— Proposed China-CONICYT Postdoctoral Research Project —
From High Mass filaments to High Mass Stars

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1. Scientific framework: State of the art and previous work

Today, the study of the physics of star formation is poised for tremendous advances. The groundwork, both theoretical and observational, over the last decade in particular have driven great discoveries and a deepening of our understanding of the relevant physical processes involved in the formation of stars and the origin of stellar masses. Advances in computational capabilities have catapulted theoretical and simulation work forward toward a far more refined and nuanced understanding of the role of turbulence in molecular cloud formation, evolution, and the birth of stars formed within. The vast majority of molecular clouds that have been observationally scrutinized to date are composed of filamentary gas structures that are the immediate environment of star formation (e.g., Motte et al. 2010, Arzoumanian et al. 2011, Stutz & Kainulainen 2015, Stutz & Gould 2016, Conteras et al. 2013, 2016, Andre et al. 2014 for a review of low-mass regions). Intriguingly, recent studies have concluded that filaments in nearby low mass clouds (with masses in the range $\sim 10^{2-4}$ $M_\odot$) have approximately uniform widths that scatter around 0.1 pc, radial density profiles approximately consistent with an r^{-2} power law shape, and relatively low mass per unit length (M/L) values of M/L($r \sim 0.1$ pc) $\lesssim 100$ $M_\odot$/pc (e.g., Arzoumaninan et al. 2011, Palmeirim et al. 2013, Kainulainen et al. 2016a, Cox et al. 2016). Meanwhile, dense cores (the sites of individual protostar birth) in low mass molecular clouds also have sizes of ~ 0.1 pc (e.g., Enoch et al. 2008), an intriguing indication that the core size scale is likely set by the filamentary structures in which they form. Thus filaments may soon supplant the concept of (semi-)spherical "cores" as *fundamental units of star formation.* Furthermore, observations of Taurus and the Pipe indicate that these clouds present subalfvénic, or at most transalfvénic, conditions (Heyer et al. 2008, Franco et al. 2010). Theoretically, the fact that turbulence simulations (e.g., Padoan 1995, Mac Low & Klessen 2004, Krumholz & McKee 2005, McKee & Ostriker 2007, Padoan & Nordlund 2011, Federrath & Klessen 2012, Hennebelle & Falgarone 2012, Chen & Ostriker 2015, Federrath 2016) reproduce these observed properties *both with and without the inclusion of magnetic fields* is a strong indication that low-mass cloud evolution is not fundamentally driven by magnetic fields.

While this so called "turbulent paradigm" outlined above captures low-mass cloud structure, it also purports to explain observed extragalactic star formation scaling relations, such as the Kennicutt-Schmidt relation between gas (surface) density and star formation rate (e.g., Bigiel et al. 2008). However, this turbulent interpretation is increasingly being questioned in the face of high resolution observations and the most advanced simulations available today. For example, there is currently strong tension between nearby low-mass molecular cloud lifetimes of 1 - 3 Myr (Taurus-like clouds, with masses in the range of $\sim 10^{2-4}$ $M_\odot$; Hartmann 2001, Ballesteros-Paredes & Hartmann 2007 their Table 1) and more massive clouds (10^{5-7} $M_\odot$) detected in both the Milky Way and external galaxies with lifetimes of ~ 20 - 30 Myr (e.g., Murray 2011, Meidt et al. 2015). Furthermore, the interpretation of Larsons Laws (Larson 1981), which provide scaling relations between cloud mass, surface density, size, and velocity dispersion previously considered to be universal across all clouds, is being transformed today. Hughes et al. (2013) find that for nearby galaxies no universal scaling relation between cloud mass and velocity dispersion is observed, when accounting for spatial resolution and the sensitivity of the observations (see also Leroy et al. 2016 for a larger sample of galaxies). On the theoretical side, e.g., Ibanez-Mejia et al. (2016) find that turbulence alone cannot account for the cloud line widths in their simulations and conclude that self-gravity must contribute significantly to the simulated velocities already at the earliest stages of molecular cloud evolution. At the same time, Zamora-Aviles et al. (2016) have demonstrated with colliding flow simulations that increased strength of the magnetic field produces higher star formation rates in relatively high mass clouds (this is interpreted as a suppression of the turbulence-induced non-linear thin shell instability by the B-field).

These advances in our understanding, forged on the basis of ever higher resolution observations and simulations, point toward the existence of two mass scales for cloud formation (Stutz & Gould 2016). On the one hand, lower mass clouds (e.g., Taurus-like) are consistent with being short-lived and having physical properties predominately shaped by turbulence. On the other hand, the situation is not so clear for filaments in high mass molecular clouds (masses in the range of $\sim 10^{5-7}$ $M_\odot$). These have much larger M/L values in the range of M/L$\sim 300 - 1000$ $M_\odot$/pc (depending on the radius out which the M/L values are calculated; e.g., Stutz & Gould 2016, Contreras et al. 2013, Kainulainen et al. 2013, Andre et al. 2016). Moreover, their estimated lifetimes that are factors of $\sim$ 10 longer than their low-mass counterparts. Furhtermore, emerging evidence indicates that their structure and star-formation potential must be understood in terms of turbulence, global gravitational collapse, and magnetic fields, in combination (e.g., Busquet et al. 2013, Contreras et al. 2013).

Orion, with a mass of $\sim 10^5$ $M_\odot$ and stellar ages up ~ 10 Myr (e.g., Slesnick et al. 2004; Fang et al. 2009, Da Rio et al. 2016), is at the cusp of transition between these two mass regimes. When combined with its proximity to Earth (~ 420 pc; e.g., Menten et al. 2007, Sandstrom et al. 2007), the fact that it straddles these two mass regimes, one very well understood and one rather poorly understood, has made Orion an ideal window to decipher the physics of star formation in the high-mass cloud regime. On the basis of a very high density of observables (Heiles 1998, Matthews & Wilson 2000, Stutz & Kainulaien 2015, Furlan et al. 2016, Da Rio et al. 2016, Tatematsu et al. 2008, Nishimura et al. 2015, Megeath et al. 2012, Di Francesco et al. in prep.) characterizing the observations of the gas, protostars, and pre-main sequence disk stars (Class IIs), Stutz & Gould (2016) argue that Orion hosts a different mode of star formation relative to the nearby low-mass clouds (e.g., Taurus) that have been studied in great detail (see references above). Stutz & Gould (2016) argue that the integral shaped filament (ISF) gas may be trapped in an auto-destructive cycle of oscillations with transverse (or torsional) waves propagating through it. Based on the measured Herschel mass distribution (assuming cylindrical geometry), they obtain a density profile for the ISF of $\rho(r) = 17\,M_\odot\,\mathrm{pc}^{-3}(r/\mathrm{pc})^{-13/8}$, where r is the radial distance from the filament ridgeline. This density profile yields a gravitational potential profile of $\Phi(r) = 6.3(\mathrm{km\,s^{-1}})^2(\mathrm{r/pc})^{3/8}$, which evaluated at the limit of the Herschel map (8.5 pc from the ISF ridgeline) is $14(\mathrm{km\,s^{-1}})^2$. This is of course a lower limit on the potential, as it only includes the gas contribution. Nevertheless, from the Heiles (1997) Zeeman observations (which provide the line-of-sight, LOS, field strength) one can evaluate the gravitational energy density compared to the magnetic field energy density. The result is that on small scales (of order 1 pc from the filament) the magnetic field appears to be approximately subcritical compared to gravity while on large scales gravity completely dominates (that is, on large scales the magnetic fields are supercritical compared to gravity). This configuration implies that the observed undulations in the ISF (and possibly other filaments, see e.g., Contreras et al. 2013) may be magnetically induced by helical fields[1], capable of confining or potentially even pinching the filament, giving rise to massive star and stellar cluster formation as seen today in the Orion Nebula Cluster (ONC) and which may have also generated the older gas–free clusters to the North (NGC 1977 and NGC 1981).

While Orion has been scrutinized in great observational detail, more distant and higher mass systems must be examined in terms of their large-scale gravitational potential, turbulence, and magnetic fields in order to quantify the physical conditions leading to high-mass star and stellar cluster formation in our Galaxy. The critical observational questions here are: What is the evidence for this "Orion" scenario, if any, in other high line-mass filaments? What is the morphology and strength of the magnetic field compared to gravity and turbulence in the filamentary sites of high mass star formation? Are all high-mass protostars (HMPOs) predominantly forming in (and connected via their cores to) high line-density filaments and/or radial networks (hubs) of filaments? Do all high-mass filaments have the same / similar density profiles? How do the possible variations in filament density profiles potentially affect the incidence and formation of stellar clusters? What is the effect of feedback (e.g., cloud destruction) near sites of high-mass star formation? And finally, within the framework set by the larger-scale gas properties, which process(es) regulates the formation and fragmentation of massive cores on kAU scales accesible with ALMA?

2. Proposed project description

This project is tuned to adress the above questions. We aim to use the established observational basis of (sub-)mm continuum surveys, and in particular HiGAL (Molinari et al. 2010, 2016) as a launching point from which to quantify the large-scale gravitational potential and density profiles in high line-mass filaments. Furthermore, since Galactic plane confusion can be significant along lines of sight passing through or near the Galactic center, we focus this program on regions outside $l\pm \sim 60$ deg, soon to be publicly available via the VIALACTEA consortium. See Figure 1. This program exploits existing and future observational radio capabilities available in Chile while leveraging the Chinese investment in the future CST facility (formerly the CSO telescope), to be relocated to the Atacama desert in 2018.

2.1 Mass, density, gravitational potential, and fragmentation.

With the measurement of the mass distributions in molecular clouds accessible with space-based Herschel data (see above), we will obtain measurements of the gravitational potential of the star forming gas (e.g., Stutz & Gould 2016), which sets the stage to analyze other observables such as the velocity structure in new light, going beyond column density profiles. The mass, (volume) density, gravitational potential, and fragmentation properties are an essential input for theoretical analysis (both in simulations and analytically) aimed at undestanding the nature of fragmentation and the effects of magnetic fields in filaments (e.g., Chandrasekahr & Fermi 1953, Habe et al. 1993, Shibata & Matsumoto 1991, Uchida et al. 1991, Hanawa et al. 1993, Nakamura et al. 1993, Fiege & Pudritz 2000ab, Hennebelle 2003, Sugimoto et al. 2004, Khezali et al. 2014). Furthermore, filament widths are of great observational interest; emerging evidence points to a uniform width of filament in low-mass regions of ~ 0.1 pc (see references above). In contrast, the Stutz & Gould (2016) ISF density profile is consistent with a scale-free power law (see above) down to a scale by the Herschel resolution of $\sim$0.05 pc (see Figure 5 of Stutz & Gould 2016). Indeed the filament width (or more precisely the power law softening radius of the power law density profile) is consistent with $r_{\rm flat} < 0.04$ pc (based on ALMA, APEX, and public SCUBA2 data; work in progress). While published measurements are few to date, this is in agreement with some estimates of high line-mass filament widths (Henshaw et al. 2016), while in others report 0.1 pc widths (Andre et al. 2016). Moreover, no universal consensus has emerged as to the density profile shapes on large scales, mainly because of the historical availability of spatially filtered ground-based continuum data which emphasize the spiny nature of filamentary structures.

Ultimately, similar measurements, both on large (Herschel) and small scales (ALMA, APEX/ARTEMIS), must be carried out in more distant high line mass filaments outside of Orion. Herschel and Planck data (see Abreu-Vicente et al. 2016 method) will be used to characterize the large scale gravitational potential of high mass filaments (e.g., Hill et al. 2011, Hennemann et al. 2012, Contreras et al. 2013, 2016, Andre et al. 2016). Ongoing and future ALMA programs will provide direct measurements of the fragmentation properties beyond the ISF (Kainulainen et al. 2016). As noted above, Galactic plane confusion along the line-of-sight (LOS) is a concern with the study of more distant systems; to adress this we aim to target high line-mass filaments outside of the environs of the Galactic center direction. This project will place the ISF in context with high mass counterparts and establish whether ISF-like mass and gravitational potential profiles are common,

[1] http://www.berkeley.edu/news/media/releases/2006/01/12_helical.shtml

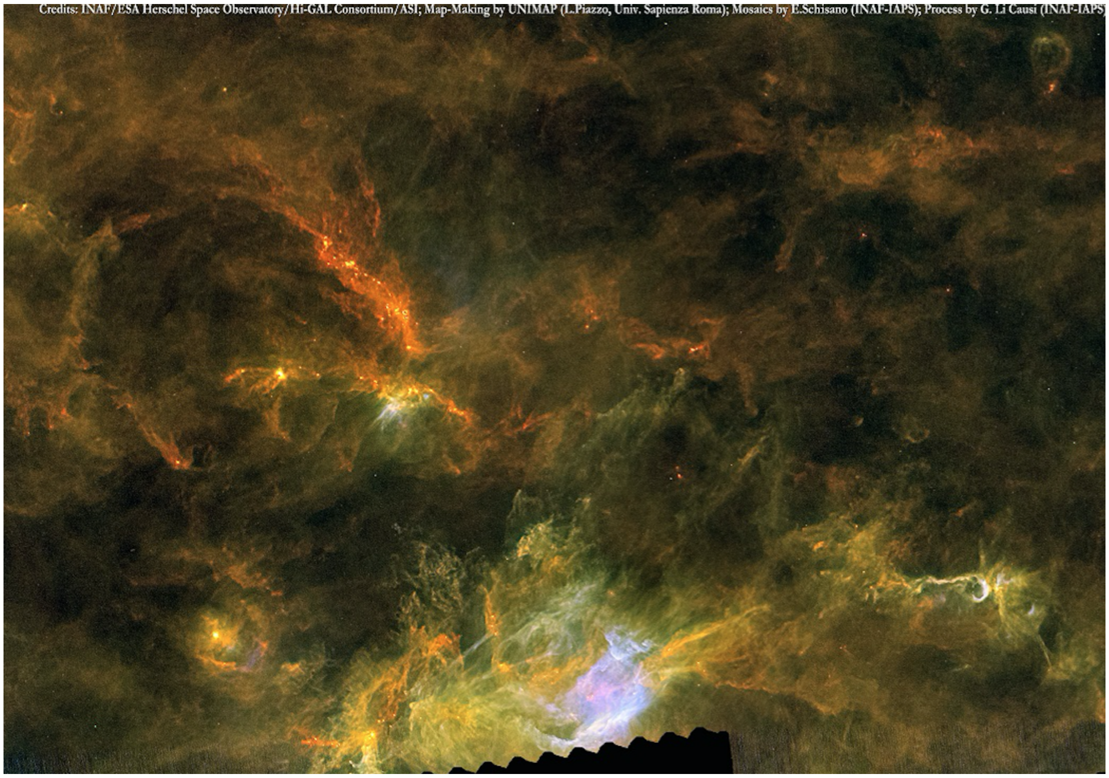

Figure 1: Combined Herschel 70 μm, 160 μm, and 250 μm false-color image of the Seagull Nebula and CMa OB1 Association, centered near $l = 224\,\mathrm{deg}$.

perhaps revealing a possible evolutionary sequence for high mass filaments. Such an analysis sets the stage for interpretation of the gas velocity profiles as a function of scale and down to the filament ridges, the next step toward a broader undenstanting of the virial state of high mass (and often filamentary) regions that are the birthplaces of high mass stars.

2.2 The measuring gas velocities: the virial state of filaments.

With observations of molecular gas emission lines from ground-based radio facilities (ALMA, APEX, ASTE, NANTEN2, and in the near future the CST), we will then evaluate the gas structure and motions in terms of the global gravitational potential of the gas, and assess the fragmentation and virial state of the gas (or its gravitational boundedness) down to the smallest scales on which protostars actually form (e.g., Kainulainen et al. 2016b, and see below). This program will focus on the measurement of turbulent velocities as a function of scale, placing essential constraints on the interpretation of line-widths in marginally and unresolved massive clouds (such as more distant filaments and even extragalactic systems). We will exploit the basis established through the mass-profile and velocity study in Orion to extend our analysis to more distant high mass filaments using for example ALMA N_2H^+ and continuum observations in concert with the single-dish capabilities listed above to constrain the larger scale and lower density velocities. We will develop follow-up samples of filaments and regions that are best suited observationally for dense and intermediate density gas tracer observations. In concert with the Herschel mass profile measurements, the first line of attack in the analysis will be to evaluate the virial state of the filamentary gas to determine if high-mass filaments are generically in virial equilibrium (c.f., Contreras et al. 2013).

2.3 The relative roles of turbulence, magnetic fields, and gravity.

Ultimately, the role of the magnetic fields in setting the structure of undulating filaments ubiquitously observed throughout the Galaxy is a major open question with far reaching implications for star formation in general, as well as for high mass star formation and molecular cloud evolution. For example, Li et al. (2013) find that in nearby Gould belt clouds the projected morphology of the B-fields in filamentary molecular clouds is bi-modal: some B-fields are parallel while others appear perpendicular to filaments, with an approximately 50:50 split. With a sample of two high-mass filaments, Pillai et al. (2015) also reproduce this bimodal behavior; furthermore, they find that the higher density filament exhibits a B-field morphology that is perpendicular to the filament axis (much like Matthews & Wilson 2000 find in the ISF in Orion; see also Li et al. 2013). Pillai et al. (2015) conclude that the magnetic fields are as important as turbulence and gravity in the two high-mass filaments they study. Furthermore, Contreras et al. (2013) conclude that for a small sample of high M/L filaments the virial parameters, when taken at face value, require additional magnetic field confinement to remain stable and long lived. In yet another high-mass filament, the infrared dark cloud (IRDC) G14.225-0.506, Busquet et al. (2013) find that the fragmentation and geometric properties of the filament are consistent with magnetic modulation of the gas flows, and thus conclude that magnetic fields play an important role in determining filament properties.

The next required step here is to build the best target list for CST single-dish and ALMA polarization observations of high mass filaments. Such work will address key questions at the heart of high mass star formation, such as: Are magnetic fields actually capable of driving oscillations in filaments (c.f., Stutz & Gould)? What are the relative levels of magnetic, turbulent, and gravitational energy densities? Which, if any, are the magnetic field properties (i.e., strength and morphology) capable of driving such oscillations (e.g., helical fields)? Can an evolutionary sequence with line-mass (or density) as the determining parameter be identified in high-mass filaments? How do the large-scale magnetic properties of filaments connect to the individual polarization properties observable in high mass cores? CST SHARC-II polarization observations will directly address these questions; thus it is imperative to establish a solid foundation for such observations. As noted above the CST is scheduled to arrive in Chile in 2018 ; now is the time to prepare. ALMA polarization observations toward individual massive clumps (identified e.g., at 250 μm) will be proposed for and carried out in parallel with the development and study of the CST polarization samples.

3. Implementation plan.

The expected length of this program is 2 years. The host institution is the Department of Astronomy at the Universidad de Concepcion. Because this program requires telescope proposals and data acquisition, applicants with already formulated samples of and/or ideas for target lists will be in an advantageous position. The fundamental outcome of this program will be to empirically measure the properties of high-mass filaments and their star formation content. A key aspect of this program it that as observers the P.I.s Amelia Stutz and Xuepeng Chen are ideally suited to guide the candidate in the ambitious goal of generating robust observational measurements of physical conditions in massive star forming filaments. Like Dr. Stutz, Co-P.I. Xuepeng Chen, based at Purple Mountain Observatory is an expert in (sub)mm observations of star forming regions. Close contact with theorists, both internationally and specifically here at Universidad de Concepcion – Prof. Dominik Schleicher is an expert in MHD simulations of turbulence and magnetic fields – will allow the candidate to take this observational line of attack on the problem of high mass star formation to a higher level.

While intelectual freedom in framing problems will be provided, and independence is expected, we also anticipate working in close collaboration with the successful candidate on this dynamic and multi-wavelength program. The proposal P.I.s will provide the intelectual framework and environment to carry out this program effectively. This will be accomplished via regular skype (or similar) project meetings between all persons involved, which will ultimately result in joint telescope proposal submission, data analysis and interpretation, and publications. In brief, our plan for the 2 year duration of this project is as follows. The first semester will consist of analysis of archival Herschel data, line data suitable for mass and velocity measurements on large scales, and proposal submission (including ALMA). The second and third semester will be dedicated to analysis of new data, the refinement of filament target lists for polarization studies with single dish facilities (CST), as well as proposal submission (including ALMA). In the last semester, analysis of ALMA data (and likely CST and other data), will take place.

4. Public outreach

Work by the P.I. has been the subject of at least 8 press releases, articles, and highlights since 2013. Most recently, the Stutz & Gould Slingshot model was featured on the cover page of the Stern und Weltraum magazine, August 2016 issue[2]. Moreover, the Universidad de Concepcion has an established track record and tradition in public outreach events and teacher training. For example, it has hosted specific workshops aimed at the education of school teachers, providing both modern teaching material and equipment. These have taken place in the framework of the "Escuelas de Verano", with over 150 participants in 2016. Key to these activities is the role of the Concepcion Astronomy department public outreach officer Marllory Fuentes and teacher training organizer Renee Manteluna. Building on this basis, within the framework of the work proposed here, the PI will be responsible for fomenting and coordinating the future development of star formation education curricula and public outreach activities highlighting and promoting work by the successful postdoctoral researcher. These activities will project new and exciting results that come out of the work proposed here and in addition, the candidates Spanish skills permitting, will provide valuable direct experience with public outreach.

[2] Slingshot work highlighted as the cover article of Stern und Weltraum Astronomy magazine, August 2016 issue: http://www.spektrum.de/magazin/modelle-der-sternentstehung/1414187