The demographics of protoplanetary disks: from Lupus to Orion

Terwisga, S.E. van

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Author: Terwisga, S.E. van
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Introduction

> But indeed all the whole story of Comets and Planets, and the Production of the World, is founded upon such poor and trifling grounds, that I have often wonder'd how an ingenious man could spend all that pains in making such fancies hang together.
>
> Christiaan Huygens, *Cosmotheoros*, 1698

The central goal in the field of protoplanetary disk studies and planet formation is to understand how a planetary system's properties – the masses, orbits, and number of planets – are linked to the circumstellar environment in the earliest parts of a star's existence. In particular, we want to understand how the earliest formation of the solar system happened, and how rare systems like it are.

This is an ancient question, and creation myths that attempt to answer it have been told around the world and through the ages. As modern science began to take shape in Western Europe in the 1600s, it is therefore not surprising that the topic was taken up by the natural philosophers of the time.

Christiaan Huygens, who had been made a Fellow of the Royal Society in 1663 (only three years after its founding) was one of those natural philosophers, and, as the chapter quote shows, he did not mince words in his assessment of the hypotheses on the formation of the Earth and the Solar System that were in fashion at the time. In the context of the book this quote comes from, the posthumously published *Cosmotheoros*, it is a surprisingly strong statement. After all, only a few chapters earlier Huygens discussed how the rings of Saturn would appear to its inhabitants, and if an alien society would have astronomy (he concludes that it would). Certainly, many of the arguments Huygens presents are antiquated, or based on premises we now know to be incorrect. But the primary reason for his apparent disdain seems to be surprisingly modern: a lack of observational data. Huygens' universe was rather static, and its fundamental principles were not well-understood; Newton's *Principia* was published only in 1687. Even with the best telescopes of his day, astronomy was significantly limited by the human eye, both in terms of surface brightness and wavelength coverage. In that context it is perhaps not so surprising that the cautious observer Huygens would consider the origin of planets beyond the realm of scientific study.

Despite this criticism, other scientists would continue to consider the origin of the Solar System. In the 18th century, the idea that the planets had contracted from a disk orbiting the young sun – the so-called Nebular hypothesis – was advanced by several scientists, most prominently Kant and Laplace, on the basis of the similar orbital planes and rotational axes of the solar system bodies. Laplace explicitly attempts to link his model to observations of variable stars. Apart from being remarkably prescient, this also shows an important shift in thinking of planet formation as an ongoing process, as opposed to something that happened in the distant past. However, a lack of observational support of this hypothesis meant that it remained controversial.

Ultimately, however, the modern understanding of planet formation and protoplanetary disk evolution, and of star formation in general, is very much the product of 20th- and 21st-century technological developments. Like the improved manufacture of lenses and the development of refracting telescopes in Huygens' time, CCDs and space-based observatories gave astronomers a new view of the universe starting from the mid-20th century. This led directly to a better understanding of star- and planet formation: protoplanetary disks and protostars are compact, faint, and emit a large fraction of their light at infrared wavelengths that are absorbed by the atmosphere. In more recent years, the enormous collecting power and resolution of telescopes like the Atacama Large Millimeter/sub-millimeter Array (ALMA) have continued this trend. Simultaneously, this wealth of observations has made it possible to develop and test much more sophisticated models of the complicated environments of young stars.

While Huygens' "poor and trifling" foundations for theories of star- and planet formation have these days been replaced by models based much more solidly on observations, it remains true that this is a large and complicated topic to discuss, and inherently difficult to study or model. In terms of timescales, the pre-main-sequence evolution of stars and the protoplanetary disks around them is an inconvenient process to observe: too slow to fit in a human lifetime (or the average PhD project), but very fast (by a factor of about 1000) compared to the total lifetime of a solar-mass star. By taking a demographic perspective, however, some of these difficulties can be overcome. Disks are ideally suited for this approach: they are long-lived enough that large samples exist in nearby star-forming regions. By observing distinct populations of protoplanetary disks, in different environments and at different ages, it is possible to gain insight into the long-term evolution of disks.

In this Introduction, some key aspects of the formation of stars and planets are discussed, focusing particularly on protoplanetary disks and their properties and evolution. In Section 1.1, the evolution of circumstellar material from the earliest embedded phase to a young planetary system is described, as well as the gas- and dust structure of a typical protoplanetary disk. Section 1.2 discusses the properties of several important nearby star-forming regions, focusing on the properties of their stellar populations. Results from surveys of these regions, both in near-infrared and submillimeter wavelengths, are shown in Section 1.3, while Section 1.4 deals with the increasingly strongly interrelated fields of exoplanetary and protoplanetary disk demographics.

1.1 Forming stars and planets

In this Section, the formation of stars and protoplanetary disks is briefly discussed, as well as the structure of disks. In the earliest phases of star formation, the star is deeply embedded. However, it is in this period that the initial conditions for the disk are set. Moreover, there is increasing evidence that significant evolution of the disk material can occur even at these early stages. As in the rest of this thesis, the focus here lies on low-mass stars. For massive stars, there is evidence that key parts of their formation proceed similarly. For instance, Keplerian disks have been identified around massive Young Stellar Objects (YSOs) by Ginsburg et al. (2018). We also focus primarily on the case of single objects. An important to caveat to this discussion is also that the evolutionary stages we discuss here do not correspond one-to-one to the observationally defined classes based on the near- to far-IR emission of these objects, as defined in (Lada 1987; Andre et al. 1993). For instance, an edge-on Class II source may appear to be similar to a Class I YSO based on its infrared emission.

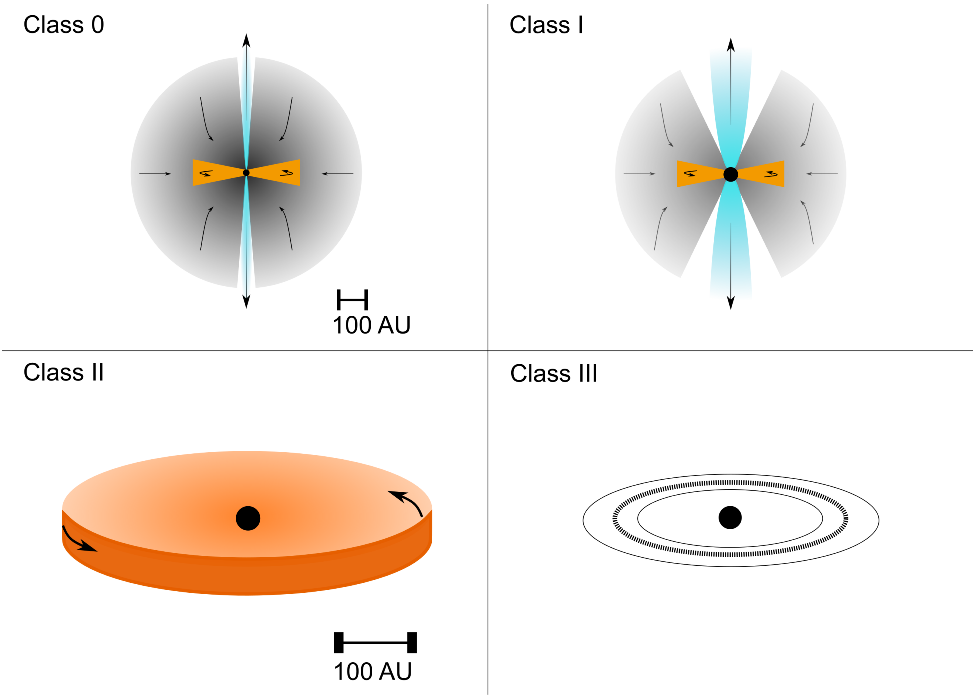

Figure 1.1: Schematic overview of the evolution of circumstellar material during the process of star- and planet formation.

1.1.1 The embedded phases of star formation

Class 0

The modern view of star formation starts from the collapse of gravitationally unstable pre-stellar cores into protostars. At the earliest stages, the protostar is therefore completely surrounded by a dense, rotating, and infalling envelope, which is massive compared to the star (Fig. 1.1, top left). These objects are still actively accreting a significant fraction of their final mass; the stellar mass is therefore very low compared to that of the envelope. Such Class 0 objects tend to be associated with outflows and have low bolometric temperatures ($T_{\mathrm{bol}} \leq 70\,\mathrm{K}$). The evolution of these deeply embedded objects is rapid, and therefore difficult to observe, with typical lifetimes of $\sim 0.2\,\mathrm{Myr}$ (Dunham et al. 2015). Even in this deeply embedded stage, however, evidence of Keplerian accretion disks has now been found, indicating that these structures form at early ages (e.g., Tobin et al. 2012; Murillo et al. 2013; Codella et al. 2014). There is also evidence that the largest of these disks may be gravitationally unstable (Tobin et al. 2016).

Class I to Class II

As the star gains mass, the outflow opening angle widens and the envelope is increasingly dispersed. Because of this the central star starts to become visible, although it is still surrounded by large amounts of circumstellar material, both in the disk and the envelope (Fig. 1.1, top right). As the Class I evolution proceeds, the envelope is progressively removed until only the disk remains, and we speak of a Class II YSO. Class I YSOs have longer lifetimes than Class 0 sources (~ 0.4 Myr versus ~ 0.2 Myr) (Dunham et al. 2015).

Like the Class 0 sources discussed above, the era of high-resolution ALMA imaging has now revealed unexpected features in Class I disks. Of particular importance is the finding of axisymmetric rings and gaps in the dust disks around some Class I YSOs. HL Tau is a class I disk, and shows multiple rings and gaps. Leaving aside, for the moment, the origin of these structures, their presence alone is a sign that substructures can form very early on in a disks' lifetime. Other evidence of significant evolution of the solid components of Class 0 and Class I disks comes from the VANDAM survey of protostars in Perseus, which found a significant decrease in the average continuum luminosity of disks going from Class 0 to Class I and Class II (Tychoniec et al. 2018). However, as with Class 0 sources, the short lifetimes of the embedded phases make it difficult to observe the evolution of disks in lower-mass regions, where only a handful of such objects may be found. In contrast, a Class II source – where the envelope is dispersed, and only the star and protoplanetary disk remain – is observable for a few million years, making it much more common and easily observable.

1.1.2 Protoplanetary disks

As we saw in the previous paragraphs, protoplanetary disks exist throughout the embedded phase, but are especially important during the Class II stage of pre-main sequence evolution. But what are the structures of these objects?

The idea that the infrared excess emission identified in the spectral energy distributions (SEDs) of certain protostars was due to the presence of a disk was first suggested in the late 1970s, in the seminal paper of Lynden-Bell & Pringle (1974), who posited that a viscous accretion disk would explain the observations of T Tauri stars. Thanks to the successful flight of the first IR satellites, it was discovered that flared disks reprocessing the stellar radiation (that is, not heated primarily by accretion) were most consistent with observations especially for Class II YSOs with low accretion rates (Hartmann & Kenyon 1985; Adams & Shu 1986; Adams et al. 1987; Kenyon & Hartmann 1987). The refurbished Hubble Space Telescope's first pictures of proplyds (ProtoPlanetarY Disks) in Orion, showing flared disks against the bright nebula's background, provided direct proof of this model (O'dell & Wong 1996). Although modern observations – particularly, the high-resolution view of dust and gas in disks that ALMA has given us – have now significantly complicated our understanding of disks, the original flared, viscous disk model remains a useful first-order approximation of disk structure.

Dust and gas

Disks, in general, are assumed to have a global gas-to-dust ratio of 100:1, the same as that measured in the interstellar medium (although this may not be true in all cases). However, the distribution of gas and dust grains is not equal even with this assumption. While the gas is supported by pressure, and small dust grains are well-coupled to the gas and distributed similarly in the vertical direction, larger dust particles can settle to the disk midplane efficiently. The approximately millimeter-sized dust grains observed with ALMA are therefore typically considered to be confined to the midplane; but disks observed in scattered light are clearly flared, since those observations trace the scattering surface of smaller grains at larger scale heights. Besides settling to the midplane, midplane dust also grows, migrates inward, and evolves due to gas drag, introducing a difference in the radial extents of gas and dust particles of different sizes (Fig. 1.2).

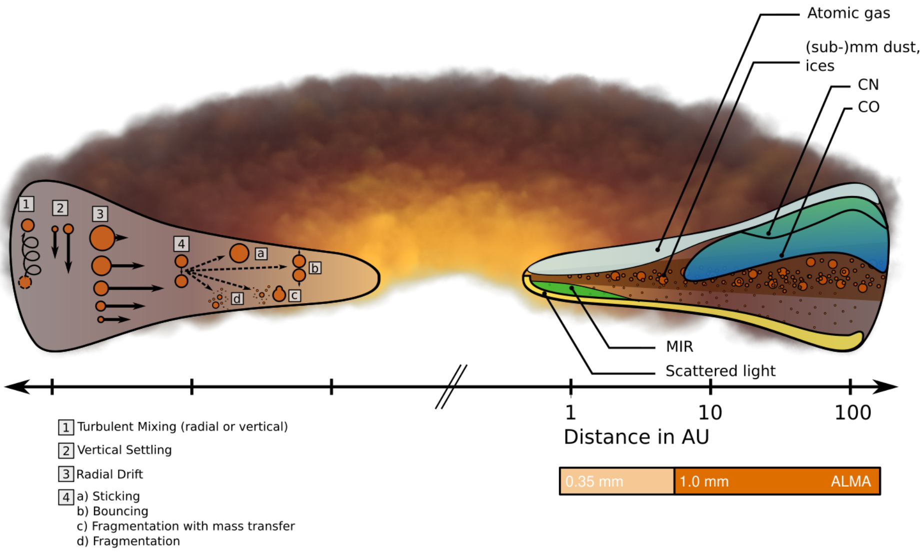

Figure 1.2: Schematic overview of the behaviour of dust *(left)* in a protoplanetary disk, and the regions probed by different tracers *(right)* relevant to this thesis. Figure adapted from Testi et al. (2014).

At the same time, the vertical temperature and density gradient in a disk leads to a rich chemical structure in the gas: in the midplane, depending on the distance from the star, various molecules can be frozen out onto the dust grains. This can affect the grains' collisional properties, especially in those areas where the temperature drops below the freezeout temperature of a gas species when moving radially outward, the so-called snow lines (e.g., Zhang et al. 2015; Okuzumi et al. 2016). Going up from the midplane, the molecular gas is increasingly warm and the reduced density of the disk leads to UV radiation impinging on the disk becoming more important to the disk chemistry, until eventually the gas becomes purely atomic at the outer surface of the disk (Fig. 1.2). This means that different molecules are tracers of different parts of the disk's three-dimensional structure. For instance, N_2H^+ is produced in areas where CO is removed but N_2 is still present (van 't Hoff et al. 2017a), while CO and its isotopologues are found in different parts of the disk which depend on the ability of the different molecules to self-shield (Miotello et al. 2014), and CN is bright in the upper parts of the disk where excited H_2 is abundant (Cazzoletti et al. 2018).

Disk substructures

While the original, smooth disk density profiles work well in many situations, it was known already in the late 1980s that some disks have smaller mid-IR excesses than average T Tauri stars (Strom et al. 1989), which was attributed to gaps in the inner disk. In recent years high-resolution observations of disks in scattered light, (sub)millimeter continuum emission, and gas lines have shown conclusively that many disks show rich structures. In scattered light, arcs and rings are seen with instruments like SPHERE and GPI (Avenhaus et al. 2018; Rapson et al. 2015). At millimeter wavelengths, many disks now show a wealth of rings and gaps (e.g., ALMA Partnership et al. 2015; Andrews et al. 2016a, 2018, Chapter 2 of this thesis). For some of these objects, there is also evidence that the gas density is decreased in the gaps (van der Marel et al. 2016a). Non-axisymmetric dust structures have now also been found, from extreme asymmetries (such as IRS 48) (van der Marel et al. 2013) to more subtle spiral structures (Huang et al. 2018).

The origin of these structures, and in particular of the axisymmetric dust rings, is currently a matter of significant debate. Any model needs to explain why these structures are seen in young, embedded objects, such as the previously mentioned HL Tau, as well as in disks like the very old ($\sim 10\,\mathrm{Myr}$) TW Hya disk (Andrews et al. 2016a). The two main hypotheses are that the dust rings are caused by planet-disk interactions, or by the presence of snowlines of different molecules. In the latter explanation, rings occur in the region where volatile molecules start to condensate on grains for the first time, and affect their collisional properties. In other words, instead of an increase in overall grain density, the sub-mm rings are an effect of local dust opacity changes. However, this hypothesis seems to be increasingly at odds with the observed locations of these rings, since they often fail to align with the expected locations of snowlines (Long et al. 2018; van der Marel et al. 2018a, Chapter 2 of this thesis). Planet-disk interactions may lead to rings at any radius, provided a sufficiently massive planet is present. In this scenario, the planet carves out a gas gap flanked by two pressure maxima. The dust will drift towards these pressure maxima and be trapped, leading to rings and gaps. However, this implies that planet formation can happen even in the embedded phase. Alternative hypotheses for ring formation include dead zone edge-effects, and (secular) gravitational instability; but the former has difficulty in producing the number of rings seen in some sources while the latter requires very massive disks, which is difficult to achieve in Class II YSOs.

Class II to Class III

Ultimately, the disk is dissipated, typically on a timescale of millions of years if viscous evolution alone is the primary mechanism. Stars without significant contribution from disk material at infrared wavelengths, but other indications of youth, are called Class III sources (Fig. 1.1, bottom right). However, the evolution of YSOs depends on external factors as well as internal processes. An extreme example is the evolution of disks in binary systems, which seem to be consistently less luminous than those around single stars (Akeson et al. 2019). Even single stars can be affected significantly by their large-scale environment, as will be discussed in Section 1.2.2.

In some cases, some orbiting dust remains around the host stars after the protoplanetary disk's gas has dissipated, and is visible as a debris disk. The other, much longer-lived outcome of the disk's evolution is of course a possible planetary system. In recent years, the rapid growth in the number of known extrasolar planets has made it clear that our theories of disk evolution do not only need to explain the Solar System, but also the wide variety of planets seen around other stars.

1.2 Star formation in the local galaxy

So far, we have discussed the evolution of protoplanetary disks from the perspective of an individual star. However, in practice, stars are formed near other stars, from larger clouds. The scale of this process varies dramatically across the universe. Star-forming clouds can produce anything from small groups with a few dozen members, such as the TW Hya moving group, to massive clusters like 30 Doradus, which contain hundreds of thousands of solar masses worth of stars, including hundreds of high-mass stars ($M_\star > 15 M_\odot$). In this thesis, we focus on the star-forming regions (SFRs) found in the local galaxy, out to distances of ~ 500 pc. While the most extreme high-mass star-formation regimes are not present in this region, the Orion Molecular cloud does host several O-type stars with masses over $15 M_\odot$, and there is a wide variety of low-mass SFRs within this distance, allowing us to study disks in different environments and at different ages.

In order to map the populations of YSOs, it is essential to have sensitive coverage at multiple wavelengths, in order to characterize their evolutionary state. Infrared observations are particularly important, since the distinction between Class I, II and III sources is based on their infrared spectral index. For this thesis, the excellent sensitivity of the *Spitzer* space telescope has been particularly important. The deep surveys of nearby star-forming regions by this telescope (the Gould Belt and c2d Legacy Programs; Evans et al. 2003; Harvey et al. 2008), as well as the survey of the Orion A and B molecular clouds by Megeath et al. (2012, 2016)) provide a uniquely deep look into the stellar populations of nearby SFRs at infrared wavelengths. For the survey of disk masses in NGC 2024, presented in Chapter 5, infrared observations with the UKIRT telescope were used (Meyer 1996). Apart from targeting the wavelength range where the presence of disks is most obvious, what makes these surveys important is that they are deep enough to be complete for objects with stellar masses down to $\sim 0.1\,M_\odot$. This means that we sample the peak of the Initial Mass Function (IMF) of these regions, which prevents the resulting analyses from being biased towards higher-mass objects.

1.2.1 Low-mass star-forming regions

The low-mass star forming regions in the nearby universe are not as visually spectacular as those which form many O- and B-type stars, like the Orion Nebula. Since the stellar masses and densities involved are lower, they are associated with dark clouds. These were systematically surveyed for the first time by Barnard (1927), who concluded, correctly, that these were foreground objects in the nearby Galaxy, as opposed to regions without stars (Barnard 1919). These clouds were soon found to contain T Tauri stars (Joy 1945), and when the young nature of these objects was realized, the link between star formation and dark clouds was quickly made.

A typical example of a nearby low-mass star-forming region which is particularly relevant to this thesis is Lupus (Fig. 1.3). About half the size of the Taurus-Auriga and Chamaeleon regions, it contains a population of about one hundred Class II YSOs, associated mostly with the Lupus I, II, III and IV molecular clouds. The Class II sample is dominated by Lupus III, which hosts a small but – for low-mass clouds – quite dense cluster of young stars, and the more massive HR5999 and HR6000 stars (located in the center of Figure 1.3) (Comerón

2008a). The ages of YSOs are subject to large uncertainties. However, Lupus as a whole is generally assumed to be 1–3 Myr old.

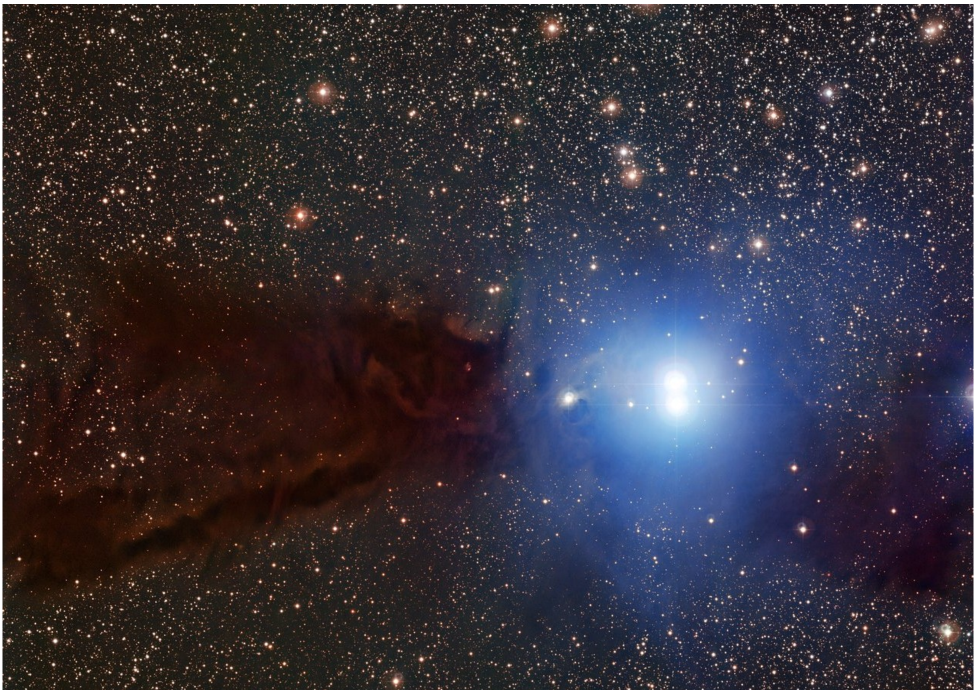

Figure 1.3: The Lupus III dark cloud at optical wavelengths, hosting a group of Class II YSOs studied in this thesis (Chapter 2). *ESO/F. Comeron, 2013*

The Lupus disk population is very well characterized at sub-millimeter wavelengths, thanks to an ALMA program in Band 6 and Band 7 that observed the known Class II population with high resolution ($\sim 0.25''$, or $\sim$ 20 AU radius in physical distance). The observations targeted continuum wavelengths as well as several key gas lines :^{12}CO and its rarer isotopologues ^{13}CO and C^{18}O, as well as CN (Ansdell et al. 2016, 2018; van Terwisga et al. 2019c). At the same time, a large VLT/X-SHOOTER program produced consistent and accurate stellar properties (Alcalá et al. 2017). Like for other star-forming regions in the nearby galaxy, the *Gaia* satellite also provides important information on the absolute and relative distances of cloud members. In this thesis, these projects stood at the basis of Chapter 2 and Chapter 3: the completeness of the Lupus ALMA survey makes it possible to compare extraordinary individual objects to the rest of the population, while the gas line coverage sheds light on the properties of relatively abundant simple molecules.

Lupus is interesting also because it is, in many ways, rather generic. Lupus, Taurus-Auriga, and Chamaeleon show similar small groups with higher densities and a more dispersed population of Class II sources (Kenyon et al. 2008; Luhman 2008); ρ Ophiuchus and Corona Australis have simpler morphologies with only one density peak, but otherwise seem to have similar population sizes, containing 50–250 disks (Wilking et al. 2008; Cazzoletti et al. 2019). Comparing their ages (and taking into account again the substantial uncertainties involved), these regions also seem to be very similar. This leads to one of the central questions in the field of disk demographics: given the apparent large-scale similarities between these regions, are the disks also similar?

In contrast with these young regions, the older Upper Scorpius/Centaurus OB association is also important to mention. As its name suggests, this region contains rather more massive stars than the low-mass SFRs discussed so far, although not as many as Orion (see Section 1.2.2). It is significantly older: its age is typically given at 6–10 Myr (Preibisch et al. 2002; Pecaut et al. 2012). Despite this, it has a well-characterized disk population, and has therefore become an important data point for the properties of evolved disks. Another important sample of young stars in the solar neighbourhood is the TW Hya Association. Like Upper Sco, it has an age of between 6–10 Myr (Ducourant et al. 2014; Bell et al. 2015). However, it is much smaller in terms of membership: apart from the famous TW Hya disk, it contains only a handful (~ 30) young stars, and fewer disks (Gagné et al. 2018).

1.2.2 Massive star-forming regions

Figure 1.4: The Orion Nebula along the Integral-Shaped Filament (ISF), the most massive nearby star-forming region. North is to the right in this image. *ESO/J.Emerson/VISTA/Cambridge Astronomical Survey Unit*

Compared to a region like Lupus, the Orion nebula is a far more spectacular sight: the bright glow of gas, ionized by hot young stars, contrasts with the dark molecular clouds (Fig. 1.4). Indeed, the nebula is visible to the naked eye and was already an object of interest for astronomers with access to telescopes in the 16th century, who discovered its nebulous character and identified the Trapezium stars.

In terms of its stellar population, the massive star-forming regions of Orion are in every way scaled-up from the low-mass case. Massive stars do not form on their own: the IMF peaks at M-types and therefore several thousand low-mass YSOs are also found throughout the Orion complex. The Trapezium cluster reaches a much higher peak stellar density than any of the low-mass groups discussed so far, of 10^4 YSOs pc^{-2}, two orders of magnitude higher than the densest low-mass counterpart (Megeath et al. 2016).

The Orion molecular cloud complex extends far beyond the Nebula, and hosts multiple well-studied sites of massive star formation. The most important of these are the Trapezium cluster, located in the southern Orion A cloud. Immediately to the north of the Trapezium, a dense molecular cloud – the Integral-Shaped Filament, or ISF – also hosts a large population of low-mass stars, and star formation is also ongoing to the south of the Trapezium, along the full Orion A cloud. In Orion B, the NGC 2024 cluster is the most massive. However, other massive stars are also found throughout the complex: σ Ori is a late O-type star, and also accompanied by a large population of young stars.

The different sites of (massive) star formation in Orion do not all have the same ages. Typically, the Trapezium is assumed to be 1–3 Myr old, while NGC 2024 is very young in comparison, with an age of ~ 0.5 Myr; σ Ori, in contrast, is expected to be 3–5 Myr old (Oliveira et al. 2002, 2004). However, there is evidence of age gradients in the Trapezium and NGC 2024, which complicates this view (Getman et al. 2014).

Orion's massive stars do not just lead to the formation of visually spectacular ionized nebulae: their impact on the environment also extends to the YSOs formed in these regions. The discovery of proplyds (Churchwell et al. 1987) did not just confirm the model of protoplanetary disk structure (Section 1.1.2) Many of these objects have emission from ionized species (particularly, [O III]), seem to be concentrated around the primary ionizing source in the Trapezium, θ^1 Ori C, and have tails pointing radially away from that star (O'dell & Wong 1996). These properties all point to the circumstellar material in the proplyds being ionized and removed from the envelopes and disks due to the strong ultraviolet (UV) radiation field in this environment.

The dramatic impact of external irradiation by massive stars on circumstellar material of YSOs has since then been a source of significant research interest. Since regions like Orion likely form the majority of stars in the galaxy (Lada & Lada 2003), and are likely representative of the environment in which the early solar system formed (Adams 2010), understanding the evolution of circumstellar material in these conditions is an important constraint on the formation of planetary systems. There is now a large amount of literature discussing this, both from an observational and modeling perspective (e.g., Scally & Clarke 2001; Haworth et al. 2018; Concha-Ramírez et al. 2019) The results show that external photoevaporation is a common and important process for disk mass-loss in massive SFRs. Precise solutions to photoevaporative disk structures are difficult, since they form compact photon-dominated regions wih complex extinction properties. However, the general behaviour seen from these models is that material evaporates off the disk from the outside in, since the outer material is less strongly bound. Puzzlingly, disks in the ONC seem to be more abundant than their predicted lifetimes would suggest. To explain this observation, the 'proplyd lifetime problem', ongoing star formation has been suggested as an explanation (Winter et al. 2019). Interestingly, most research into disk mass loss in massive SFRs has also shown that disk truncation by dynamic interactions is less important by far except in the densest and most massive regions (Wijnen et al. 2017).

1.3 Protoplanetary disk demography

The existence of multiple distinct populations of YSOs, in different environments and at different ages, is what enables astronomers to study them from a demographic perspective, as opposed to focusing on individual objects. Here, we will focus first on some of the key results from pre-ALMA studies that used this approach, before considering the main results from ALMA surveys of disk populations. Like in all fields of astronomy, results from different wavelength regimes provide information on different, but often complementary, processes.

1.3.1 The optical and near-infrared perspectives

Near-infrared continuum emission from protoplanetary disks is a useful tool for demographic studies. Since it traces the optically thick, warm dust in the inner regions of the disk, it is a (relatively) simple indicator of the presence of any amount of such material around a YSO. It is also a relatively accessible tracer, since the relevant wavelengths can already be targeted by Earth-based infrared telescopes in the J, H, K and L-bands; as usual, however, the *Spitzer* space telescope has allowed this type of study to be extended to longer-wavelengths Haisch et al. (e.g., 2001); Calvet et al. (e.g., 2005); Ribas et al. (e.g., 2014).

The central idea here is to observe the fraction of stars belonging to a young star-forming region with and without disks, and compare the disk fractions between different regions. This means that it is extremely important that the sample be selected uniformly and that no contamination is present. In addition, we must assume here that all disks have an NIR excess. While this is normally the case, transition disks may have sufficiently empty inner gaps that they appear to be similar to Class III sources if no longer-wavelength information is taken into account (Merín et al. 2010).

Haisch et al. (2001) showed, based on JHKL photometry, that the disk fraction across different regions is a strong function of age: young (~ 0.5 Myr) regions have disk fractions of $\sim$ 80%, but this drops to less than half in 3 Myr; this result is shown in Figure 1.5. A single characteristic lifetime of 6 Myr governs the loss of inner disks. Other work, in Orion OB1, and with *Spitzer* supports this fundamental result, but with added complexity from deeper wavelength coverage. Calvet et al. (2005) show that not just disk fractions but also disk structures as traced in NIR wavelengths change, consistent with the process of dust settling discussed previously. *Spitzer*'s excellent mid-IR performance allowed Ribas et al. (2014) to extend the idea of disk fractions to longer wavelengths. This revealed that dust emitting at $12 - 24\,\mu$m evolves more slowly ($\sim$ 6 Myr, rather than $\sim$ 3 Myr) in nearby SFRs, suggesting that colder dust in the outer regions of disks remains present for longer than the optically thick warm disk. Another important result is that the disk and stellar masses are strongly linked, with massive stars hosting fewer disks in Upper Sco, suggesting that these disks may evolve more rapidly (Carpenter et al. 2006; Ribas et al. 2015).

Apart from tracing the fraction of disks in general, disk surveys have also been used to characterize populations of peculiar objects, such as disks with inner dust cavities (Merín et al. 2010; van der Marel et al. 2016c). The fraction of such objects is particularly interesting, as they are thought to host massive planets. Accurately determining the structure of such objects, however, is difficult, and it has therefore not been possible until the advent of ALMA to compare such objects to the known giant planet population in an unbiased way.

Infrared spectral indices do, however, allow us to constrain another important set of timescales: those relevant for the evolution of Class 0 and Class I sources. By comparing the numbers of Class 0, I and II sources in different regions and assuming a single evolutionary

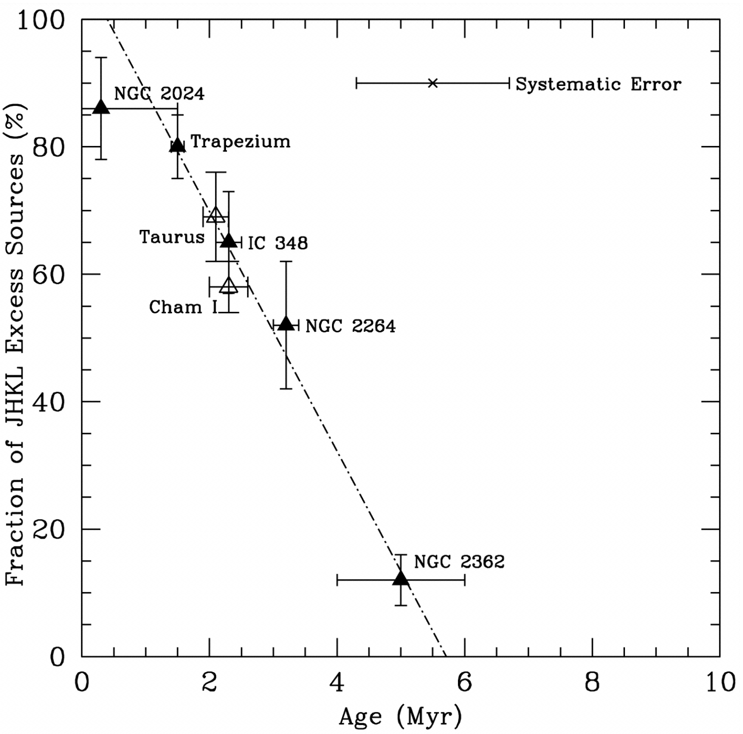

Figure 1.5: The disk fraction based on JHKL-band photometry as a function of cluster age for a range of nearby star-forming regions. Vertical error bars represent the statistical errors in the derived disk excess fraction, while horizontal error bars show the standard deviation and mean of the ages of the individual sources, assuming a single model. The systematic error in the top right shows the effect of using different models for pre-main sequence stellar evolution on region ages. Figure taken from Haisch et al. (2001)

timescale for all Class II sources, it is possible to convert the fractions of younger Classes into lifetimes (Dunham et al. 2015; Carney et al. 2016). This does, however, imply that star formation is continuous over the lifetime of a Class II disk, and implicitly averages over different regions.

So far, we have discussed tracers of dust in various parts of the disk. However, the flow of gas from the disk onto the star can also be traced, using accretion tracers like the Hα line; other lines are used as well (Hartmann et al. 2016). As with disk fractions, comparing the accretion rates of objects in different regions and with different ages can provide important constraints on how disks accrete onto their stars. There is a large body of research into this topic, which we cannot fully discuss here, and which is complicated by the fact that accretion is not a steady process, but instead variable. This is particularly problematic for Class I and younger objects, but even the case for 'normal' T Tauri-stars. However, some trends can be seen. While the accretion rate for older regions is lower (e.g., Hartmann et al. 1998; Manara et al. 2012), large accretion rates can be found in old regions, and in general there is a real but otherwise unexplained scatter along the accretion-age relation. Likewise, accretion rate and stellar mass are correlated, with higher-mass stars accreting more rapidly;

again, this relation has a quite large intrinsic scatter (e.g., Muzerolle et al. 2003; Calvet et al. 2004; Alcalá et al. 2017).

1.3.2 The submillimeter perspective

While they clearly provide important information on the evolution of disks, the disk fractions discussed above do not reflect the total mass of the disk. In the submillimeter wavelength regime, this is less of a problem. Observing the continuum and gas line emission from protoplanetary disks at these long wavelengths, however, is difficult, since these observables are faint. In addition, ideally, we would want to *resolve* the disk's gas and dust in order to study their spatial distribution, something that is difficult to infer from SEDs. This means that sub-arcsecond resolution is often needed. The combined requirements of sensitivity and resolution mean that the study of disks at (sub)millimeter wavelengths has been sensitively dependent on the development of large interferometric arrays at these wavelengths. The Sub-Millimeter Array (SMA), and in particular ALMA, have therefore been crucial tools for disk surveys in the past decade, since their sensitivity makes it possible to study the large samples needed for disk demography studies with sufficient completeness.

At the time of writing of this thesis, a large fraction of the nearby star-forming regions have been the subject of large, unbiased (with regards to stellar mass) surveys: Taurus (Andrews et al. 2013), Chamaeleon I (Pascucci et al. 2016; Long et al. 2017), Upper Sco (Barenfeld et al. 2016), ρ Ophiuchus (Cieza et al. 2019; Williams et al. 2019), σ Ori (Ansdell et al. 2017), IC 348 (Ruíz-Rodríguez et al. 2018), the Orion Nebula Cluster (ONC) (Eisner et al. 2018), Corona Australis (Cazzoletti et al. 2019), OMC-2 (this thesis; van Terwisga et al. 2019a) and NGC 2024 (this thesis; van Terwisga et al. in prep.). All of these surveys have observed the unresolved continuum flux from the disk populations they targeted; in all but the OMC-2 survey, at least some disks were resolved, with most surveys in regions at less than 250 pc reaching resolutions of $\sim$ 30 AU in radius. In addition to this, for a few regions (Lupus, σ Ori, Upper Sco, Chamaeleon I, the Trapezium, and Corona Australis) at least one CO isotopologue line was included in the survey settings, giving access to the molecular gas component of disks.

In addition to these Class II disk populations, there is now also an increasing number of well-studied Class 0 and Class I disks (in Perseus and Orion; Tychoniec et al. 2018, Tobin et al. subm.). For debris disks, the sample is less complete, but they were included in the Upper Sco survey by Barenfeld et al. (2016), and Panić et al. (2013) presented a sample of nearby debris disks.

Dust masses

One key result from these surveys is shown in Figure 1.6, which shows the disk luminosity distributions in several different regions, estimated using a Kaplan-Meier estimator. If we assume that all disks have the same effective midplane temperature and dust emissivity, and that all disks are optically thin, the disk flux can be converted to the total mass of millimeter-size dust grains:

$$M_{\text{dust}} = \frac{d^2 F_{\nu,\,\text{dust}}}{\kappa_\nu B_\nu(T_{\text{eff}})}. \tag{1.1}$$

The most commonly used assumptions on the values of the parameters in Eq. 1.1 are that $T_{\text{eff}} = 20\,\text{K}$ (Andrews & Williams 2005), $\kappa_\nu = \kappa_0\ (\nu/\nu_0)^\beta$ with $\beta = 1$ and $\kappa_{1000\,\text{GHz}} = 10\,\text{cm}^2\,\text{g}^{-1}$ (Beckwith et al. 1990).

Leaving aside, for the moment, the validity of these assumptions, and just looking at the luminosity of circumstellar material, it becomes immediately obvious that the picture is much more complicated than for disk fractions. However, some general observations can be made: disk luminosities in Lupus, Chamaeleon I, OMC-2, and Taurus appear to be very similar, while these regions are also known to have similar ages. The disk flux distribution in the older Upper Sco region, in contrast, shows much lower luminosities, suggesting a similar evolution to that of disk fractions takes place here. Compared to younger regions, however, Tychoniec et al. (2018) show that the difference between disk luminosities in Class 0 and I and Class II YSOs is large enough that significant changes must occur in the early evolution of the disk, and that the simple, single-timescale model for disk fractions may not apply. Another important result from disk surveys with ALMA is that stellar mass and disk continuum mass (or luminosity) are correlated in these regions, but that the steepness of this correlation changes by region and with age (Ansdell et al. 2017; Pascucci et al. 2016).

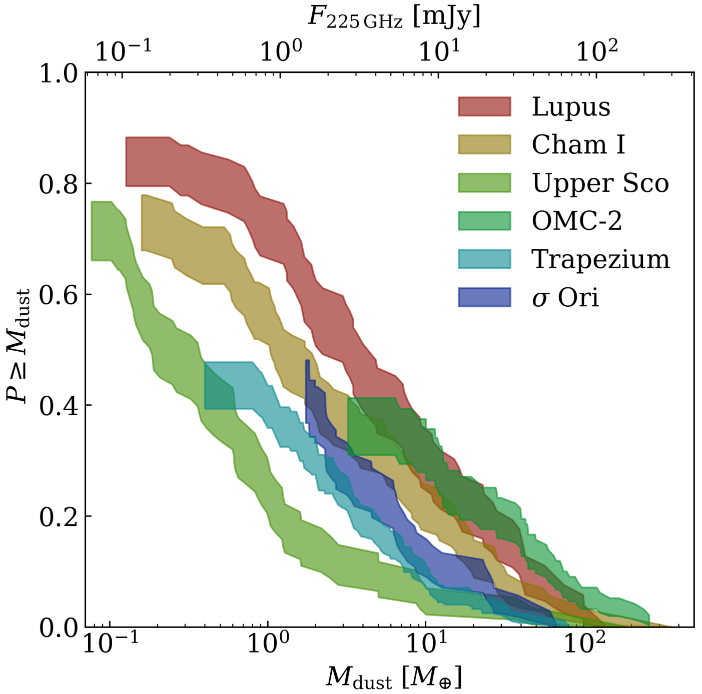

Figure 1.6: Disk flux and mass distributions determined with the Kaplan-Meier estimator for 6 nearby star-forming regions: Lupus (Ansdell et al. 2016, 2018), Chamaeleon I (Pascucci et al. 2016), Upper Sco (Barenfeld et al. 2016), OMC-2 (van Terwisga et al. 2019a), the Trapezium (Eisner et al. 2018), and σ Ori (Ansdell et al. 2017). Disk fluxes have been normalized to 200 pc. For the disk masses, optically thin emission is assumed.

The Trapezium, in contrast, a young stellar population hosts disks much less luminous than those in Lupus or Chamaeleon. In this region, however, we see strong evidence of external photoevaporation, which is likely to affect the disk masses. A similar effect has also been posited in σ Ori; both regions are in the vicinity of O stars.

The similar continuum luminosity distributions of young disk populations in distinct regions without external photoevaporation might suggest that, as we implicitly assumed in Fig. 1.5, disk evolution proceeds similarly everywhere. However, there are some uncertainties in this, mostly driven by the small number of distinct populations that have been sampled. As Cazzoletti et al. (2019) show, the Corona Australis region appears to have ‘old’, low-mass disks but a young stellar population – a puzzling result in this context. Surveying more populations is a straightforward solution to this problem.

Another important consideration here is to what extent disk continuum fluxes really trace the disk solids. Even those populations with high average disk masses do not contain large amounts of millimeter-sized dust at 1–3 Myr. Thus, massive planet formation should either be relatively rare, or a significant amount of mass is not observed. The latter is possible if sufficiently large bodies form early on: we would not see protoplanets at submillimeter wavelengths easily with these sensitivities. Alternatively, the assumption that the disk is optically thin may not be true. This is now a topic of active debate: from disk surveys, a clear correlation in disk luminosity and radius is seen (Tripathi et al. 2017), which might be caused by optically thick rings. The DSHARP project did find abundant narrow rings in its sample of massive disks (Andrews et al. 2018), but with opacities $\tau < 1$; the V1094 Sco disk, studied in this thesis, shows indications of similar behaviour. This has been suggested to be a natural cause of ongoing planetesimal formation (Stammler et al. 2019), or alternatively the effect of self-scattering at millimeter wavelengths (Zhu et al. 2019) or the effect of radial drift setting grain sizes (Rosotti et al. 2019), but is still a matter of very active debate.

Gas masses

Apart from dust, submillimeter observations also give a window on an elusive, but important part of the disk: the molecular gas that makes up the majority of a disk’s mass, which is typically assumed to be one hundred times the dust mass. However, there are some significant difficulties in both observing and interpreting the observations from gas. First, gas lines are faint, even for relatively abundant molecules like ^{12}CO, leading to low detection rates. This is especially unfortunate from the perspective of a demographic approach of disk evolution, which depends on large sample sizes and sampling multiple populations. Second, the bright lines quickly become optically thick – this is the case for ^{12}CO, and even the less abundant isotopologue ^{13}CO, especially in massive disks. Lastly, the interpretation of any molecular line observation depends sensitively on our understanding of the disk structure and the chemical network that underlies it. However, on this front, important advances have been made in recent years.

For surveys, large grids of disk models to interpret the observations are particularly important. Such grids have now been made for CO, both from relatively simple parametrization (Williams & Best 2014), and from much more sophisticated physical-chemical modelling codes. In particular, Miotello et al. (2016) used a grid that included isotope-selective photodissociation for CO and its isotopologues, as well as freeze-out, created with the DALI code (Bruderer et al. 2012; Bruderer 2013). Since disk mass is the most important parameter for setting the CO flux in these models, this has made it possible to calculate CO-based disk masses for large samples of disks in Lupus and Taurus (Ansdell et al. 2016; Miotello et al. 2017; Long et al. 2017).

The CO-(isotopologue)-based gas masses, however, show unexpected behaviour in both Lupus and Taurus. Compared to the usual assumption that the bulk gas-to-dust ratio in protoplanetary disks is ~ 100, the average gas-to-dust ratio in both regions is significantly lower, when inferred using these models (Ansdell et al. 2016; Miotello et al. 2017; Long et al. 2017). Together with observations of individual disks where CO isotopologues do not seem to be good tracers of the total gas mass (e.g., Favre et al. 2013; Kama et al. 2016a; Bergin et al.

2016), this has been interpreted as a sign that the chemical evolution of disks is more complex than previously expected. In the average disk, a large fraction of volatile CO is removed.

For CN, which is more sensitive to a combination of incident UV flux and surface area, a DALI-based grid is now also available (Cazzoletti et al. 2018); these models are used in this thesis (Chapter 2; van Terwisga et al. 2019c) to compare to observations of this molecule in Lupus. In the future, homogeneous, deep observations of gas lines in disks in different SFRs will hopefully provide more information on the structure and the chemical evolution of this and other species.

Disk radii

The ability of an instrument like ALMA to not just detect faint gas and dust emission but also to resolve it means that we can also consider the properties of disk radii in different populations. However, this should be done carefully: observations with different convolving beams and different sensitivities can lead to different disk radii. Additionally, the optical depths of gas and dust differ, and dust may migrate radially inward (Trapman et al. 2019). However, some general trends can be seen: large dust disks ($R_{\mathrm{dust}} > 100$ AU) are often transition disks in Lupus (van der Marel et al. 2018a); similar behaviour is seen in other regions. In the Trapezium cluster, dust disk radii are particularly compact on average; this is likely due to external photoevaporation, which removes material from the outside in (Eisner et al. 2018). In general, even in the low-mass star-forming regions, compact dust disks seem to be present, and their counterpart gas disks appear to be compact as well (this thesis, Chapter 3; van Terwisga et al. 2019c).

1.4 From disk populations to planet populations

So far, the demographics of one of the possible outcomes of the evolution of circumstellar material, the formation of one or more planets, has not been discussed in depth. To do so would require more space than is necessary here, but given the rapid growth in the numbers of extrasolar planets and planetary systems, and the increased sensitivity with which these objects are now observed, increasingly direct links can be made between the observed population of disks and planets.

One of the reasons that such comparisons are often still quite tentative is that the two approaches are sensitive to different environments: ALMA, even with its extraordinary sensitivity, is only beginning to probe AU-scale features in the nearest disks (Andrews et al. 2016a) and most surveys have effective resolutions of more than 20 AU in radius. At the same time it is relatively easier to find a massive, close-in (< 1 AU) planet with most current planet-searching techniques. The wealth of rings and other substructures that are now being found in the most massive disks by high-resolution ALMA imagining campaigns provide another way to make the link between planets and disks more explicit. As Zhang et al. (2018) show, the overlap in mass and semimajor axis-space is still small.

However, it is possible to compare bulk disk dust masses to the total mass in solids in a protoplanetary disk. This was done by Manara et al. (2018), who find that disks are significantly less massive than the typical planetary system. Apart from the previously discussed ongoing debate on how accurate the mass estimates from millimeter continuum observations are, several explanations for this puzzling result are possible. The authors suggest that disks may continue to accrete material from the larger-scale cloud, which would replenish the material lost to planetesimal formation. Alternatively, a common suggestion is that planet formation is already complete by the time the YSO reaches Class II. This interpretation is also consistent with the observations of rings in the young HL Tau system which may be carved by planets (ALMA Partnership et al. 2015). Detections of planets inside protoplanetary disks are still rare at the moment, but likely to increase, and should make it easier to answer this question.

1.5 This thesis

The work presented in this thesis is based on ALMA surveys of protoplanetary disks in three star-forming regions: Lupus, OMC-2, and NGC 2024. The motivation for this thesis is to study the evolution of protoplanetary disks from the population level, and each of these regions offer new information from this perspective. The first two chapters focus on the Lupus clouds: a typical low-mass star-forming region. It has been the subject of a deep, uniform, and complete survey in two ALMA bands, targeting both bright gas lines (from CO, its isotopologues, and CN), as well as the continuum emission from millimeter-sized grains. This allows us to answer two important questions on disk evolution: how common are $>$ 200 AU-sized disks with continuum substructure, and how are these substructures formed? Do the compact disks observed in the continuum observations also correspond to compact gas disks?

The chapters focusing on disks in Orion deal with the impact of the large-scale environment, and in particular, of massive stars, on disk evolution. OMC-2 provides a view of a population of disks that are formed in a massive cloud, but are isolated from the radiation of massive stars by distance and extincting material. They are particularly interesting for linking disks that do form near these massive stars to those in low-mass YSOs. NGC 2024 also hosts several massive stars, and is the youngest region surveyed so far. It is a complex environment, where the presence of multiple populations of young stars has been suggested. ALMA provides a new view of the young stellar population in this region, allowing us to independently test the complexity of this environment.

- Chapter 2 describes observations of V1094 Sco, an extended, multi-ringed disk discovered serendipitously in ALMA Lupus disk survey and places this object in the wider context of the Lupus disk population. Due to the low temperature of the disk midplane, snow lines can be excluded as the drivers behind ring and gap formation in this disk. Disks the size of V1094 Sco, with continuum emission out to 300 AU, are rare: only 2.1 ± 1.5% of Lupus disks show continuum emission beyond 200 AU.

- In Chapter 3, we characterize the CN emission from 94 Class-II disks in the Lupus star-forming region, compare it to observations in other regions, and interpret our observations with a grid of models. The cyanide radical CN is abundant in protoplanetary disks, with line fluxes often comparable to those of ^{13}CO. However, a large fraction of Lupus disks are faint in CN. Only disks with exponential gas surface density cutoffs $R_c \leq 15$ AU can reconcile these observations with models, providing the first observational evidence of a compact gas disk population in Lupus. CN rings observed in two resolved sources can be replicated by disk models without need for dust density substructures.

- In Chapter 4, we present observations of a sample of disks in the Orion Molecular Cloud-2 (OMC-2) region, and compare their dust masses to both externally photoevaporated disks in the Trapezium cluster and to disks in nearby, low-mass star-forming regions. This allows us to test whether initial disk properties are the same in high- and low-mass SFRs, and enables a direct measurement of the effect of external photoevaporation on disks. The disk mass distribution in OMC-2 is statistically indistinguishable from that in nearby, low-mass SFRs like Lupus and Taurus, and we conclude that age is the main factor that determines these disks' evolution. The difference between the OMC-2 and Trapezium cluster samples is consistent with mass loss driven by far-ultraviolet radiation near the Trapezium. Taken together, these results imply that in isolation disk formation and evolution proceed similarly, regardless of cloud mass.

- Chapter 5 discusses the NGC 2024 star-forming region: the youngest and second most massive star-forming region in the Orion clouds, with an age of just 0.5 Myr. This environment provides a unique view of a population of 179 disks that are close to the ionizing source(s), but have not been exposed to it for a long time relative to the Trapezium disks. We find independent evidence for two distinct populations: disks along the dense molecular ridge are young ($0.2 - 0.5\,\mathrm{Myr}$) and partly shielded from the FUV radiation of IRS 2b; their masses are similar to isolated $1 - 3\,\mathrm{Myr}$ old SFRs. The western population is older and at lower extinctions; the disk mass distribution in this region resembles that of the Trapezium cluster, suggesting it has been impacted by external photoevaporation.

From the perspective of disk demographics, some of the future steps are clear. The still relatively small number of regions in which submillimeter disk masses have been measured, and the diversity of such environments, mean that more populations must be observed. This is also true for gas observations, and particularly for species other than CO and its isotopologues, which can provide valuable insight in what the chemistry of a 'typical disk' looks like, beyond our current focus on the most massive few percent of such objects. In addition, properties of the stars themselves will remain an important ingredient in our characterization and intercomparison of protoplanetary disk populations.

Between the ongoing wealth of results from ALMA, the continued development of our understanding of planetary systems and their diverse natures, and in the near future, the launch of the James Webb Space Telescope, the grounds on which our understanding of comets and planets and the production of the world will become firmer still. Although there are many open questions still, they are now, at least, firmly in "the reach of human Knowledge [and] Conjecture".