the widest cavity opening angles of the sample with a maximum angle of $30^\circ$. The modeled disks providing the best fit to the Type III sources are all required to have some form of substructure, generally an inner clearing. NGC 2264 IRS1 is the only source whose model shows a substructure other than an inner hole in the form of a gap-like structure (Frost et al. 2021). For low-intermediate mass stars such a feature is thought to form slowly through dust growth (e.g., Zhang et al. 2015) or binary interactions (e.g., Price et al. 2018) and is expected for more evolved sources. Typical timescales of disk evolution in low-mass star formations are on the order of megayears. The later timescales of disk evolution are characterized by the presence of substructures like rings and gaps. One suspected origin of such structures is dust trapping, where grains collect in pressure minima or maxima throughout the disk. Such trapping gathers grains in close proximity where they can amalgamate and grow (Williams & Cieza 2011). However, recent observational studies are providing evidence of dust trapping occurring much earlier. For example, Segura-Cox et al. (2020) found evidence of four annular gap-like structures in the source IRS 63 which is less than half a million years old. These authors state that such structures are an area of likely grain growth. The case of IRS 63 is particularly relevant to comparison with the MYSO case, as it is a so-called Class I source (Shu & Adams 1987) which, like an MYSO, is expected to have not only a disk but also surrounding envelope material. Additionally, the age of IRS 63 is within predicted massive star formation timescales (Tan et al. 2014). Thus, if grain growth is potentially occurring in a low-mass source, whose dust reservoirs and gravitational potentials are significantly smaller than those that would be expected for a massive protostellar system, it is not unreasonable to postulate that similar annular structures could form within the disks of MYSOs.

The other cause of gaps and rings in low-mass disks is the presence of companions. Recent modeling of massive protostellar disks specifically by Oliva & Kuiper (2020) shows that such spiral substructures can be expected to form in MYSOs too. The disk fragments as the MYSO evolves and eventually forms a binary system. The most complex spiral structure found in their work appears between 4000–15,000 yr before a quiescent phase where the spiral structure is more muted. While the source that was best fit with a spiral structure (NGC 2264 IRS1) has not been confirmed to be a binary, the expected high binary fraction for massive stars at both the MYSO (e.g., Meyer et al. 2018; Koumpia et al. 2019; Pomohaci et al. 2019) and evolved stages (e.g., Sana et al. 2012), combined with the fact that we see structures known to be induced by companions in modeling (e.g., Price et al. 2018; Oliva & Kuiper 2020), in the disk of a source that we also classify as evolved suggests that binarity may be the source of this substructure.

Another notable trend among the Type III disks specifically is that they are all highly flared. Varying disk flaring was required to improve the fit to the near-infrared shoulder of the SEDs and to improve the fit to the MIDI visibilities. A decrease in disk flaring has been presented as a diagnostic for evolution with the low-mass disk community, but the topic remains controversial. For example Meeus et al. (2001), through the study of infrared excess in the SEDs of Herbig disks, concluded that the earlier disks (dubbed Group I disks) were more likely to be flared and the second group (Group II) were more likely to be flat, attributing the change to dust growth. However, recent high-resolution imaging by Garufi et al. (2017) found that within a sample of 17 Herbig disks (half of all known at the time) over half of the flared disks are older than 10 Myr, stating that the idea of evolution from flared to flat disks may need to be revised. The flaring of the disk could then be due to some other characteristic of the protostellar environment. The presence of flared disks in our more evolved MYSO sources is consistent with these findings that flared disks can be found even at later evolutionary stages in low-mass sources.

The Type II sources within this sample display very different geometries. G305 has a large inner hole and a low density environment similar to the more evolved Type III sources. The nature of W33A is less clear. Modeling work by Izquierdo et al. (2018) found that the region is very active, supporting the idea that this source may be young among the wider population of MYSOs. The fact that the final model of W33A has a disk with no substructure also supports that this may be a younger source, if it is assumed that substructure appears with evolution as it does for low-mass stars. Alternatively, van der Tak & Menten (2005) note the presence of multiple millimeter sources in their work at 3000–5000 au separations. Given the shorter
wavelength range of our high-resolution data sets we do not probe the outer, cooler regions of the disk in detail. These multiple sources may explain the complexity of the region seen with ALMA (Maud et al. 2017) but do not assist with the interpretation of our single-source models of the observed data.

S255 IRS3 has been shown to be actively accreting (Caratti o Garatti 2017) and this corroborates the young classification made from its spectra. The evolution of disks around low-mass stars is marked by inside-out dispersal. This can be initiated by photoevaporation or the presence of a secondary body, which causes the inner regions of protoplanetary disks to shift from a continuous structure to a more radially concentrated one (Williams & Cieza 2011). The inner geometry of the disk of S255 IRS3 supports the postulation that this is a young source, as it is not one of the sources that displays inner clearing—the minimum dust radius is the sublimation radius. The envelope infall rate of S255 IRS3 may imply an older source, but the data used to determine the source’s geometry are from an accretion lull. Thus, this is likely just a result of the confirmed variable accretion associated with the source. The cavity density (∼10⁻¹⁹ g cm⁻³; Frost et al. 2021) for the source is one of the higher among the sample and again supports the younger age found for the source, as less envelope dispersal would have occurred. The differences observed between the MYSOs with type is illustrated in Figure 1. To summarize, cavity opening angle appears to increase with evolutionary stage, while the overall density of the dust environment decreases and substructure in disks appears over time, being most prevalent in the eldest classified disks.

3.1. What is Causing the Inner Clearing in These MYSOs?

Within our sample, the presence or absence of substructure seems to be associated with evolutionary type. The histogram in Figure 2 displays how the presence of substructure varies with type. Two kinds of substructure are inferred from the fitting: inner holes and one case of spiral/gap structure. In order for the inner holes to be present, something must be disrupting the dust beyond the sublimation radius. A number of theories exist as to what causes inner clearing in low-mass protostellar disks: photoevaporation (Alexander & Armitage 2007), viscous evolution (Espaillat et al. 2014), the presence of binary/multiple companions (Price et al. 2018), and the presence of planets (Muley et al. 2019). For massive stars, modeling works such as Meyer et al. (2018) show that gaps can evolve around massive sources. Photoevaporation and the presence of a binary companion appear to be the best candidates for these MYSOs, given their large luminosities and the high multiplicity fraction expected for massive stars. A calculated Pearson correlation coefficient of 0.93 (a measure of linear correlation calculated as the covariance of two variables divided by the product of their standard deviations) between the luminosity and the model minimum dust radius indicates a strong correlation. Since the minimum dust radius is often larger than the sublimation radius, this could suggest that photoevaporation is the mechanism that is disrupting the dust. The classified types of the MYSOs also appear to support that photoevaporation is the cause of this clearing. Photoevaporation occurs due to the presence of UV photons. When an MYSO starts producing UV photons it passes into its next stage of evolution, the ultra-compact H II region. One of the defining features of the Type III sources is that they display emission lines associated with photoevaporation. As a result, it is consistent that more evolved MYSOs are starting to generate a surplus of these disrupting photons, and therefore, this is the cause of the clearing. As the Type III disks are also all flared, this also lends support to photoevaporation being present and a mechanism of dispersal, as it is thought that photoevaporation inflates disks around low-mass protostars (Williams & Cieza 2011). These effects would only be enhanced for disks subject to more ionizing photons, which is more likely from MYSOs. Flaring could be indicative of relatively higher disk temperatures caused by lower opacity (lower disk densities) and increased irradiation of the disk. This implies that the disk density is lower, that more energetic stellar irradiation is present, and that photoevaporation could be occurring (Williams & Cieza 2011).

The presence of multiplicity cannot be ruled out, however. Recent work has shown that a large proportion of MYSOs are expected to exist in multiple systems (Pomohaci et al. 2019), IRAS 17216-3801 is the only confirmed binary in the present sample (Kraus et al. 2017), and is classified as a Type III source. Further spectrotinterferometric measurements at H- or K-band wavelengths, which could directly probe the inner rims of the disks and the photospheres of the protostars in this sample, could allow the direct detection of binary systems, as has been used in works such as Gravity Collaboration et al. (2018). Work by Oliva & Kuiper (2020) has shown that spiral structures (such as those included in the final model of NGC 2264 IRS1) can appear due to disk fragmentation/binary formation. These are most prominent after timescales of up to 15,000 yr, and past 15,000 yr the spiral density perturbations become less pronounced; however, we note that their simulations do not include outflows nor consider that the disk could be continually fed by the surrounding envelope, which could sustain such structures. Additionally, we note that theoretical work has shown through hydrodynamical modeling that the inner disk is removed for low-mass/Herbig binary systems over timescales of ∼0.5 Myr (Price et al. 2018), but such clearing is not apparent in current fragmentation models such as those done by Oliva & Kuiper (2020). Follow-up observations, such as image reconstruction at 0.01 scales using the VLTI, would allow these cleared inner regions to be investigated in more detail. In particular, observations with GRAVITY or MATISSE that operate at shorter wavelengths and could directly probe these inner regions.

The processes associated with asymmetric substructures in low-mass disks, like the spiral/gap structure inferred around NGC 2264 IRS1, are the presence of binary/multiple systems, dust trapping/growth (Zhang et al. 2015), and the presence of planets (Pinte et al. 2019). Given the high multiplicity fraction for MYSOs at wide separations (Pomohaci et al. 2019), we conclude that dust growth and the presence of a binary/multiple system are the most likely candidates for any substructure in this disk. Both the effects of binaries and dust growth take tens of thousands of years to occur, implying that NGC 2264 IRS1 may be a more evolved source, which is in agreement with its classification as a Type III source.

4. Conclusions

Through the unique combination of a multiscale study of the physical nature of MYSOs and near-infrared spectroscopic work, we have attributed the physical characteristics of a sample of MYSOs to a potential evolutionary sequence based on IR-line emission. The sample constitutes the largest
modeled with infrared-derived constraints on physical properties spanning several orders of magnitude in physical size through the simultaneous fitting of interferometric, imaging, and SED data. The MYSOs themselves cover a range in suspected masses and luminosities of 8–38 solar masses and ~4000–151,000 $L_\odot$. The disappearance of lines associated with outflow shocks colliding with dense envelope material in the near-infrared spectra and the emergence of lines associated with the production of UV photons indicates evolution. In tandem, the sources that display the lines suggest the presence of UV photons are best fit with models with low densities through the RT modeling. This suggests that the envelopes and outflows of the environments are dissipating. Additionally, we find that the models of sources who are spectrally classified as more evolved are the only ones to show evidence of substructure. This implies that envelopes and disks are coevolving for MYSOs, similar to low-mass stars and despite the rapid timescale of massive star formation. Future studies continuing to exploit milliarcsecond resolution observations on an expanded sample, particularly on younger MYSOs who are in the minority in our sample, will be important aids in confirming these and ultimately probing the physics and chemistry of the disk evolution MYSOs. Among the sample, the sources modeled with the largest outflow cavities also fall into the category associated with the latest evolutionary phase. We compare the geometrical characteristics of the sample (Frost et al. 2021) with the results of 3D radiation-hydrodynamical simulations of YSOs to put quantitative values to the ages of the MYSOs based on their cavity opening angles and find an age range across the types from ~10^3–10^5 yr. The presence of substructures within the elder MYSO disks with suspected ages of ~10^4–10^5 yr implies that disk evolution can occur around massive protostars, despite these fast formation timescales. Follow-up work to investigate the nature of the
observed inner holes and structures of these disks can shed light on the mechanisms that form these structures and further improve our understanding of the role of disks in massive star formation.

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Figure 2. Histogram showing whether substructure is present with the MYSOs for each evolutionary type. Within this work we define substructure as (1) a deviation from axisymmetry within the disk or (2) the expansion of the inner dust radius beyond the dust sublimation radius.