# Properties of the Cores and Filaments in the Ophiuchus Molecular Cloud and its L1688 Hub-filament System Postprint

**Authors:** Bo-Sheng Jia, Guo-Yin Zhang, Alexander Men' shchikov, Sami Dib, Jin-Zeng Li et al.

**Date:** 2025-09-28T12:32:54+00:00

## Abstract

Analyzing filaments and cores in molecular clouds is key to understanding galactic star formation and its environmental dependence. This paper studies the properties and distribution of dense cores and filaments in the Ophiuchus molecular cloud, with a focus on the L1688 hub-filament system (HFS) and its star formation potential. We extracted sources and filaments from Herschel images and a 13. 5 resolution surface density map using the getsf method, identified dense cores among the extracted sources, evaluated core mass segregation, and constructed the core mass function (CMF). We derived properties of the filaments from their radial surface density profiles, constructed the filament linear density function (FLDF), and assessed the mass distribution in the L1688 HFS to estimate the core and filament formation efficiencies (CFEs, FFEs). We identified 64 protostellar, 132 prestellar, and 686 unbound cores. The CMF of the prestellar cores has a power-law exponent of −0.86, and the FLDF of the densest filaments has a similar slope of −0.97, whereas the CMF of the unbound cores is found to be −1.36. Mass segregation is prominent among the most massive cores, with only slight differences between the bound and unbound cores. The low-mass unbound cores affect the overall spatial distribution. Among the 769 well-resolved filaments, we find a median half-maximum width of 0.12 pc and a median slope of −1.4 for the filament radial profiles. Mass distribution in the L1688 hub is dominated by the filaments, and outside the hub, it is dominated by the molecular cloud background. There exists a strong correlation between FFE and CFE, which reach their respective maxima of 71% and 5% within the hub and decrease to 21% and 0.9% outside it. The results suggest that the gravitational potential in the L1688 HFS influences core clustering in its high-density regions and that the filament-dominated core formation is a key mechanism in star formation within the system.

# Full Text

## Preamble

Research in Astronomy and Astrophysics, 25:085018 (24pp), 2025 August © 2025. National Astronomical Observatories, CAS and IOP Publishing Ltd. All rights, including for text and data mining, AI training, and similar technologies, are reserved. Printed in China. https://doi.org/10.1088/1674-4527/ade383 CSTR: 32081.14.RAA.ade383 aaaaaaa Properties of the Cores and Filaments in the Ophiuchus Molecular Cloud and its L1688 Hub-filament System Bo-Sheng Jia (贾博生)1,2,9,10aa, Guo-Yin Zhang (张国印)2aa, Alexander Men' shchikov3aa, Sami Dib4aa, Jin-Zeng Li (李金增)2aa, Ke Wang (王科)5aa, Di Li (李菂)6,2,7aa, Xue-Mei Li (李雪梅)2aa, Zhi-Yuan Ren (任致远)2aa, Chang Zhang (张昶)8aa, Nageen Pervaiz2aa, and Lin Xiao (肖琳)1,9,10aa

## 1 Department of Physics, Hebei University, Baoding 071002, China

2 National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China; zgyin@nao.cas.cn, ljz@nao.cas.cn 3 Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM, 91191, Gif-sur-Yvette, France; alexander.menshchikov@cea.fr

## 5 Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China

6 New Cornerstone Science Laboratory, Department of Astronomy, Tsinghua University, Beijing 100084, China

## 8 School of Aerospace Science, Harbin Institute of Technology, Shenzhen 518055, China

9 Hebei Key Laboratory of High-Precision Computation and Application of Quantum Field Theory, Baoding 071002, China

## 10 Hebei Research Center of the Basic Discipline for Computational Physics, Baoding 071002, China

Received 2025 April 7; revised 2025 May 13; accepted 2025 May 26; published 2025 July 11

## Abstract

Analyzing filaments and cores in molecular clouds is key to understanding galactic star formation and its environmental dependence. This paper studies the properties and distribution of dense cores and filaments in the Ophiuchus molecular cloud, with a focus on the L1688 hub-filament system (HFS) and its star formation potential. We extracted sources and filaments from Herschel images and a 13 5 resolution surface density map using the getsf method, identified dense cores among the extracted sources, evaluated core mass segregation, and constructed the core mass function (CMF). We derived properties of the filaments from their radial surface density profiles, constructed the filament linear density function (FLDF), and assessed the mass distribution in the L1688 HFS to estimate the core and filament formation efficiencies (CFEs, FFEs). We identified 64 protostellar, 132 prestellar, and 686 unbound cores. The CMF of the prestellar cores has a power-law exponent of $-0.86$, and the FLDF of the densest filaments has a similar slope of $-0.97$, whereas the CMF of the unbound cores is found to be $-1.36$. Mass segregation is prominent among the most massive cores, with only slight differences between the bound and unbound cores. The low-mass unbound cores affect the overall spatial distribution. Among the 769 well-resolved filaments, we find a median half-maximum width of 0.12 pc and a median slope of $-1.4$ for the filament radial profiles. Mass distribution in the L1688 hub is dominated by the filaments, and outside the hub, it is dominated by the molecular cloud background. There exists a strong correlation between FFE and CFE, which reach their respective maxima of 71% and 5% within the hub and decrease to 21% and 0.9% outside it. The results suggest that the gravitational potential in the L1688 HFS influences core clustering in its high-density regions and that the filament-dominated core formation is a key mechanism in star formation within the system.

Key words: stars: formation -ISM: molecules -infrared: ISM

## 1. Introduction

Stars form within the densest areas of molecular clouds, known as dense molecular cores, where their self-gravity overcomes the gas pressure and all other supporting forces, thereby leading to their collapse and the formation of stars (Williams et al. 2000; Bergin & Tafalla 2007; Dib et al. 2008; André et al. 2014; Heyer & Dame 2015).

Over the last decade, filamentary structures of molecular clouds gained significant attention as the key sites of core formation, playing a crucial role in the process of star formation. Filaments are now considered to be ubiquitous in star-forming regions and are thought to channel material from the diffuse interstellar medium into the densest regions, where prestellar cores emerge and eventually form stars (André et al. 2010; Molinari et al. 2010; Arzoumanian et al. 2011; Zhang et al. 2020; Ren et al. 2023). Analyses of observations with the Herschel Space Observatory have shown that these filaments typically exhibit a characteristic width of 0.1 pc, across different environments and cloud types, suggesting a common formation mechanism (Arzoumanian et al. 2019; André et al. 2022). However, this typical width has been debated (Panopoulou et al. 2017, 2022), as interferometric observations using dense gas tracers (e.g., N2H+ and NH3) in regions such as Orion and Serpens South have revealed significantly narrower filament widths (Fernández-López et al. 2014; Hacar et al. 2018; Monsch et al. 2018).

Mass distribution of cores within filaments is described by the core mass function (CMF), which for some star-forming regions was shown to have a shape similar to that of the Galactic field stellar initial mass function (IMF), particularly at its high-mass end (Motte et al. 1998; Könyves et al. 2015). Understanding the connection between the CMF and IMF is essential, as the CMF likely represents the initial conditions for the processes governing star formation, especially the influence of molecular cloud structures on the distribution of core masses and the IMF, remain topics of active investigation (Shu et al. 1987; Krumholz 2014; Dib 2023; Zhang et al. 2024). Numerous studies suggest the fragmentation of filaments into prestellar cores is a hierarchical process driven by the interplay of gravitational instability and turbulence (Padoan & Nordlund 2002; Hennebelle & Chabrier 2008). However, understanding the detailed physical processes that link filaments, core formation, and their subsequent evolution into stars remains an area of ongoing research (André 2017).

The Ophiuchus molecular cloud, at its distance d   144 pc (Zucker et al. 2020), is a perfect target for studying low-mass star formation, because of its proximity and rich population of prestellar and protostellar cores (Wilking et al. 2008; André et al. 2014). A census of the starless, prestellar, and protostellar cores from the multiwavelength Herschel Gould Belt Survey (HGBS) images was done by Ladjelate et al. (2020) using the source and filament extraction methods (Men' shchikov et al. 2012) and getfilaments getsources (Men'shchikov 2013). Previous studies, based on the Herschel images, have revealed a complex filamentary network in Ophiuchus, with the L1688 region identified as a hub-filament system (HFS) where multiple filaments converge and drive star formation (Ladjelate et al. 2020). These dense filaments concentrate material and are conducive to core formation and star formation as shown by the tight core–filament correlation in Ophiuchus (Ladjelate et al. 2020).

In this work, we used the new source and filament extraction method getsf11 (Men' shchikov 2021b) with significantly improved algorithms over those used by Ladjelate et al. (2020). The getsf method separates the structural components of sources, filaments, and backgrounds before extracting both cores and filaments within a consistent approach, which results in their more accurate detection and measurement (Men' shchikov 2021a). Benchmark tests (Men' shchikov 2021a) show that getsf achieves a completeness of about 60%–70% for core detection in complex backgrounds, with measurement uncertainties of 5%-10%. In simple backgrounds, the completeness exceeds 80%. By comparison, getsources reaches 50%–70% completeness and systematically underestimates source sizes by approximately 20%. Furthermore, getsf enables accurate extraction of filamentary structures, with width uncertainties of 10%–20%, whereas getsources treated filaments as part of the background and failed to reconstruct their structures reliably. Crucially, the tools used by Ladjelate et al. (2020) did not support radial filament measurements, making such analyses unfeasible. In contrast, getsf allows us to quantitatively characterize filament radial profiles and derive new physical parameters. We also employed the maps of H2 surface densities and dust temperatures created at a high 13 5 resolution with the hires method (Men’ shchikov 2021b), in contrast to the 18 2 resolution adopted by Ladjelate et al. (2020). The higher angular resolution enables the identification of finer structural details and a more accurate detection and measurement of both cores and filaments. The enhanced sensitivity and ability to detect faint, complex filamentary structures are paramount in refining the characteristics of the L1688 HFS, hence in understanding the mechanisms driving star formation and the role of these structures in regulating the star formation efficiency (SFE). Detailed studies of core mass segregation and filament alignment within the HFS are essential for advancing our knowledge of star formation processes in this region (Dib & Henning 2019; Kumar et al. 2020).

In Section 2, we present the Herschel dust continuum data for the Ophiuchus molecular cloud and the construction of the high-resolution surface densities. Section 3 describes the extraction of sources and filaments, the identification of reliable cores and filaments, their measured properties, CMFs, linear density functions (FLDFs). Section 4 and filament analyzes the L1688 hub morphology, spatial distribution and mass segregation of starless cores, radial structure of the hub, and core and filament formation efficiencies (CFEs, FFEs). In Section 5, we discuss the implications of the CMF, FLDF, mass segregation, and their roles in the filament-driven core formation in the L1688 HFS. Key results and conclusions are summarized in Section 6.

## 2. Observational Data

The Ophiuchus molecular cloud is one of the regions mapped in the HGBS (André et al. 2010). The observations were carried out using the Photodetector Array Camera and Spectrometer (PACS; Poglitsch et al. 2010) and the Spectral and Photometric Imaging Receiver (SPIRE; Griffin et al. 2010) in the parallel mode with a scanning speed of 60  s−1. The resulting PACS data at 70 and 160  m have the angular resolutions of 8 4 and 13 5, respectively, whereas the SPIRE data at 250, 350, and 500  m have the resolutions of 18 2, 24 9, and 36 3, respectively.

The data products were retrieved from the Herschel Science Archive (using the level 2.5 data).12 Specific observations for different parts of the Ophiuchus cloud include L1688, observed in 2010 September (IDs 1342205093 and 1342205094) and L1712 (IDs 1342204088 and 1342204089). For the Northern Streamer, the observations were done in 2011 February (IDs 1342214577 and 1342214578). An additional observation was conducted in 2012 March to address incomplete coverage in the PACS 70 and 160  m bands at the overlapping areas of these three regions (IDs 1342241499 and 1342241500).

We used the montage software13 to stitch the level 2.5 images into a complete map of the Ophiuchus cloud (Figure A1), applying background corrections at the overlapping edges to eliminate jagged noise structures. The Ophiuchus cloud covers an area of approximately 26 deg2 at 70 and 160  m, and approximately 27 deg2 at 250–500  m. Derivation of high-resolution images of surface densities and temperatures (at 13 5, Appendix A) consisted of estimating zero offsets by comparing the Herschel data with the Planck data (e.g., Bernard et al. 2010; Bracco et al. 2020) and pixel-by-pixel spectral energy distribution (SED) fitting using the hires algorithm (Men’ shchikov 2021b). Consistency of temperature measurements across different wave bands and Fourier analysis of surface density maps are discussed in Appendix A.

## 3.1. Source and Filament Extraction

Sources and filaments were extracted with the multiscale, multiwavelength method getsf (Men’ shchikov 2021b). For the detection of both sources and filaments, we used the Herschel images at 250, 350, and 500  m, along with the 13 5 surface density map. Sources were measured in all Herschel images (70–500  m) and the surface densities, whereas filaments were measured only in the image of surface densities.

The single free parameter of getsf, a maximum size of the structures to be extracted in an image, was visually constrained from the observed images as the radius of the footprint (full extent of the structure) of the largest source or filament of interest. A value 4 times the maximum size sets practical upper limits on the largest scales to be processed in the spatially decomposed images during separation of structural components and detection of sources and filaments (Section 3.1.3 in Men’ shchikov 2021b). We adopted the source maximum sizes of 13 , 90 , 120 , 160 , and 240  for the images at 70–500  m, respectively, and 90  for the 13 5 resolution map of surface densities. The sizes (widths) of filaments of interest were set to 15 , 110 , 150 , 200 , and 300  for the images and 110  for the surface densities.

Observed peak emission of the relatively hot protostars and their parent cores (with colder dust) can appear at slightly different positions across different wavelengths, mainly because of the differences in angular resolutions. Protostars are usually identified by their emission at shorter wavelengths, such as 70  m, where the internal heating by accretion energy makes them more prominent (André et al. 2010; Hennemann et al. 2010). Accordingly, we separated protostars from starless cores by detecting protostars in the 70  m Herschel image (Könyves et al. 2015).

## 3.2. Selection of Candidate Cores

Sources are defined in getsf as the emission peaks with relatively circular intensity profiles, which are significantly stronger than the local background and noise fluctuations (Men’ shchikov et al. 2012). In total, getsf extracted 2758 sources. To remove possible spurious detections and have only the reliable and well-measurable sources, we applied the basic (weak) selection criteria described in Men’ shchikov (2021a).

For each acceptably good source, we required that (for the integrated flux) signal-to-noise ratios monochromatic detection significance $\Xi > 1$ and goodness $\Gamma > 1$. These criteria were applied to the sources measured at 160-500  m, and in the 13 5 surface densities. We also employed stronger selection criteria (see Equation (1) in Men’ shchikov 2021a), based on benchmarking results. They require that the ratio of the major and minor half-maximum sizes $AB-1 < 2$ (source footprint not too elongated), and the footprint size obeys $AF\ A-1 > 1.15$ (footprint not too small). A source was considered a candidate core if it satisfied the basic selection criteria in at least two different wave bands and in the 13 5 surface densities, as well as the benchmark selection criteria in at least one wave band. With the above criteria, we identified 882 candidate cores, displayed in Figure 1 [Figure 1: see original paper]. Individual images of each candidate core in each band and in the 13 5 surface density map have also been used for examination, as illustrated in Figure 2 [Figure 2: see original paper].

Following the methodology employed in the HGBS studies (e.g., Könyves et al. 2015), we performed an additional source extraction in the 70  m image and identified protostars by requiring that the sources exhibit narrow peaks with relatively round shape: their average half-maximum sizes and major to minor size ratio $AB-1 < 1.3$. To further refine the sample, we cross-referenced these sources with the SIMBAD database14 and the NASA/IPAC extragalactic database (NED),15 excluding galaxies and other non-stellar objects.

## 3.3. Nature of Extracted Cores

Starless cores are cold, dense regions in space, devoid of significant infrared emission at wavelengths $\lambda$   160  m because of the absence of internal heat sources; they represent the earliest stage in star formation. Such cores are further categorized as the gravitationally bound, prestellar cores that are likely to collapse and form stars, and unbound starless cores, which may disperse with time (Alves et al. 2001; Bergin & Tafalla 2007; Ward-Thompson et al. 2007; André et al. 2014).

Protostellar cores represent a more advanced stage than the starless cores in the star formation process, because they contain an accreting stellar embryo or protostar at their centers (di Francesco et al. 2007; Evans et al. 2009). Gas and dust in these cores are actively accreted by the protostar that gradually accumulates its mass (Andre et al. 2000; Dunham et al. 2014). In our analysis, the candidate cores are classified as protostellar ones if they contain a protostar within them, manifested by a detectable and measurable peak at 70  m (Figure 2). We found 64 protostellar cores.

The stability of the prestellar cores is often determined using the Bonnor–Ebert (BE) model, which describes the equilibrium between gas pressure and self-gravity in isothermal, hydrostatic spheres (Ebert 1955; Bonnor 1956). Although this is a simplified model that neglects turbulence (Galli et al. 2002; Ballesteros-Paredes et al. 2003; Dib et al. 2007b; Li et al. 2013) and magnetic fields (Dib et al. 2010a), it is widely used to approximately estimate the mass sufficient for the onset of core collapse. The critical mass can be expressed as M_{BE} = (c_s^2 R_{BE})/G, where c_s is the sound speed, R_{BE} the BE sphere radius, and G the gravitational constant. We adopted the sound speed c_s for a temperature of 10 K and approximated R_{BE} by the deconvolved half-maximum size R = (H^2 - O$^{2)}$(1/2), where H = (AB)^(1/2) is the geometric mean of the major and minor half-maximum sizes A and B of the cores from their surface densities (resolution O = 13.5 ). The approximation is valid to within 20% (Figure 4 [Figure 4: see original paper] in Men' shchikov 2023). To avoid large errors, we deconvolved only the partially resolved and resolved cores with H $>$ 1.1 O, whereas for the unresolved cores with H $\leq$ 1.1 O we arbitrarily adopted R = H (Men' shchikov 2023).

Masses M of the cores were derived by fitting their SEDs, using the background-subtracted fluxes F_T measured in the 160, 250, 350, and 500 m wave bands. We employed the fitfluxes utility from the getsf software, applying a modified optically thin blackbody model (thinbody, Men'shchikov 2016). We adopted the distance d = 144 pc to the Ophiuchus molecular cloud and _ = _0 ( / _0)^$\beta$, where is the frequency, the dust opacity _0 = 0.1 cm^2 g^$-$1 (per gram of dusty gas), _0 = 10^3 GHz, and $\beta = 2$. The fitting provided the estimated core masses M, mass-averaged dust temperatures T, and the associated uncertainties. It is necessary to emphasize that the mass uncertainties are usually large (at least a factor of 2–3, Men' shchikov 2016).

We denote starless cores with the ratio $\alpha${BE} = M{BE}/M $\leq$ 2 as the "robust" prestellar cores, because the BE sphere represents an equilibrium solution, where the gravitational stability is more stringent than the virial mass condition for a core to be gravitationally bound (Li et al. 2013). We identified 85 robust prestellar cores. Furthermore, studies of the Aquila and California molecular clouds (Könyves et al. 2015; Zhang et al. 2024) suggested that using the $\alpha$_{BE} $\leq$ 2 condition might be overly conservative for identifying the gravitationally bound cores. Following Zhang et al. (2024), we adopted the modified empirical critical value $\alpha$*c = 10 (O/H) that is inversely proportional to the core resolvedness (defined as H/O, Men' shchikov 2023) in surface densities. With the additional condition 2 <* $\alpha${BE} $\leq$ $\alpha$*c, we identified 47 candidate prestellar cores. The remaining 686 unbound starless cores (with* $\alpha${BE} > $\alpha$_c) are unlikely to collapse and form stars. The spatial distribution of all identified cores and the core mass–size diagram are presented in Figures 1 and 3, respectively.

## 3.4. Mass Functions of the Cores

The CMF is defined as the number of cores per unit mass interval and its high-mass part is usually approximated by dN/dlogM M^$\delta$. This form is compatible with the Salpeter IMF for stars ($\delta = -1.35$) and it captures the observed power-law distribution of core masses in molecular clouds (Salpeter 1955; Motte et al. 1998; Johnstone et al. 2000; Dib et al. 2008; Ballesteros-Paredes et al. 2020). The CMF of the entire sample of starless cores in the Ophiuchus molecular cloud displays a slope $\delta = -0.53 \pm 0.03$ for the masses in the range 0.04-10 M (Figure 4), much shallower than that of the Salpeter IMF. However, the most massive prestellar cores of 1-20 M reveal a substantially steeper CMF with $\delta = -0.86 \pm 0.12$, whereas the sample of unbound cores shows $\delta = -1.36 \pm 0.17$, essentially the Salpeter slope.

To better understand these results, we spatially separated the CMFs for two regions of the Ophiuchus molecular cloud, above and below a certain surface density level of the cloud. With a core background value Σ_D 2 × 10^{22} cm^−2, chosen as the level dividing the high- and low-density regions, most of the robust prestellar cores are found in the hub and densest filaments outside it, whereas most of the unbound starless cores are located in the lower-density area of the map in Figure 1. In a range of surface densities within a factor of two above and below Σ_D, relatively small fractions of the unbound and bound cores co-exist with the candidate prestellar cores. The spatially separated CMFs are very similar to those in Figure 4, therefore they are not presented here.

The steep CMF of the unbound starless cores suggests that the cores represent low-background density enhancements of the Ophiuchus molecular cloud. Indeed, Herschel observations clearly demonstrated that such interstellar clouds spatially fluctuate quite significantly on all scales. On the other hand, the shallow CMF slopes of the prestellar cores must be related to their formation in the high-density areas. The shallow CMF of prestellar cores in the Ophiuchus cloud is similar to that presented by Ladjelate et al. (2020). It is relevant to note that recent ALMA-IMF observations (Pouteau et al. 2022; Louvet et al. 2024) also found a similar slope ($\delta = -0.97$) for dense regions of high-mass star formation.

An important uncertainty, implicitly present in the astrophysical interpretations of CMFs, is that the masses derived by the SED fitting of integrated fluxes may be insufficiently accurate to make reliable conclusions. The biases and wide ranges of errors associated with the masses (Men' shchikov 2016) can significantly redistribute the cores between the mass bins and distort the shape of an observationally determined mass function with respect to the true CMF of the observed objects.

When analyzing and interpreting derived CMFs, observational studies often employ simulated images populated with radiative-transfer models of sources and/or filaments. Extractions in such images allow us to judge how complete the extracted set of dense cores can be and below what limiting mass M_0 the fraction of extracted cores or filaments starts to rapidly drop. However, it is a non-trivial problem to construct simulated images closely resembling the observed set of sources and filaments.

In the absence of a satisfactory, accurate solution of the problem, we decided not to perform the simulations for completeness evaluation in this work. However, we scaled the limiting masses M_0 of prestellar cores, obtained in previous studies of nearby star-forming regions, to the distance of the Ophiuchus molecular cloud to see whether its CMF (Figure 4) is compatible with the previously published CMFs. The scaled values turned out to be fairly consistent with each other: for the California region (Zhang et al. 2024) it scales to M_0 = 0.1−0.2 M , for the Aquila region (Könyves et al. 2015) to M_0 = 0.1 M , and for the Orion B region (Könyves et al. 2020) to M_0 = 0.14 M . Taking into account that the values may be underestimated by roughly a factor of 2–3, we presume that they are likely to point to M_0 0.4-0.6 M for prestellar cores for the Ophiuchus cloud. The value is in the mass bin (Figure 4), where the CMF starts to deviate from the high-mass power law and to morph into a shape reminiscent of the log-normal curve. Similarly, the CMF of the unbound starless cores deviates from the power law at much lower masses M < 0.04 M , where our population of extracted starless cores becomes incomplete.

## 3.5. Filaments and Their Properties

Filaments in molecular clouds are significantly elongated structures (e.g., Figure 5 [Figure 5: see original paper]) that are thought to play a fundamental role in the process of star formation (Men'shchikov et al. 2010; André et al. 2014; Zhang et al. 2024). Observations of nearby molecular clouds with Herschel suggested that widths W of the filaments are distributed in a relatively narrow range around 0.1 pc (Arzoumanian et al. 2011, 2019). Filaments are believed to form via an interplay of various physical processes that include supersonic turbulence, gravitational collapse, and magnetic fields (see André 2017). Concentrations of gas and dust within the filaments lead to the formation of prestellar cores that eventually collapse and form stars (Könyves et al. 2015; Zhang et al. 2020).

Accurate detection of the filaments is complicated by the fact that they are blended with other filaments and various nearby structures on the complex backgrounds in the Herschel images. Measurements of the filament properties are also made inaccurate by background subtraction, when their true background is unknown (complex) and can only be guessed. Further difficulties are caused by the significantly nonuniform angular resolutions in the far-infrared wave bands. Images become much less sharp at longer wavelengths with lower angular resolutions, which aggravates the problems in distinguishing overlapping and intertwined filaments (Men' shchikov 2023). Moreover, filaments are three-dimensional structures that are interpreted on the basis of their observed two-dimensional projections.

Filamentary structures are observed on quite different spatial (angular) scales (see Figure 13 [Figure 13: see original paper] in Men' shchikov 2021b). Filaments in the Ophiuchus molecular cloud were extracted using getsf, simultaneously with the source extraction. In this paper, we analyzed the filaments that are most prominent and detectable around spatial scales 110 (corresponding to the filament widths of 0.08 pc) (Figure 5). To exclude spurious detections, we selected only those filaments whose skeletons are traceable in at least five consecutive spatial scales (a factor of 1.3 in the scales). Some visually obvious but faint filaments were not detected (e.g., Figure 5), primarily because the getsf algorithm employs a multiscale analysis combined with stringent signal-to-noise criteria when extracting filament skeletons. Although such filaments appear visible in the filament component map, they do not show up in the final skeleton map (Men' shchikov 2021b). At each individual spatial scale, getsf applies a cleaning threshold: only signal peaks exceeding the local background noise by approximately $2\sigma$ are retained as candidate filaments. If a faint filament falls below this threshold at any given scale, it is treated as noise and removed, thereby weakening its continuity and significance across multiple scales. To simplify the complex network of detected skeletons, getsf eliminates their intersections, thereby creating a non-branching set of skeletons tracing the "elementary filaments." Surface density measurements for each filament were taken in the images where the sources had been removed and large-scale backgrounds subtracted. Radial density profiles were taken along the normals to the filament skeletons and, to ensure reliable measurements, only sufficiently isolated and well-resolved filaments were selected.

Following Zhang et al. (2024), we deemed a one-sided profile of a filament acceptably good if the profile on that side extended to values below its half-maximum and the width was narrower than twice the width determined from the opposite side. To exclude the profiles contaminated by background fluctuations or blending with other nearby filaments, we considered only the one-sided profiles that met these requirements. If both sides of a filament profile were acceptably good, the width W was estimated as the arithmetic average of the one-sided median half-maximum widths W_A and W_B. With this approach, we identified 769 filaments with measurable widths that met these criteria, whose average profiles are displayed in Figure 6 [Figure 6: see original paper].

In our analysis, the filament widths W and crest surface densities Σ_C refer to the values averaged over the entire filament length. The widths are distributed in a range 0.02 W 0.4 pc and become exponentially less abundant beyond a median width of 0.12 pc (Figure 7 [Figure 7: see original paper]). On average, filaments have a tendency to have larger W (by a factor of 4) when Σ_C increases by three orders of magnitude (Figure 8 [Figure 8: see original paper]).

Although the median width is consistent with that found by Arzoumanian et al. (2011, 2019), the agreement should not be interpreted as the confirmation of the previous findings of the quasi-universal width of filaments in star-forming regions. It is rather the consequence of our choice of the size of filaments of interest (110 ) in the getsf filament extraction. An investigation of the dependence of the filament properties on spatial scales will be made in our next paper.

Slopes of the filament radial profiles Σ(r) r^$\gamma$ are defined as $\gamma$ = d ln Σ / d ln r. In practice, we evaluated the one-sided slopes in the range 0.3 ≤ Σ/Σ_C ≤ 0.6 to exclude the inner flattened parts of the profiles, as well as their much fainter outer segments that are increasingly affected by the spatial fluctuations of surface density of the molecular cloud and inaccuracies of background subtraction. Only the slopes for the filaments with acceptably good one-sided widths were evaluated. If both sides of a filament had acceptable widths, then we adopted an arithmetically averaged slope. With this approach, we identified 443 filaments with measurable slopes, distributed in a relatively wide range −3.4 γ −0.6 with a median value of −1.4 (Figure 7). The surface density slopes correspond to the volume density profiles (r) r^ with −4.4 −1.6 and a median value of −2.4, similar to that found by Arzoumanian et al. (2011, 2019). The filament slopes are practically invariant with the crest surface densities (Figure 8).

It is useful to define contrasts of filaments as C = Σ_C/Σ_B, where Σ_B is the average background surface density along their skeletons. We can also define a representative average linear density of the set of filaments, used for illustration purposes in our paper, as Λ = m_H Σ_C W , where is the mean molecular weight of gas per H2 molecule and m_H is the hydrogen mass. The relationship between the filament contrast and the surface density Σ_C or representative linear density Λ is displayed in Figure 9 [Figure 9: see original paper]. The data show a clear positive correlation between C and both Σ_C and linear density, which implies higher contrast values as filaments accumulate more material. Figure 9 also shows an inverse relationship between the average crest dust temperatures T_C and the surface (or linear) densities. The crest temperature decreases by roughly 10 K as Σ_C increases by three orders of magnitude. As expected, the denser filaments shield their interiors from external radiation more efficiently, which leads to lower dust temperatures.

## 3.6. Linear Density Function of the Filaments

Filamentary structures in molecular clouds are essential for understanding the star formation processes, because dense cores are usually found (and presumably formed) within dense filaments (André et al. 2014; Könyves et al. 2015). The FLDF is an important characteristic of the distribution of filaments over their linear densities Λ, similar to the CMF (Zhang et al. 2024). Defined analogously, it also shows a power-law distribution at high linear densities. Analyses of Herschel observations showed that −1.5 for dense filaments with Λ Λ_c 16 M pc^−1 (André et al. 2019a; Zhang et al. 2024). Filaments with such linear densities are expected to become gravitationally unstable and fragment into dense cores (e.g., Zhang et al. 2020). However, the critical value Λ_c 16 M pc^−1 may be uncertain within a factor of 3 (e.g., Li et al. 2023) and, therefore, it should be considered only as a rough indicator of filament instability.

The linear densities of 769 measurable filaments were computed by getsf as the ratio of the filament mass M_F to its length L_F (Men' shchikov 2021b). For more accurate results, we selected one-sided measurements of Λ or arithmetic averages from both filament sides, following the approach we used to select the well-measurable widths of filaments (Section 3.5). In other words, we adopted a good median width of a filament as a proxy to determine the goodness of linear density measurements. The FLDF for the Ophiuchus molecular cloud shows a shallow slope of −0.70 ± 0.08 in the range of linear densities 2 < Λ < 300 M pc^−1 (Figure 10 [Figure 10: see original paper]). The densest, likely gravitationally unstable filaments with $\Lambda_c < \Lambda < 300$ M pc$^{-1}$ display a steeper slope of $-0.97 \pm 0.12$.

In principle, local physical conditions in filaments must be more relevant for the onset of instabilities and fragmentation of the filaments into cores than average properties of the entire (sometimes long) filaments. We explored this idea by producing another FLDF based on short segments of the filaments. Following the approach used by Zhang et al. (2024), we segmented all filaments into 0.1 pc chunks, a scale of the typical half-maximum width of the observed filaments. As shown in Figure 10, the segmented filaments produced an almost identical shape with the slopes of $-0.70 \pm 0.08$ for $\Lambda > 2$ M pc$^{-1}$ and $-1.03 \pm 0.09$ for $\Lambda > \Lambda_c$. The two approaches give, therefore, consistent results for the Ophiuchus cloud.

## 4. Structural Analysis of the L1688 HFS

HFSs are the regions within molecular clouds where multiple filaments converge, characterized by high surface densities and compact rounded morphologies (Myers 2009; Schneider et al. 2012; Peretto et al. 2014; Chen et al. 2019; Dib et al. 2020; Kumar et al. 2020; Xu et al. 2023). In star-forming regions such as L1688 in the Ophiuchus molecular cloud, short, high-density filaments form hub networks (Figure 5) rather than single massive clumps (Kumar et al. 2020). Hubs concentrate mass and serve as the sites for star formation, facilitating the coalescence of filaments and directing the flow of material that leads to the formation of dense cores (Schneider et al. 2012; Kumar et al. 2020).

### 4.1. The Hub Morphology

Figure 11 [Figure 11: see original paper] delineates the hub shape and extent in the surface density map with two ellipses, defined at $2.5\sigma$ and $5\sigma$ fluctuation levels, where $\sigma = 10^{21}$ cm$^{-2}$ was estimated in the source- and filament-free regions. The ellipses have semimajor and semiminor axes of 2400  and 1700  (1.7 and 1.2 pc) and 1400  and 1000  (1.0 and 0.7 pc) and they are centered at R.A. = 16h27m04s and decl. = −24°30 45 . The smaller ellipse (position angle PA = 135°) includes the inner dense area of the hub and the larger ellipse (PA = 90°) encompasses the entire hub extent (see Figure 15 [Figure 15: see original paper]). A cross-verification with the low-resolution Planck data contours confirmed the ellipse parameters. It is worth noting that the hub extent in the L1688 region is similar to that measured by Dib et al. (2020) for the hubs in Cygnus-X North.

The L1688 hub encloses dense filamentary structures that are roughly parallel to the major axis of the inner ellipse (Figure 5), as indicated by the position angles of filamentary structures in the L1688 HFS. Two prominent peaks in the filament orientations within the hub are almost orthogonal to each other, at PA  135° and 50° (Figure 12 [Figure 12: see original paper]). A significant fraction of the filamentary structures outside the hub region is also aligned at PA  50°. The orientations are found to be non-random, consistent with previous studies that found alignments of filaments in star-forming regions (Goldsmith et al. 2008; Palmeirim et al. 2013).

These results suggest that the filamentary structures in the L1688 HFS exhibit a non-random, preferential alignment, particularly outside the central hub, which might indicate the influence of the hub's gravitational potential or other localized processes affecting the alignment of filaments. We refer to André (2017) for a discussion of the gravitational and magnetic effects on filament alignment.

## 4.2. Spatial Distribution of Cores

The structure parameter Q is a quantitative measure for assessing the spatial distribution of stars within clusters, particularly in distinguishing between centrally condensed and fractal-like substructured configurations. It has been widely applied in the analysis of both young and evolved star clusters (Fernandes et al. 2012; Gouliermis et al. 2012; Delgado et al. 2013; Parker et al. 2014; Gregorio-Hetem et al. 2015; Dib et al. 2018), as well as in studies of the spatial distribution of dense cores and young stars in star-forming regions, such as Aquila, Taurus, Orion B, and W43 (Gutermuth et al. 2009; Alfaro & Román-Zúñiga 2018; Parker 2018; Dib & Henning 2019), and distant massive clumps (Xu et al. 2024).

The parameter Q is defined as the ratio of the normalized mean edge length of the minimal spanning tree (MST) to the normalized correlation length of the star cluster: $Q = (\bar{m}/\sqrt{(A/N_{tot})}) / (\bar{s}/R)$, where $\bar{m}$ represents the mean edge length of the MST, normalized by $\sqrt{(A/N_{tot})}$, with A denoting the cluster area and $N_{tot}$ the total number of stars. The mean separation between stars $\bar{s}$ is normalized by the overall cluster radius R (Cartwright & Whitworth 2004). The parameter Q is particularly valuable in distinguishing cluster morphologies; $Q > 0.8$ values are typically associated with centrally condensed clusters that exhibit a smooth radial density gradient following a power-law distribution $r^{-\alpha}$. In contrast, $Q < 0.8$ values suggest a more hierarchical or fractal structure characterized by significant subclustering (Cartwright & Whitworth 2004; Schmeja & Klessen 2006).

The Q values obtained for the entire ensemble of starless cores, prestellar cores, and unbound cores are 0.61, 0.63, and 0.60, respectively. The relatively higher Q value for the prestellar cores suggests a slightly more evolved and centrally concentrated state, compared to a more dispersed distribution of the unbound cores. The unbound cores are more numerous, therefore they heavily influence the overall distribution, resulting in a close resemblance of the Q value for the entire sample to that of the unbound cores.

## 4.3. Mass Segregation of Cores

The Q parameter does not contain information about the core mass segregation. The mass segregation ratios $\Lambda_{MSR}$ and $\Gamma_{MSR}$ provide quantitative measures of how the massive cores are distributed relative to the lower-mass ones (Allison et al. 2009).

The mass segregation ratio is defined as Λ_{MSR} = l_{norm} *{rand} / l*{norm} *{massive}, where the numerator is the average MST length for a randomly selected subset of cores and the denominator is that for the most massive cores. Values Λ*{MSR} > 1 indicate mass segregation, when the massive cores are more centrally concentrated. Conversely, Λ_{MSR} < 1 points to inverse mass segregation, when the massive cores are less centrally concentrated, whereas Λ_{MSR} 1 suggests a random distribution of massive cores. Some studies suggested, however, that mass segregation corresponds to Λ_{MSR} > 2 (e.g., Dib & Henning 2019). The MST-based mass segregation description was refined by Olczak et al. (2011) in a parameter Γ_{MSR}. The redefinition, which incorporates the use of a geometric mean as an intermediate step, enhanced the method sensitivity, enabling a more robust detection of lower levels of mass segregation.

Mass segregation in star-forming regions and clusters was evaluated using these methods by several groups (Dib et al. 2018; Parker 2018; Dib & Henning 2019; Sadaghiani et al. 2020; Paulson et al. 2024). Notably, Dib & Henning (2019) provided a comprehensive analysis of mass segregation in star-forming regions, particularly focusing on the correlation between the structure of molecular clouds and their star formation activity. They found that regions of star formation with higher surface densities (such as W43) exhibit higher levels of mass segregation, with massive cores being more centrally concentrated. In contrast, regions like Taurus with low star formation activity show no significant mass segregation, evidenced by Λ_{MSR} and Γ_{MSR} close to unity.

Figure 14 [Figure 14: see original paper] displays the mass segregation ratios for the entire set of 818 starless cores, 132 (candidate and robust) prestellar cores, and 686 unbound cores in the Ophiuchus molecular cloud. We calculated Λ_{MSR} and Γ_{MSR} for both prestellar and unbound cores by selecting 100 random sets of n_{MST} cores from the 818 starless cores. Using the same parent sample for random selection facilitates comparison of the segregation values for the sub-samples of cores. The results for the entire set of starless cores show very significant mass segregation (Λ_{MSR} 4–5 and Γ_{MSR} 5–10) for up to n_{MST} 40. The mass segregation of the most massive cores continuously declines until larger numbers of n_{MST} are included.

The mass segregation essentially vanishes for n_{MST} 300, declining until (Λ_{MSR}, Γ_{MSR} → 1). The sample of prestellar (candidate and robust) cores (Figure 14) is mass-segregated almost identically to the entire set of extracted cores for n_{MST} 100. The strongest mass segregation is exhibited by the 60 most massive prestellar cores with M > 0.5 M (Figure 4), indicating that the cores are spatially clustered. In contrast, the sample of unbound starless cores shows a more dispersed spatial distribution for n_{MST} 100 with very low or no mass segregation (Λ_{MSR} 1.5 and Γ_{MSR} 2). Therefore, mass segregation is the property that markedly separates the (more massive) prestellar cores from the unbound cores.

## 4.4. Radial Distribution of Filament and Core Properties

The properties of filaments and cores significantly depend on the distance from the L1688 hub center. Figure 15 shows the radial dependence of the filament crest surface densities $\Sigma$_C, average linear densities $\Lambda$ , and the stability parameter *$\alpha${BE} for the starless cores. The $\Sigma$_C values of all 769 measurable filaments were averaged within concentric rings of 1 pixel width, originating at the hub center, whereas the* $\alpha${BE} values correspond to each of the selected 818 starless cores.

With increasing distance, both $\Sigma$_C and $\Lambda$ decrease almost by two orders of magnitude (Figure 15), revealing a well-developed Gaussian-like (Plummer) profile $\Sigma$_C(r) of the hub and a transition from its dense structures to the less dense filaments in the molecular cloud outside the hub (r $>$ 1 pc). There are several clear, relatively strong peaks in $\Sigma$_C(r) outside the hub (at r 3, 7, and 18 pc), that correspond to the dense parts of the filamentary structures in the Ophiuchus molecular cloud (Figure 5).

The gravitational stability parameter *$\alpha${BE}(r) reveals that most of the bound starless cores tend to reside within the hub area (Figure 15). Although there is a large scatter in* $\alpha${BE}, on average the values tend to significantly increase toward larger distances from the center, indicating that the starless cores tend to become progressively less bound within the hub and mostly unbound outside it. Distribution of the masses M(r) of starless cores within the hub is (approximately) inversely proportional to r (Figure 15), although there is a large scatter in the masses. Outside the hub, the core masses remain much scattered, but tend to follow a shallower average distribution. The population of candidate and robust prestellar cores is mostly located inside the hub and at two radial locations outside it (r 3 and 7 pc). The fact that the two radii coincide with the peaks in $\Sigma$_C(r) indicates that the prestellar cores belong to the dense filaments found in the molecular cloud at these distances from the hub (Figure 5).

## 4.5. Core and Filament Formation Efficiencies

The Herschel images and surface density map were decomposed by getsf into separate images of the structural components of sources, filaments, and their backgrounds (Men' shchikov 2021b). Based on the component separation, we analyzed the radial mass distribution of the structural components, examining the CFE and FFE as functions of the radial distance from the hub center. The formation efficiencies are defined as the mass ratios of the dense cores and filaments to the total mass of the molecular cloud (Zhang et al. 2018).

Our results show that both CFE and FFE in the Ophiuchus molecular cloud vary significantly with the radial distance r from the hub center (Figure 15). The

CFE values display much larger fluctuations than the FFE values do, because of the much greater spread of the core masses M than of the surface densities Σ_C within the circular annuli (Figure 15). On average, however, CFE and FFE demonstrate quite similar behaviors, decreasing from the maximum values at the hub center toward much lower values at the hub boundary and in the cloud outside the hub, where they exhibit several local peaks. This is likely due to the elongated and asymmetric distribution of filaments around the hub, which causes locally enhanced core formation along certain directions. It should be noted that a particularly prominent peak at a radial distance of 3 pc corresponds to the eastern and southeastern parts of the cloud, where the nearby star-forming regions L1709 and L1689 are located. These regions host multiple filaments and dense cores, which contribute significantly to the elevated CFE and FFE at that distance. Logarithmic values of FFE and CFE are positively correlated within the hub (Pearson correlation coefficient p = 0.78), whereas the correlation becomes weaker outside the hub (p = 0.52). The significant correlation suggests that the filamentary hub may be enhancing the efficiency of star formation processes.

## 5.1. CMF, FLDF, and Their Implications for Star Formation

Empirical and numerical studies of the CMF consistently show that the number of cores declines with increasing mass, particularly at the higher-mass end of the mass distribution (Klessen et al. 2005; Dib et al. 2008; André et al. 2010; Anathpindika 2013). A power-law behavior is thought to result primarily from the self-similar and hierarchical nature of turbulence and fragmentation in molecular clouds (Larson 1981; Elmegreen & Falgarone 1996; Padoan & Nordlund 2002; Federrath & Klessen 2012; Myers 2014). The CMF is often seen as a precursor to the IMF, suggesting that the stellar mass distribution is inherited from the mass distribution of prestellar cores (Alves et al. 2007; Zhang et al. 2024).

Our analysis (Section 3.4) reveals relatively shallow slopes of the CMF of prestellar cores ($\delta$ $-0.53$ to $-0.86$) in the Ophiuchus molecular cloud, compared to the IMF ($\delta = -1.35$), consistently with several other observational studies of star-forming regions (Li et al. 2007; Zhang et al. 2015, 2018; Marsh et al. 2016; Pouteau et al. 2022). The shallow slopes might suggest that the relationship between CMF and IMF depends on some additional factors, such as the environments and evolution of the cores. Gas accretion by the cores can play a pivotal role in the transition from the CMF to the IMF by allowing the cores that are near the critical mass for collapse to grow and eventually form stars (McKee & Ostriker 2007; Hennebelle & Chabrier 2008; Dib et al. 2010b). In the densest environments, collisions between the cores can lead to the formation of more massive cores and to modifications of the CMF shape inherited from turbulent fragmentation (Dib et al. 2007a; Dib 2023).

Additionally, other theoretical and numerical studies have demonstrated that feedbacks from stellar winds, radiation, and outflows can significantly alter core growth by restricting accretion and potentially dispersing the low-mass cores (Dale et al. 2005; Krumholz & McKee 2005; Padoan et al. 2017).

However, the CMFs based on the masses derived by SED fitting may not be accurate enough (Section 3.4) to draw reliable conclusions on star formation. Errors and biases of the derived masses (Men’ shchikov 2016) can redistribute the cores between the mass bins with respect to the true CMFs of the physical objects and alter the intrinsic shape of the mass functions. Nevertheless, if the adopted mass bins are larger than or comparable to the typical uncertainties in mass, the overall shape of the CMF remains relatively robust, as individual cores are unlikely to move across multiple bins due to uncertainties alone. Simulated images may not be fully consistent with the observed images, therefore the limiting mass obtained in core extraction completeness simulations may be inaccurate. For these reasons, while the CMF provides useful insights into the core population, we stress the need to be cautious in its astrophysical interpretations and to keep in mind that the observationally derived mass functions may still carry significant implicit uncertainties.

Our MST analysis (Sections 4.2 and 4.3) reveals a clustered distribution of massive cores in the Ophiuchus molecular cloud, indicating a higher degree of central concentration driven primarily by core mass. This central clustering enhances the gravitational potential, facilitating further accretion by massive cores and reinforcing the link between the CMF and IMF. While some massive cores remain unbound, they are expected to become bound within $10^{3-10}4$ yr through continued accretion (e.g., Zhang & Tan 2011; Zhang et al. 2023). Regions with deeper gravitational potentials, associated with higher star formation rates, facilitate this process, consistent with observations in other star-forming regions (Parker & Goodwin 2015; Dib & Henning 2019). However, the MST also identifies a significant fraction of spatially dispersed, low-mass unbound cores that are unlikely to accumulate enough mass to become bound, consistent with findings that many low-mass cores do not evolve into stars (Padoan & Nordlund 2002; di Francesco et al. 2007; Ward-Thompson et al. 2007; Offner et al. 2014).

FLDFs offer an additional perspective on mass distribution along filaments in molecular clouds, complementing insights from the CMFs (André et al. 2019a; Zhang et al. 2024). For the Ophiuchus molecular cloud, we found the FLDF with power-law slopes  $= -0.70$ to $-0.97$ (Section 3.6), similar to those of the CMF and shallower than the Salpeter slope. Hierarchical filamentary structures, shaped by turbulent processes, can lead to a broad range of filament linear densities $\Lambda$ with a power-law distribution (Padoan & Nordlund 2002; Hennebelle & Chabrier 2008). Filaments with supercritical $\Lambda >$ $\Lambda$_c are more prone to gravitational fragmentation into dense cores. The shape of the resulting CMF could be consistent with the distribution of $\Lambda$ (masses per unit length) of their parent filaments. This would be in line with the central role of gravitational instability in the formation of cores (Inutsuka & Miyama 1997; André et al. 2014; Toci & Galli 2015; Zhang et al. 2020). Other star-forming regions, such as the California molecular cloud, also show strong correlations between $\Lambda$ and core formation, with the denser filaments preferentially forming more massive cores (Zhang et al. 2024). The shallower slopes of both the FLDF and CMF in Ophiuchus reinforce the idea that the filament properties significantly impact core mass distribution (André et al. 2010; Roy et al. 2015). Limited sensitivity and angular resolution of observations and the structural complexity of the dense molecular clouds affect the observed slopes by under-representing the lower-density filaments and lower-mass cores and underestimating their masses (André et al. 2014; Arzoumanian et al. 2019; Men’ shchikov 2023).

Our results emphasize significant roles of the core mass segregation, gravitational potential, and local environments in determining the evolution of starless cores and the eventual stellar population. CMFs and FLDFs are useful tools, but their predictive power is limited, particularly for the low-density filaments and low-mass cores, affected by incomplete sampling. For a more comprehensive understanding of star formation we need to take into account both the environmental factors and physical properties and processes governing the dynamical evolution (e.g., turbulence, gas pressure, temperature gradients, and gravitational collapse) that would determine whether the filaments would eventually fragment into cores and whether the latter would ultimately form stars.

## 5.2. Filament-driven Core Formation in the L1688 HFS

The filament alignment within the L1688 HFS reveals two distinct position angle peaks at PA 50° and 135°, suggesting that external forces influence their orientation. The primary component at PA 135° aligns with the orientation of the main axis of the hub (Figure 11). The PA 50° component is suggestive of a directed material flow roughly from the northeast side, because the opposite southwest side displays almost no alignment of filaments in that direction (Figure 5).

Such an asymmetry could be created by the influence of large-scale external forces, likely from the nearby Sco OB2 association, located at a distance of 11 ± 3 pc from the Ophiuchus molecular cloud. The Sco OB2 association exerts feedback pressure on L1688, compressing the molecular cloud and facilitating the formation of dense filamentary structures (Howard et al. 2021). The region between the B stars S1 and HD 147889 shows signs of localized heating and compression, which supports the idea that external feedback has its role in shaping the filaments (e.g., Abergel et al. 1996; Liseau et al. 1999; Wilking et al. 2008). Such feedback could enhance star formation by enhancing the density of filaments and material accretion into the hub, contributing to the observed high SFE (Schneider et al. 2010; Peretto et al. 2013). The external pressure from Sco OB2 likely plays a critical role in determining both the orientation and mass distribution within the filaments, significantly impacting star formation processes in L1688 (Loren & Wootten 1986; Abergel et al. 1996; Motte et al. 1998; Liseau et al. 1999; Johnstone et al. 2000; Nutter et al. 2006).

Besides the external feedback from Sco OB2, effects of the magnetic fields and gas accretion on the filament orientations must also be considered. The magnetic fields are known to guide the flow of gas along filaments, where their alignment is controlled by the interaction between magnetic tension and gravitational forces. In star-forming regions, the magnetic fields can align either parallel or perpendicular to filaments, depending on the local density, influencing filament orientation (Palmeirim et al. 2013; André et al. 2019b). Studies like Planck Collaboration et al. (2016) show that the magnetic field orientations vary significantly between molecular clouds, shaping their filamentary structures. Gas accretion in the radial direction toward dense filamentary structures can increase the gravitational potential of hubs and align filaments toward the dense regions of star formation. Observations from systems like Taurus B211/B213 and California supercritical filaments suggest that such accretion is ongoing, with filaments acting as conduits for material flow (Palmeirim et al. 2013; Shimajiri et al. 2019; Zhang et al. 2020). Theoretical models support these ideas, with simulations of molecular cloud collapse showing that accretion onto filaments aligns with the observed mass inflow rates in star-forming environments (Gómez & Vázquez-Semadeni 2014; Vázquez-Semadeni et al. 2019).

Our analysis of the radial distribution of filaments indicates that the filaments inside the L1688 hub are dense and tightly packed, likely because of gravitational forces pulling the cloud material inward. With increasing distance from the hub center, the filament density decreases and they take a more diffuse configuration. This pattern is consistent with observations in other HFS regions, such as Serpens and Mon R2 (Kirk et al. 2013; Kumar et al. 2022). The positive correlation between FFE and CFE underscores the critical role of filaments in organizing mass and facilitating core formation. Regions dominated by diffuse gas exhibit lower CFE and FFE, indicating the importance of dense filaments for core collapse and efficient star formation. The high CFE within the hub (reaching 5%) demonstrates the efficiency of such filamentary environments in the production of prestellar cores. The significant decline of CFE outside the hub may support the hierarchical star formation model, where filaments act as the mass reservoirs that feed star-forming regions (Schneider et al. 2012; Chen et al. 2019; Kumar et al. 2020; Ren et al. 2021, 2023). Our results suggest that the formation of prestellar cores in the L1688 HFS is predominantly driven by the filamentary structures that efficiently channel material into the hub.

## 6. Conclusions

This study used the getsf extraction method to analyze the Herschel observations of the Ophiuchus molecular cloud, with a focus on the L1688 HFS. By examining the structural and physical properties of the extracted filaments and cores, we derived the following results.

A total of 882 candidate cores were identified, including 85 robust prestellar cores, 47 candidate prestellar cores, 686 unbound starless cores, and 64 protostellar cores. A substantial fraction of the low-mass unbound cores (78%) suggests that they will likely dissipate, rather than form stars individually.

The CMF of the starless cores follows a power-law distribution with a relatively shallow slope of $\delta = -0.53$ over the masses M of 0.04–10 M , compared to the Salpeter IMF with $\delta = -1.35$. Although the most massive prestellar cores with $M > 1$ M display a steeper power law with $\delta = -0.86$, the latter is still significantly shallower than the IMF slope.

Spatial distribution of the starless cores in the Ophiuchus molecular cloud indicates substructured, fractal-like configurations (Q 0.61). Mass segregation is prominent among the most massive cores, with only slight differences between the gravitationally bound and unbound cores. The low-mass unbound cores significantly influence the overall spatial distribution. Central clustering of the massive cores enhances the gravitational potential and promotes accretion in high-density regions, such as the L1688 HFS.

We identified 769 well-resolved filaments that have measurable widths, with a median half-maximum value W = 0.12 pc, and 443 filaments that have measurable slopes of their profiles, with a median value $\gamma = -1.4$ that corresponds to a power-law exponent $= -2.4$ of the volume density profiles. On average, the filament widths tend to increase by a factor of 4 with crest surface densities in the range of $10^{\{20\}\text{-}10}$\{23\} cm^−2, whereas the slopes show almost no average trends with the surface densities, although there is a large scatter in both quantities.

The FLDF of the filaments reveals a power-law shape with a relatively shallow slope of $= -0.70$ over the linear densities $\Lambda$ of 2–300 M pc^−1, consistent with the CMF slope that we find for the starless cores. The dense filaments with $\Lambda >$ Λ_c 16 M pc^−1 display a steeper power law with $= -0.97$, also similar to the CMF slope for the massive prestellar cores with $M > 1$ M .

The filament and core formation efficiencies (FFE, CFE) in the Ophiuchus molecular cloud strongly depend on the radial distance from the hub center and are positively correlated. The CFE reaches high values of 5% within the dense hub (r 0.85 pc), whereas it decreases to 0.9% in the molecular cloud outside the hub. The FFE is as high as 71% within the dense hub and it decreases to 21% outside the hub, reflecting a transition from the filament-dominated hub to the background-dominated cloud at larger distances.

Filaments seem to play a central role in concentrating mass and driving the core formation, particularly within dense star-forming hubs. They accrete gas, thereby promoting their gravitational fragmentation and the subsequent clustering of cores. An important problem is to study the feedback effects and how they affect the core and filament evolution.

Expanding the sample size for various environments and incorporating regions at different distances are important for testing the general validity of our results and conclusions.

## Acknowledgments

This work was supported by the National Natural Science Foundation of China (NSFC, No. 12588202). D.L. is a New Cornerstone investigator. G.-Y.Z. acknowledges additional support from the China Postdoctoral Science Foundation (No. 2021T140672), and the NSFC (No. U2031118). K.W. acknowledges support from the NSFC (Nos. 12041305 and 12033005), the China-Chile Joint Research Fund (CCJRF No. 2211), and the Tianchi Talent Program of Xinjiang Uygur Autonomous Region.

This work was also supported by the Key Project of International Cooperation of the Ministry of Science and Technology of China under grant No. 2010DFA02710, as well as by the NSFC under grants 11503035, 11573036, 11373009, 11433008, 11403040, and 11403041. This work was carried out at the China-Argentina Cooperation Station of NAOC/CAS.

We acknowledge contributions of the Herschel Gould Belt Survey (HGBS) consortium and all researchers involved in the observations and data processing of the Ophiuchus molecular cloud, which laid down the foundation of this work. This research utilized data from the HGBS project, a Herschel Key Program conducted by the SPIRE Specialist Astronomy Group 3 (SAG 3), along with scientists from the PACS Consortium (CEA Saclay, INAF-IFSI Rome, INAF-Arcetri, KU Leuven, MPIA Heidelberg) and the Herschel Science Centre (HSC).

## Appendix A High-resolution Surface Densities

Surface density maps are important for understanding the structure and physical properties of the cold interstellar medium. Derivation of the maps involves estimating zero offsets of images of a certain region by comparing them with the Planck images of the same region (e.g., Bernard et al. 2010; Bracco et al. 2020). High-resolution surface density and temperature maps are then computed by fitting the spectral shapes of pixel intensities using the hires method (Men' shchikov 2021b).

### A.1. Zero Offsets for Herschel Images and Derivation of Surface Densities and Temperatures

Herschel imaged the Ophiuchus molecular cloud within its large 3.5 m aperture, in the wavelength range from 70 to 500 m (see Figure A1). However, the observational technique used by the Herschel instruments could not guarantee accuracy of the intensities at the largest spatial scales. This deficiency could be reasonably well corrected using the so-called Planck offsets (Griffin et al. 2010; Poglitsch et al. 2010). Planck conducted an all-sky unbiased survey within its relatively small 1.5 m aperture, providing images with a much lower, 5 angular resolution. The data, officially released by Planck, are well-calibrated (Planck Collaboration et al. 2014), hence they can serve as a reliable standard for correcting the Herschel images at their largest spatial scales.

For the purpose of deriving the Planck offsets for the Herschel images, certain dust opacities and temperatures must be adopted, describing the physical properties of the observed region. The process involves calculation of the Planck images at the Herschel wavelengths, using the dust optical depth *$\tau${353} GHz (at 850 m) and temperature T from the Planck observations (Planck Collaboration et al. 2014) and assuming the optically thin blackbody radiation: I_* = $\tau${353} GHz B_ (T), where is the frequency corresponding to the wave bands of the Herschel images and B_ (T) is the blackbody intensity at the temperature T. Adopting $\beta = 2$ and _0 = 353 GHz, we obtain the optical depth directly from the Planck images and, therefore, we calculate the Planck images at the Herschel wavelengths. The Herschel observation maps are then smoothed and resampled to match the Planck pixels. The offsets between the Herschel and Planck images are calculated as their median differences over all pixels for each wavelength (Figure A2). The resulting offsets of 134.2, 37.2, 12.8, and 3.5 MJy sr^−1 at 160, 250, 350, and 500 m, respectively, were added to the Herschel images to create the high-resolution surface density and temperature maps.

The hires algorithm derives the high-resolution surface density and temperature images from multiwavelength far-infrared observations assuming optically thin dust emission. The images are resampled to a common (the smallest) pixel size and then convolved to all available angular resolutions of the Herschel images. The spectral shapes of pixel intensities in the observed images are then fitted with a modified blackbody using the fitfluxes utility (Men' shchikov 2016), assuming that the dust opacity is _$\lambda$ = 0.1 ($\lambda$/300 m)^−2 cm^2 g^−1 (per gram of dusty gas). The hires algorithm obtains a series of surface density and temperature images for available combinations of the wavelengths (Men' shchikov 2021b). Making differential improvements to the image with the lowest angular resolution of 36.3 , it produces additional images with higher resolutions of 13.5 , 18.2 , and 24.9 . For an illustration, Figure A3 displays the surface density and temperature maps with a resolution of 13.5 .

### A.2. Consistency Checks for the Derived Surface Densities and Temperatures

Overall compatibility of the images with added offsets can be tested with a simple approach (Men' shchikov 2021b). When all four images are convolved to the 36.3 resolution of the 500 m image, a pixel-to-pixel SED fitting of the three pairs of images (160, 250 m), (250, 350 m), and (350, 500 m) must give the same temperatures, if the images are consistent and the fitting model and assumptions are realistic. This can be verified in an average sense, using a median value of the relative differences between the derived temperature images in each pixel, for each of the pairs. For the (160, 250 m) images, we find the median temperature of 19.55 K, for the (250, 350 m) images, the median temperature of 19.89 K, and for the (350, 500 m) images, the median temperature of 19.95 K. These median values imply no serious inconsistency in the images and offsets used in the derivation of the surface densities and temperatures.

We computed Fourier amplitudes and power spectra for surface density maps of the L1688 region at resolutions of 13.5 , 18.2 , 24.9 , and 36.3  (Figure A4) to visualize the differences between high-resolution and low-resolution images. The power spectra confirm that the higher-resolution images capture finer details with larger Fourier amplitudes at higher spatial frequencies and that at much lower spatial frequencies, representing larger-scale structures, the values are almost the same across the different resolutions. This is because the hires method integrates the higher-resolution contributions into the lower-resolution surface densities, accumulating them to enhance the accuracy and resolution of the resulting images.

To verify consistency of the surface densities and temperatures of the Ophiuchus cloud, derived from the Herschel observations, we computed the Planck surface densities Σ_P from the 353 GHz (850  m) image of optical depths τ*{353} (Planck Collaboration et al. 2014), where Σ_P =* τ{353}/ _{353}, with  _{353} being the dust opacity defined in Appendix A.1. We smoothed the surface densities and temperatures derived from Herschel observations to the angular resolution of the Planck images and computed their relative differences in each pixel. Figure A5 demonstrates that the differences between the two are mostly within  20% in the surface densities and within  10% in the dust temperatures. The largest differences are found in the low surface density areas and/or close to the edges of the Herschel coverage (Figure A3). However, the main area of the surface density image of the Ophiuchus molecular cloud, where we performed our source and filament extractions, has substantially smaller differences with the Planck data.

## Appendix B Catalogs of the Extracted Cores and Filaments in Ophiuchus

Using the getsf method with the Herschel SPIRE and PACS images of the Ophiuchus molecular cloud, we extracted 882 reliable cores and 769 well-resolved filaments. A template of the online catalog with the observed properties of the cores is provided in Table B1, with one protostellar core (illustrated in Figure 2) included as an example. Tables B2 and B3 present templates of the derived properties of cores and filaments, respectively. Tables B1–B3 were generated by fitfluxes, smeasure, and fmeasure, respectively, the utilities from the getsf software. The notation follows the conventions from Men'shchikov (2021b), and the formatting is consistent with Li et al. (2023). The tables illustrate the contents of the full catalog, which is available online at https://www.scidb.cn/en/s/Y3AFv2.

### Table B1

Catalog of 882 Reliable Cores Identified in the Multiwavelength Herschel Maps of the Ophiuchus Molecular Cloud (Template, Full Catalog only Provided Online at https://www.scidb.cn/en/s/Y3AFv2)

[Table content preserved exactly as in original]

**Table B2**

Derived Properties of 882 Reliable Cores Identified in the Multiwavelength Herschel Maps of Ophiuchus Molecular Cloud (Template, Full Table only Provided Online at https://www.scidb.cn/en/s/Y3AFv2)

[Table content preserved exactly as in original]

**Table B3**

Catalog of the 769 Well-resolved Filaments Identified in the Multiwavelength Herschel Maps of the Ophiuchus Molecular Cloud (Template, Full Catalog only Provided Online at https://www.scidb.cn/en/s/Y3AFv2)

[Table content preserved exactly as in original]

## References

[References preserved exactly as in original]

*Note: Figure translations are in progress. See original paper for figures.*