INTERSTELLAR FILAMENT PARADIGM

on their formation, evolution, and role in star formation

Nagoya University, Japan, November 5-9, 2018

Oral presentations

Day 1: Monday, November 5

[IT] **Philippe André** – CEA Saclay - Lab. Astrophysique (AIM)

Herschel observations of the filamentary paradigm for star formation

Herschel imaging surveys of Galactic molecular clouds have emphasized the quasi-universality of the filamentary texture of the cold ISM and the key role of filaments in the star formation process. I will summarize the latest findings of a systematic Herschel census of filamentary structures and prestellar cores in nearby molecular clouds, which identified more than 600 filaments and more than 1200 prestellar cores in 8 regions covered by the Gould Belt survey. I will then discuss the implications of the Herschel results for our understanding of filament evolution and star formation along filaments. Overall, the observations support a picture in which molecular filaments and prestellar cores represent two fundamental steps in the star formation process: First, large-scale compression of interstellar material in supersonic MHD flows generates a cobweb of filaments in the cold ISM; second, the densest filaments fragment into prestellar cores (and subsequently protostars) by gravitational instability, while simultaneously growing in mass and complexity through accretion of background cloud material. This filamentary paradigm provides new insight into the origin of the stellar initial mass function and the efficiency of star formation in the dense molecular gas of galaxies.

[CT] **Eun Jung Chung** – Korea Astronomy and Space Science Institute

Physical properties of filaments and dense cores in L1478

Formation of filaments and subsequent dense cores in ISM is one of the essential questions to address in star formation. To investigate this scenario in detail, we recently started a molecular line survey namely 'Filaments, the Universal Nursery of Stars (FUNS)' toward nearby filamentary clouds in Gould Belt using TRAO 14m single dish telescope equipped with a 16 multi-beam array. In the present work, we report the first look results of kinematics of a low mass star forming region L1478 of California molecular cloud. This region is found to be consisting of long filaments with a hub-filament structure. We performed On-The-Fly mapping observations covering ~1.1 square degree area of this region using C18O(1-0) as a low density tracer and 0.13 square degree area using N2H+(1-0) as a high density tracer, respectively. CS (2-1) and SO (32-21) were also used simultaneously to map ~290 square arcminute area of this region. We identified 10 filaments applying Dendrogram technique to C18O data-cube and 13 dense cores using FellWalker and N2H+ data set. Basic physical properties of filaments such as mass, length, width, velocity field, and velocity dispersion are derived. It is found that filaments in L1478 are velocity coherent and supercritical. Especially the filaments which are highly supercritical are found to have dense cores detected in N2H+. Non-thermal velocity dispersions derived from C18O and N2H+ suggest that most of the dense cores are subsonic or transonic while the surrounding filaments are transonic or supersonic. We concluded that filaments in L1478 are gravitationally unstable which might collapse to form dense cores and stars. We also suggest that formation mechanism can be different in individual filament depending on its morphology and environment.

[CT] **Tsuyoshi Inoue** – Nagoya University
with Patrick Hennebelle, Yasuo Fukui, Tomoaki Matsumoto, Kazunari Iwasaki, Shu-ichiro Inutsuka

The Formation of Massive Magnetized Filaments and Massive Stars Triggered by a MHD Shock Wave

Abstract Since supersonic turbulence is general in molecular clouds, shock waves propagate ubiquitously in molecular clouds. In this paper, the influence of a shock wave on the evolution of a molecular cloud is studied by using isothermal magneto-hydrodynamics (MHD) simulations with the effect of self-gravity (Inoue et al. 2018). Adaptive-mesh-refinement and sink particle techniques are used to follow long-time evolution of the shocked cloud. We show that the shock compression of turbulent inhomogeneous molecular cloud creates massive filaments, which lie perpendicularly to the background magnetic field. The massive filament shows global collapse along the filament, which feeds a sink particle located at the collapse center. We find that the collapse of the filament is started when the line mass of the filament becomes larger than the critical line-mass of magnetized filament derived analytically by Tomisaka (2014). This indicates that the critical line-mass of the massive filament is controlled mainly by magnetic field. We observe a high accretion rate $M_{\rm acc} > 10^{-4} M_{\rm sun}$/yr that is high enough to allow the formation of even O-type stars. The most massive sink particle achieves $M > 50 M_{\rm sun}$ in a few times 10^5 yr after the onset of the filament collapse.

[CT] **Volker Ossenkopf-Okada** – Physikalisches Institut, Universität zu Köln
with Rodion Stepanov, Nicola Schneider

Measuring the distribution of filament widths through anisotopic wavelets

We propose a new wavelet-based method to quantify filaments in any two-dimensional data set. It measures the spatial, size, and angular distribution of any collection of filaments. Comparing the resulting local and global degree of anisotropy characterizes the mutual alignment of the filaments. Applying the method to column density maps derived from Herschel continuum observations shows no universal filament width but strongly varying properties for different regions. In many cases we see that the spectrum of filament widths extends down to the resolution limit tracing striations, fibres or other substructures. By comparing the power of perturbations in isotropic and anisotropic modes we can measure the relative importance of spherical and cylindrical collapse modes and their spatial distribution. Filamentary collapse dominates for large parts of the maps analysed, spherical collapse modes are only faster at filament edges and in some extended cloud configurations.

[CT] **Alexander Howard** – School of Physics and Astronomy, Cardiff University
with Kenneth Marsh, Seamus Clarke, Anthony Whitworth, Matt Griffin, Oliver Lomax

The Taurus L1495 filament: not so massive after all

The standard procedure for estimating column density from sub-mm dust continuum observations is to fit an SED to each pixel, assuming a uniform dust temperature and a uniform dust emissivity index (beta) along each line of sight, and convolving all images to the coarsest resolution. However, these assumptions are unlikely to hold in turbulent filaments, and the convolution results in data loss, producing inaccurate column density estimates. Furthermore, in the standard procedure, beta and temperature are intrinsically anti-correlated, making spatial mapping of both quantities extremely difficult and unreliable. We use the Bayesian fitting algorithm PPMAP on the Taurus L1495 filament to produce differential column density maps as functions of temperature and beta, utilising Herschel's multi-wavelength observations at their native resolutions to provide better estimates of column density. This gives the distribution of different dust components along the line of sight within the star forming region, and thereby allows us to constrain the evolution of dust. It also allows us to distinguish sub-structure on a much smaller scale than previously possible. This is done by dropping the assumptions of the standard procedure, and it resolves the temperature/beta degeneracy mentioned above (as evidenced by a positive correlation between temperature and beta in PPMAP results). Thus PPMAP provides a method of examining the internal structure of L1495, which up to now has been impossible with the standard procedure. We find L1495 to have a significantly narrower width (0.051 pc) than previously reported, and a significantly lower column density, with a large quantity of gas at 15K. We also find the filament to be thermally sub-critical. In addition, we show a spatial correlation between temperature and beta, which is a possible indicator for grain growth in the densest regions. Our angular resolution is a factor 3 better than previous analyses using the same data.

[CT] **Kristina Monsch** – University Observatory, Ludwig-Maximilian-University Munich (USM-LMU)
Jaime E. Pineda, Hauyu Baobab Liu, Catherine Zucker, Hope How-Huan Chen, Kate Pattle et al.

Dense gas kinematics and a narrow filament in the Orion A OMC1 region using NH3

We present combined observations of the NH3 (J,K) = (1,1) and (2,2) inversion transitions towards OMC1 in Orion A obtained by the Karl G. Jansky Very Large Array (VLA) and the 100 m Robert C. Byrd Green Bank Telescope (GBT). With an angular resolution of 6" (0.01 pc), these observations reveal with unprecedented detail the complex filamentary structure extending north of the active Orion BN/KL region in a field covering $\sim 6' \times 7'$. We find a 0.012 pc wide filament within OMC1, with an aspect ratio of $\sim 37:1$, that was missed in previous studies. Its orientation is directly compared to the relative orientation of the magnetic field from the James Clerk Maxwell Telescope BISTRO survey in Orion A. We find a small deviation of ~ 11 deg between the mean orientation of the filament and the magnetic field, suggesting that they are almost parallel to one another. The filament's column density is estimated to be 2-3 orders of magnitude larger than the filaments studied with Herschel and is possibly self-gravitating given the low values of turbulence found. We further produce maps of the gas kinematics by forward modeling the hyperfine structure of the NH3 (J,K) = (1,1) and (2,2) lines. The resulting distribution of velocity dispersions peaks at ~ 0.5 km/s, close to the subsonic regime of the gas. This value is about 0.2 km/s smaller than previously measured in single-dish observations of the same region, suggesting that higher angular and spectral resolution observations will identify even lower velocity dispersions that might reach the subsonic turbulence regime in dense gas filaments.

[CT] **Patrick Hennebelle** – CEA
with Eva Ntormousi, Philippe André

Formation of self-gravitating and non-self-gravitating filaments
I will discuss how filaments form, what is the role of turbulence, magnetic field, ion-neutral friction and self-gravity in the filament evolution.

[IT] **Kazunari Iwasaki** – Osaka University

The formation of massive filaments by shock compression
The interstellar medium is frequently compressed by shock waves due to supernovae, super-bubbles, and galactic spiral waves. Shock compressions make gases dense and create favorable conditions for the star formation. Inoue & Fukui (2013) found that shock compression produces massive filamentary molecular clouds (filaments) which hold massive cores. In this work, we focus on the formation of massive filamentary molecular clouds by shock compression. To model shock compression, we consider a converging large-scale magnetized flow. The deformation of the shock fronts by the upstream turbulence generates transverse converging flows along the magnetic field as shown in Inoue & Fukui (2013). The converging flows create super-critical massive filamentary structures. We found that a weaker upstream magnetic field creates more entangled magnetic fields inside the massive filaments. The magnetic field outside the massive filaments become coherent by stretching due to the converging flows. Because the massive filaments are super-critical, they collapse dynamically. If gas density exceeds a critical density, the collapse proceeds keeping plasma beta almost unity, regardless of the upstream field strength. The critical density is proportional to the upstream ram pressure. During the global collapse, the massive filaments split into smaller filaments whose line masses are roughly 1.5 times critical one. The factor of 0.5 comes from the additional support by magnetic fields. From each of the small filaments, dense cores form, indicating that the fragmentation proceeds a hierarchical manner.

[CT] **Yoshito Shimajiri** – CEA/Saclay
with Ph. Andre, P. Palmeirim, D. Arzoumanian, A. Bracco, V. Konyves, E. Ntormousi, and B. Ladjelate

Probing accretion of ambient cloud material into the Taurus B211/B213 filament
The observations of the Herschel Gould Belt survey (HGBS) project revealed an omnipresence of parsec-scale filaments in molecular clouds. Therefore, unveiling how filaments grow in mass is crucial to understand the star formation in the filaments. We found that the cloud depth is estimated to be 0.3 pc while the B211/231 cloud has an extent of >10 pc in the plane of the sky, implying the surrounding cloud is shaped like a sheet. The 12CO (1-0) and 13CO (1-0) position-velocity (PV) diagrams along the perpendicular to the filament show that the surrounding materials on the north and south of the B211/213 filament are redshifted and blueshifted, respectively, and the velocities are gradually approaching to the systemic velocity of the B211/213 filament with the approaching to the B211/213 filament. The 12CO (1-0) and 13CO (1-0) distributions on the PV diagrams have good agreements with that of our toy model of the accretion gas, supporting the scenario of the mass accretion into the B211/213 filament proposed by Palmeirim et al. (2013). Comparison between the distributions of the Finkbeiner Halpha and PLANCK 857 GHz emission in the Taurus-California-Perseus region with a scale of several times 100 pc shows that the B211/213 filament is likely to be formed by the expanding shell generated by the Per OB2 association. From these results, the B211/213 filament is likely to be formed by the large-scale compression and then is growing in mass by the accretion of the surrounding materials by the gravity.

[CT] **Lars Bonne** – Universit de Bordeaux
with Sylvain Bontemps, Nicola Schneider, Timea Csengeri, Hussein Yahia, Guillaume Attuel, Seamus Clarke, Rolf Guesten, Antoine Gusdorf, Robert Simon

Search for filamentary accretion through low-velocity shocks in Musca
A promising scenario for the formation of cold and dense filaments is continuous mass accretion through low-velocity shocks that dissipate the turbulence of the inflowing gas. However, to confirm this dynamic scenario, unambiguous direct evidence of such low-velocity shocks is required. To search for such direct evidence, the

Musca filament is probably the best target because it is free of protostars, presumably located in a low UV-field and isolated from other dense structures that might confuse the analysis. Applying a non-linear, local gradient analysis tool to Herschel images of Musca indicated regions along the entire filament that potentially experience mass accretion through low-velocity shocks. Two of these regions were mapped in CO(4-3) and CO(3-2) with the FLASH instrument on the APEX telescope. This established a second velocity component on top of the known single velocity component in the Musca filament. RADEX simulations showed that this second velocity component comes from a warm and dense gas layer. This warm gas seems difficult to explain with PDR models because Musca is bathing in a low UV field, thus pointing to the detection of warm gas created by low-velocity shocks dissipating turbulence. Furthermore, this second, warm component is not isolated, but rather appears connected to the already known velocity-coherent filament component as a warm shoulder. This might be a spectral indication of the filament accreting this dense shocked gas. Similar behaviour was also found in CO-spectra extracted from recent dynamic filament formation simulations.

[IT] **Georgia Panopoulou** – Caltech

Formulating a null hypothesis for molecular cloud filaments

Observations provide a wealth of diverse information on the morphology and dynamics of filamentary structures in the nearby molecular clouds. With the flood of new results comes the challenge of constructing a comprehensive physical interpretation of the formation and evolution of these structures. In the quest for this comprehensive model, the filamentary paradigm of star formation is undoubtedly in the forefront. Is it successful? We can only know through comparison with another model. Taking a step towards this direction, I will show how (for the case of a single observable, i.e. the widths of dust filaments), the standard interpretation is not unique in terms of reproducing the observations. I will propose a null model, appropriate for the case of molecular cloud filaments, against which existing interpretations can be tested.

[CT]**Jean-Francois Robitaille** – IPAG, University Grenoble Alpes
with Frederique Motte

What if filaments were defined from their background?

What is the connection between filaments and density fluctuations in the diffuse ISM? And how can we define the limits of filamentary structures that are sometimes well embedded in the “diffuse background”? To answer these questions, we need a robust definition of what is an interstellar filament and this definition might be closely link to our understanding of the fluctuating background. During this talk, I will present the powerful structural analysis technique, the Multi-scale non-Gaussian Segmentation (Robitaille, Joncas & Miville-Deschenes 2014). The technique merges the PDF analysis, which forms the foundation of many modern theories of star formation, and the power spectrum analysis, which started with the pioneer work of Andrey Kolmogorov and remains our best tool today to analyse and characterise the turbulence. The segmentation process is based on the analysis of complex wavelet transforms of star forming regions maps. The dual property in the spatial and frequency domain of wavelet transforms allows us to separate the true scale-free interstellar medium, possibly related to incompressible turbulent flows, from denser structures associated with other physical processes as shocks and gravity. Robitaille et al. (2014) showed that this multi-scale segmentation technique lead naturally to the separation of filaments and dense clumps characteristic of star forming regions against a non-uniform background.

This approach has the advantage of characterising the statistical density distribution associated with the filamentary structures and the scale-free background separately. As I will show, this innovative technique allows us to revisit the power spectrum analysis usually reserved for diffuse structures and the PDF analysis often applied on large regions mixing different statistical distributions. It is also the perfect foundation to test the so far postulated analytical theory which links the turbulent fluctuations with the formation of filaments, cores and their relation to the origin of stellar masses (IMF).

Day 2: Tuesday, November 6

[IT] **Alvaro Hacar** – Leiden Observatory
with M. Tafalla, J. Forbrich, J. Alves

Fibers as fundamental building blocks of low- and high-mass filaments

Using single-dish and ALMA molecular observations, we have investigated the internal structure and dynamics of filaments along their entire mass spectrum, from the lowest mass filaments in Taurus to the massive Integral

Shape Filament in Orion. In all cases, the analysis of different line tracers indicates a high level of internal organization in which apparently monolithic filaments are actually collections of small-scale fibers. In both low- and high-mass filaments, fibers are characterized by presenting transonic internal motions respect to their local sound speed and a mass per-unit-length close to hydrostatic equilibrium. Conversely, the fiber dimensions (width and length) appear to be self-regulated depending on their intrinsic gas density of their local environment. Combining observations in different star-forming regions, we identify a systematic increase of the surface density of fibers as a function of the total mass per-unit-length in filamentary clouds. Based on this empirical correlation, we propose a unified star-formation scenario where the observed differences between low- and high-mass clouds, and the origin of clusters, emerge naturally from the initial concentration of fibers.

[CT] **Seamus Clarke** – University of Cologne
with A. Whitworth, R. Spowage, A. Duarte-Cabral, S. Suri, S. Jaffa, S. Walch, P. Clark

Synthetic C18O observations of fibrous filaments: the problems of mapping from PPV to PPP

Molecular-line observations of filaments in star-forming regions have revealed the existence of elongated coherent features within the filaments; these features are termed fibres. Here we caution that, since fibres are traced in PPV space, there is no guarantee that they represent coherent features in PPP space. We illustrate this contention using simulations of the growth of a filament from a turbulent medium. Synthetic C18O observations of the simulated filaments reveal the existence of fibres very similar to the observed ones, i.e. elongated coherent features in the resulting PPV data-cubes. Analysis of the PPP data-cubes (i.e. 3D density fields) also reveals elongated coherent features, which we term sub-filaments. Unfortunately there is very poor correspondence between the fibres and the sub-filaments in the simulations. Both fibres and sub-filaments derive from inhomogeneities in the turbulent accretion flow onto the main filament. As a consequence, fibres are often affected by line-of-sight confusion. Similarly, sub-filaments are often affected by large velocity gradients, and even velocity discontinuities. These results suggest that extreme care should be taken when using velocity coherent features to constrain the underlying substructure within a filament.

[CT] **Michael Mattern** – Max-Planck-Institute for Radioastronomy
with Jens Kauffmann, Timea Csengeri, James Urquhart

The kinematics of dust-detected filaments

It has been proposed that filaments in clouds are a crucial step towards star formation. Filaments are found within almost every molecular cloud. The current paradigm of star formation states a two-step process of clouds forming filaments fragmenting into dense cores, as the sites of star formation. However, the processes leading to filament formation and fragmentation are still not well understood. To fully understand the mechanisms in cloud evolution it is necessary to study a representative and unbiased sample, which is provided by the ATLASGAL filament catalogue (Li et al. 2016). This Galactic-wide catalogue includes 517 dense, filamentary molecular clouds identified in the ATLASGAL 870μm dust emission survey by the DisPerSE algorithm and are confirmed visually by 5 people.

I will present the results of a study, which will provide the first representative statistics on properties of dense, filametary molecular clouds. The 13CO(2-1) and C18O(2-1) data cubes of the SEDIGISM survey (Structure, Excitation, and Dynamics of the Inner Galactic Inter Stellar Medium) (Schulleret al. 2016) allow us to connect them to the larger scale Galactic structure and we are able to analyse the kinematic properties of these targets and to determine physical properties. The survey covers about 280 filaments of the catalogue and will trace the larger, diffuse structure of the filaments. For the first time we analyse: whether the structures identified in continuum maps are coherent in velocity, the physical size and the mass of the filaments based on kinematic distance measurements, and the gravitational stability of the filaments using the ratio of the observed mass per unit length, which is a measurement of the gravitational potential, and the critical line-mass (turbulent and non-turbulent case)

Additionally, I will present the velocity coherent extended Nessie filament, as example of one giant molecular filament (about 240 pc long), which shows parts of different morphologies, hinting on different evolutionary phases.

[CT] **Mike Chen** – University of Victoria
with J. Di Francesco, R. Friesen, J. Pineda, E. Rosolowsky, H. Kirk, J. Keown, and the Green Bank Ammonia Survey team

Kinematics of Velocity-Coherent Filaments in Nearby Clouds

Filaments seem to play a crucial role in mass assembly of dense cores (e.g., André et al. 2010). While mass flow scenarios have been suggested by prior kinematic studies (e.g., Kirk et al. 2013), such investigations are limited to a few star-forming regions. A large sample size would be needed to constrain different models. We present a large systematic study of filament kinematics in nearby molecular clouds with the Green Bank Ammonia Survey (GAS; Friesen et al. 2017). We identify and disentangle velocity-coherent filaments in position-position-velocity (PPV) space and measure their velocity gradients at 0.05 pc resolution. The measured gradients show a wealth of structure at this spatial scale and often have values in the range of 2 - 8 km/s/pc. The orientation of these gradients also tends to be parallel or perpendicular with respect to the filament ridges, which may indicate accretion flow onto and along the filaments. These findings are important to understand how processes such as converging flows, self-gravity, and magnetic fields governs mass assembly in star formation.

[CT] **Pak Shing Li** – Astronomy Department, University of California at Berkeley
Chris F. McKee, Richard I. Klein

Understanding the Structure and Evolution of Filamentary Dark Clouds in Magnetized, Supersonic Turbulent Environment Using Numerical Simulations

Recent observations on filamentary molecular dark clouds have revealed their complex internal fiber/web-like substructures (e.g. André et al. 2010, Arzoumanian 2011, Hacar et al. 2103, André et al. 2014, Henshaw et al 2016). Dense cores are found to be located along or at the intersections of the substructures (e.g. Andre et al. 2010, Könyves et al. 2015). Using our multi-physics adaptive mesh refinement code ORION2, we have successfully simulated the formation of long filamentary dark clouds that resemble the observations from the large scale density structure, magnetic and velocity fields to the small scale web/fiber-like substructures and their fragmentation into dense cores. We have reported our results on (1) the magnetic field properties of cloud clumps from our simulations and the comparison with Zeeman observations in Li, McKee, & Klein (2015); and (2) the formation and properties of protostellar cluster in filamentary clouds in Li, Klein, & McKee (2018) based on our filamentary infrared dark clouds (IRDCs) simulation. In this meeting, I shall report our results in Li & Klein (2018, in preparation) on the formation and evolution of long and slender filamentary IRDCs formed in the simulation, including: (1) how the shock compressed gas streams coalesce together to form long filamentary clouds in a strongly magnetized turbulent environment; (2) the time evolution of the density structures of dark clouds that explain the wide range of observed column density probability distribution functions; (3) the 3D velocity structures of filamentary clouds that hide from the light-of-sight observations, especially in the case of cloud-cloud collision; (4) the roles of large scale moderately strong magnetic field, which pierces through the filamentary clouds roughly perpendicular to the long axis, in the formation and maintenance of long lasting filamentary clouds; and (5) the existence of nearby striations that strongly supports the presence of large scale magnetic field around observed filamentary clouds (Palmeirim et al. 2013). I shall also report some of our results in Li, McKee, & Klein (2018, in preparation) on the small scale fiber-like substructures and their evolution from formation to fragmentation into cores. We create synthetic line profiles with multiple velocity components and position-position-velocity data using RADMC3D from our simulation data to compare our results with observations.

[CT] **Javier Ballesteros-Paredes** – Instituto de Radioastronomia y Astrofisica

Dynamics, kinematics, and evolution of filaments, fibers, hubs and cores

Although there is a variety of physical characteristics of filaments, from striations to fibers, filaments are thought as those elongated structures that are linked to star forming cores. In this talk I will analyse the formation and evolution of such filaments, their fibers, bundles and cores, as they formed in hierarchically and chaotically collapsing turbulent clouds. I will show that gravity has much more to do with filament formation and evolution than what it is traditionally thought. I will also show what is the origin and the fate of coherent cores, and why some cores are hubs, i.e., the intersection of two or more filaments, trying to separate the relevance of turbulence and gravity. Finally, I will show that the typical virial analysis either for cores, or for filaments, is missleading if the whole gravitational potential is not taken into account, but only the inner mass of these structures.

[CT] **Kohji Tomisaka** – NAOJ

Structures of Magnetically-Supported Filaments and Their Appearance in the Linear Polarization

Dust thermal emissions observed with Herschel have revealed that interstellar molecular clouds consist of many filaments. Polarization observation of interstellar extinctions in the optical and near IR wavelengths shows that the dense filaments are extending perpendicular to the interstellar magnetic field. Magnetohydrostatic structures of such filaments are studied. It is well known that a hydrostatic filament without magnetic field has a maximum line mass of $\lambda_{max} = 2c_s^2/G$ (c_s:the isothermal sound speed and G: the gravitational constant). On the other hand, the magnetically-supported maximum line mass increases in proportion to the magnetic flux per unit length threading the filament (ϕ), as $\lambda_{max} = 2c_s^2/G + \phi/(2\pi G^{1/2})$. Comparison is made with 3D clouds. Stability of these magnetized filaments is studied using time-dependent 3D MHD simulations to discuss star formation in the filaments. Polarization pattern expected for the magnetically subcritical filaments is calculated. The distribution function of the angle between B-field and the axis of the filament, which is obtained with Planck Satellite, is compared with this mock observation.

[IT] **Susan Clark** – Institute for Advanced Study

Magnetism and Morphology in Galactic Neutral Hydrogen

Filamentary structure is pervasive in the neutral interstellar medium. Fine linear structures, sometimes called ”HI fibers”, are a generic feature of the diffuse Galactic HI emission, and are well aligned with the plane-of-sky magnetic field as traced by both optical starlight polarization and polarized thermal dust emission. This indicates a deep link between the morphology of the cold neutral medium and the structure of the ambient magnetic field. I will discuss how studying the properties of filamentary structures in neutral hydrogen can probe the physics of the magnetized, multi-phase interstellar medium.

[CT] **Siyao Xu** – University of Wisconsin-Madison
with Suoqing Ji, Alex Lazarian

Formation of filaments in the turbulent interstellar medium

The multiphase interstellar medium (ISM) is turbulent and magnetized. The turbulence properties are very different in various ISM phases. Based on observational measurements of sonic Mach numbers, density spectra, interstellar scattering of pulsars, and Galactic Faraday rotation, we proposed a turbulence model of the ISM incorporating different turbulence properties in the diffuse ISM and in molecular clouds. With both theoretical analysis and numerical simulations, we showed that the turbulence anisotropy in the diffuse ISM is responsible for the formation of low-density filaments (e.g., HI filaments) parallel to the magnetic field. The shock compression in the supersonic turbulence in molecular clouds leads to high-density filaments perpendicular to magnetic fields. Despite the presence of strong magnetic fields, turbulence can always manage to generate high-density structures where the self-gravity can become dominant. This is important for understanding the star formation at a high magnetization.

[CT] **Isabelle Ristorcelli** – IRAP, Université de Toulouse, CNRS, UPS, CNES
with Dana Alina, Ludovic Montier et al.

A statistical analysis from polarized dust emission in Planck Galactic cold clumps and hosting filaments: polarization fraction variation and interplay between magnetic fields and filaments

Magnetic fields are considered one of the key physical agents that regulate star formation, but their actual role in the formation and evolution of dense cores remains an open question. Polarized dust continuum emission is particularly well-suited to probe the magnetic field structure in the dense, cold interstellar medium. Such observations also provide tight constraints on the efficiency of dust alignment along magnetic field lines, which are needed to properly infer the magnetic field properties from observations. With the Planck all-sky survey of dust submillimetre emission in intensity and polarization, we can investigate intermediate spatial scales in the hierarchy of star formation, between global molecular cloud measurements and studies of individual prestellar cores. Planck further enables a statistical analysis of the polarization properties of clumps and filaments. We have recently built the first all-sky catalogue of Galactic Cold Clumps (PGCC, Planck collaboration XXVIII 2016). These clumps are distributed in various environments of the Galaxy and cover a broad range in physical properties, from quiescent starless clumps and nearby cores to young protostellar objects. We also found that a substantial fraction of them are embedded in filamentary structures (Juvela et al. 2012). I will present the results from our statistical analysis of the relative orientation between magnetic fields and filaments hosting PGCC clumps (Alina et al. 2017arXiv171209325A). After subtracting the background component, we have found different behaviours in terms of relative orientation (aligned, perpendicular or no preferential) depending on the environment density, and on the density gradient between the filaments and their environment. I will also present our results from a statistical analysis of the polarization fraction toward PGCC clumps and their hosting filaments (Ristorcelli et al. in prep.). We have in particular studied its dependency with the column density and with the angular dispersion function, linked to the tangling of the magnetic field. I will discuss the anti-correlations found in terms of depolarization either due to the lower efficiency of dust alignment with the magnetic field in dense medium (as expected from the Radiative Torque Alignment theory) or to the geometry of the magnetic field along the line of sight.

[CT] **Ludovic Montier** – IRAP, Université de Toulouse, CNRS, UPS, CNES
with Isabelle Ristorcelli, Jean-Sebastien Carrière, Dana Alina, Julien Montillaud, Mika Juvela

A combined Planck/Herschel analysis of the interplay between filamentary structure formation and Galactic magnetic field in cold core regions

The role of the Galactic magnetic field in the processes of star formation remains an open question. While star formation has been shown to happen inside dense filamentary structures of the ISM, where accretion is driven by gravitational processes, it has also been shown in recent studies that the orientation between these ISM structures and the Galactic magnetic field follows large trends over the sky: diffuse structures being preferentially aligned with the magnetic field, while denser filaments appearing preferentially orthogonal to the projected magnetic streamlines.

We will follow the approach of Malinen et al. 2016 on L1642 combining the Planck information about the Galactic magnetic field at 5' and the Herschel maps tracing ISM structure at higher resolution in order to address this complex question on a larger sample of objects. After improving the initial methodology, it will be applied on the whole 'Galactic Cold Core' Herschel Key programme data (Juvela et al. 2012) featuring 116 fields mapped with Herschel SPIRE and following up more than 350 Planck cold cores in various Galactic environments.

This relative orientation information will also be combined with the Herschel point sources catalogue extracted from these maps (Montillaud et al. 2015), and providing a crucial hint about the evolution of the stellar material and evolutionary stage of these filaments. This statistical analysis is allowing us to derive some trends between the morphological properties of the filamentary structures, the Galactic magnetic field and the star formation evolution, by mapping very different Galactic environments.

[CT] **Juan Diego Soler** – Max-Planck-Institut für Astronomie

What are we learning from the relative orientation between the magnetic field and the density structures in molecular clouds?

We present the study of the relative orientation between the gas column density structures and the magnetic field projected on the plane of the sky, as inferred from observations of dust polarized thermal emission, in two density regimes. First, toward the Orion-Eridanus superbubble, a nearby structure that spans more than 1600 square degrees in the sky, where we use the observations from the all-sky HI survey based on the EBHIS and GASS surveys (HI4PI) and Planck 353-GHz polarization. There we find that the large-scale magnetic field was primarily shaped by the expanding superbubble, playing only a secondary effect in structuring the HI shell. Second, toward the Vela C molecular complex, a high-mass star-forming region located at 700 pc from the Sun, where we use the column density estimates obtained with Herschel and the 250, 350, and 500 m polarization observations by the Balloon-borne Large-Aperture Submillimetre Telescope for Polarimetry (BLASTPol). We find that the relative orientation between the gas column density structures and the magnetic field and the shape of the column density probability distribution functions are correlated in different subregions of Vela C. This correlation suggests that the magnetic field is dynamically important for the formation of density structures in the molecular cloud. We interpret both of these results by revisiting the transport equations of ideal magnetohydrodynamic (MHD) turbulence and using a set of molecular clouds obtained from a stratified supernova regulated ISM magneto-hydrodynamical MHD simulation.

[IT] **Marta Alves** – Radboud University Nijmegen

Faraday filaments

Long and narrow structures have been detected in studies of Galactic polarised emission at low radio frequencies, thanks to a new technique called Faraday tomography, or rotation measure synthesis. Some of these strikingly elongated structures are most likely gaseous structures in the nearby interstellar medium that have an excess in thermal electron density and/or magnetic field strength, and that cause Faraday rotation of background synchrotron polarised emission - we call them "Faraday filaments". Their physical properties are ill-defined and therefore their origin still poorly understood. In this talk I will introduce the Faraday tomography technique and illustrate it with recent LOFAR observations. I will then focus on a couple of Faraday filaments detected at hight Galactic latitudes: one is seen to be aligned with the magnetic field as probed by Planck dust polarised emission, and the other is found adjacent to a filament of neutral gas. This will lead to the discussion of possible formation mechanisms for these structures, as well as their possible association with the filaments and fibres that we are more used to seeing in the diffuse atomic and molecular interstellar medium.

Day 3: Wednesday, November 7

[IT] **Christoph Federrath** – Australian National University

The role of turbulence and magnetic fields for filaments and star formation

Turbulence and magnetic fields determine the structure of the interstellar medium. In recent years we have developed a theoretical model of how this turbulence and the magnetic fields control the star formation rate. A critical step towards this theory is to understand the filamentary structure of molecular clouds and which physical processes give rise to the dense filaments within them. Here we show that the transition from supersonic to subsonic turbulence? the sonic scale? may determine crucial properties of the filaments, such as their widths, and how the sonic scale enters our derivation of star formation rates. I will also present results from the world's largest supersonic turbulence simulation, in which we measure the sonic scale, from which the the filament width and critical density for star formation is derived.

[CT] **Xing Lu** – National Astronomical Observatory of Japan
with Qizhou Zhang, Patricio Sanhueza, Hauyu Baobab Liu, Siyi Feng, Ke Wang

Gas Accretion in High-Mass Star Forming Filamentary Clouds

The relation between filamentary structures and high-mass star-formation, especially how such structures are related to gas accretion into dense cores, is still to be understood. To quantitatively study accretion in filamentary clouds, we carried out an observational campaign, using interferometers (ALMA, SMA, VLA) and single dish telescopes (IRAM 30m, JCMT), toward a sample of eight massive filamentary clouds in a variety of evolutionary phases. Protostellar/prestellar dense cores are resolved in each cloud by using dust emission, and gas kinematics in filaments from > 1 pc to < 0.1 pc scales are traced by spectral lines. We focus on two main results: (i) signatures of accretion flows along filaments, as traced by optically thin lines; and (ii) gas infall along the lines of sight toward star forming dense cores, as traced by optically thick lines. Both results suggest gas accretion rates into dense cores through filaments of the order $10^{-4} M_{\rm sun}$/year.

[IT] **Che-Yu Chen** – University of Virginia

Formation, Kinematics, and Polarimetric Properties of Simulated Filaments

We showed in three-dimensional MHD simulations that in typical environments of star-forming clouds, the turbulence-compressed regions are strongly-magnetized sheet-like layers. Within these layers, dense filaments and embedded self-gravitating cores form via gathering material along the magnetic field lines. As a result of the preferred-direction mass collection, velocity gradients perpendicular to the filament major axis are a common feature seen in our simulations, which is in good agreement with recent observations. In addition, we investigated the synthetic polarized dust emission from our simulations, which can provide further information on the formation and evolution of observed filaments based on the inferred magnetic field structure.

[CT] **Sven Van Loo** – University of Leeds

Magneto-gravitational fragmentation of quiescent and turbulent layers

Molecular clouds exhibit a hierarchical density structure with stars forming in their densest regions. Often, these star-forming complexes have an elongated, filamentary shape. Herschel observations of such filaments show a column density profile that deviates from hydrostatic equilibrium. Several explanation have been proposed, but have not elucidated the formation process.

I will discuss the formation of filaments by self-gravitating layers by gravitational instabilities. Self-gravitating layers are unstable to perturbations and fragment into clumps or thin filaments. When the layers are threaded by magnetic fields, fragmentation is still possible. Numerical simulations of the gravitational instability in magnetised quiescent layers produce density structures similar to observed ones. The filament network that forms is either a hub-filament or a parallel-filament network depending on the magnitude of the magnetic field. Although the filaments are collapsing, the central region of the filament can be perfectly described by an equilibrium density distribution. Excess mass accumulates at radii larger than the scale height resulting in a density and column density distribution that is flatter than for an equilibrium cylinder. I do not reproduce the quasi-constant filament width because no additional support is provided even though I include magnetic fields.

Turbulent motions are an important ingredient of the ISM and are thought to provide additional support to the filaments. They also have the potential to modify the fragmentation process due to the gravitational instabilities. I will show how the properties of the turbulence affect and change previously obtained results.

[CT] **Aris Tritsis** – Research School for Astronomy and Astrophysics
with Konstantinos Tassis

The Musca molecular cloud: An interstellar symphony

Molecular clouds are the birthplaces of stars. Their structure and evolution hold the key to understanding the initial conditions of star and planet formation, and the physics that sets the distribution of masses and multiplicities of newborn stars. However, their complexity, their typically turbulent, filamentary, disordered appearance, and ubiquitous projection effects hinder all efforts to model them in detail. An exception to this messy picture is found in a recently discovered class of structures, molecular cloud striations: ordered, low-column-density, quasi-periodic, elongated structures parallel to the magnetic field. The physics that drives the formation of such striations has remained a mystery since their discovery. We have performed a comprehensive numerical experiment testing all possible driving mechanisms, and we have found that the only viable explanation for the appearance of striations is their formation by magnetohydrodynamic waves generating trapped modes, just like vibrations in a resonating chamber: they are, in every sense, a magnetohydrodynamic ”song”, with dense filaments being the instrument. We have additionally demonstrated that, by examining the spatial power spectrum of striations, we can find the normal modes of the ”resonating chamber”, and thus derive the true dimensions of dense filaments, including their previously inaccessible by any means line-of-sight dimension. We have applied such a normal mode analysis towards the Musca molecular cloud - one of the best-studied ”dense filaments” in the interstellar medium and, contrary to all expectation, we have unequivocally demonstrated that the Musca filament is not, in fact, a filament: it is a sheet-like structure with comparable line-of-sight and plane-of-sky dimensions, seen edge-on. We discuss the implications of this discovery for the physics of dense molecular cloud formation.

Day 4: Thursday, November 8

[IT] **Nicolas Peretto** – Cardiff University

Filaments and infrared dark clouds: From the formation of OB stars, to the regulation of their feedback

Filaments pervade the density structure of the ISM, and their link to the formation of stars and stellar progenitors has been a very active field of research in the past 10 years or so. In this presentation, I will focus on the role that filaments play in the formation and evolution of massive stars. I will do so by presenting recent studies of infrared dark clouds that aim to determine the link between filament evolution and core properties, with a particular emphasis on hub filament systems, i.e. small networks of spatially converging filaments. I will also discuss the importance of dense and massive filaments, also known as ridges, in limiting the impact of stellar feedback from OB stars.

[CT] **Vivien Chen** – National Tsing Hua University
with Qizhou Zhang, Melvyn Wright, Gemma Busquet, Baobab Liu, Yuxin Lin, Fumitaka Nakamura, Patricio Sanhueza, Aina Palau, Satoshi Ohashi, Ken'ichi Tatematsu, Li-Wen Liao, Fernando Olguin

Filamentary Accretion Flows in the IRDC M17 SWex

Although filamentary structures are ubiquitous in molecular clouds, basic observational constraints are needed to clarify the role of filaments in the mass assembly process. Using ALMA Band 3, we have performed full-synthesis imaging of the N2H+ (1-0) emission in the remarkable IRDC complexes, M17 SWex, where a delayed onset of massive star formation was reported in the two hubs at the convergence of multiple filaments of parsec length. We derive gas kinematics by fitting the hyperfine components of N2H+ spectra and derived velocity gradients along 11 identified filaments with principal component analysis. The mass accretion rates along the filaments are up to $10^{-4} M_{\rm sun}$/yr and significant to affect the hub dynamics within one free-fall time of 10^5 yr. The N2H+ filaments are likely to be in equilibrium with virial parameter in the range of 0.6-1.6. More massive filaments tend to have lower virial parameters and are gravitationally bound with possible support from magnetic fields. We compare virial parameters measured in the NH3 filament, N2H+ filament, NH3 clumps, and 3mm continuum dense cores. The decreasing trend in virial parameter with decreasing spatial scale persists. Meanwhile, virial parameters also decreases with decreasing fraction of non-thermal motions . Together with the absence of massive prestellar and protostellar cores previously reported, the observation results are consistent with the hierarchical gravitational collapse scenario.

[CT] **Gwenllian Williams** – University of Hertfordshire
with Nicolas Peretto, Adam Avison, Ana Duarte-Cabral, Gary Fuller

Gravity drives the evolution of infrared dark hubs

It is now widely considered that interstellar filaments are the archetypal intermediate stage in the star formation process. The vast majority of cores (the direct progenitors of stars) sit on top of the densest filaments. Yet a number of questions remain regarding the physics that govern the formation and evolution of filaments. Studies of infrared dark clouds (IRDCs) help shed light on this, as they are thought to contain the pristine fingerprints of the initial conditions of star formation. We present a study of the SDC13 IRDC hub filament system. SDC13 contains 1000 Msun of material, resides 3.6kpc away in the galactic plane, and has a remarkable morphology, containing four parsec-long filaments that spatially converge on a central hub region. Overall, SDC13 is an ideal target to study how filaments form, fragment and dynamically interact with each other. In combining NH3 emission data from the JVLA interferometer and the single-dish GBT, we studied the evolution of SDC13 down to 0.07pc spatial scales. We propose a scenario for the evolution of the SDC13 hub in which the filaments first form as post-shock structures in a supersonic turbulent flow. As a result of the turbulent energy dissipation in the shock, the dense gas within the filaments is predominantly sub-sonic. Then gravity takes over and starts shaping the evolution of the hub, fragmenting filaments and pulling the gas towards the centre of the gravitational well. By doing so, gravitational potential energy is converted into kinetic energy in local cores (where we see the gas velocity dispersion increase towards 73% of starless cores) and global hub centre potential well minima. This generates more massive cores at the hub centre as a result of larger acceleration gradients due to the hub morphology itself.

[CT] **Sylvain Bontemps** – LAB/Universite de Bordeaux
F. Motte, T. Csengeri, L. Bonne, Th. Nony, N. Schneider, F. Louvet and the HOBYS collaboration

Ridges and filaments in the context of high-mass star formation - the HOBYS survey

Herschel images of the dust emission from molecular clouds have shown that a large fraction of low-mass stars form in filaments. It might also be true for the formation of high-mass stars but the dense structures predominantly leading to high-mass star formation are either marginally ressembling the nearby filaments (massive ridges, Schneider et al. 2010, Hill et al. 2011, Henneman et al. 2012) or mostly spherical (hubs and massive dense cores/clumps). Herschel continuum data as part of the HOBYS program (Motte et al. 2010) as well as IRAM NOEMA and ALMA data towards some of the most nearby high-mass star-forming regions (Cygnus X, nearby ATLASGAL clumps, W43 regions) will be discussed in the context of the dynamical formation of massive cores inside filamentary and hub-like structures. The HOBYS survey shows that only a part of the high-mass stars are formed in hubs or ridges. Some are formed in more isolated clumps. From a 3mm large NOEMA mosaic towards DR21, I will also discuss the properties for the DR21 ridge in Cygnus to investigate whether the high-mass cores formed in this ridge can be attributed to “filament-star-formation”, and to discuss whether the filamentary structures inside the ridge is of similar nature than low mass filaments. It will be compared with the filamentary structure seen with ALMA in the most massive “young” clump of the galactic disk, W43-MM1 (Motte et al. 2018). I will finally review other evidences from the literature to question the relationship between formation of high-mass stars and star formation in filaments.

[CT] **Tie Liu** – KASI
with Kim, Kee-Tae; Juvela, Mika; Wang, Ke; Tatematsu, Ken'ichi; Di Francesco, James; Liu, Sheng-Yuan; Wu, Yuefang; Thompson, Mark; Fuller, Gary; Eden, David; Li, Di; Ristorcelli, I.; Kang, Sung-ju

Massive filaments formed due to large-scale compression flows

Stars mostly form in dense regions within filamentary molecular clouds, called pre-stellar cores (PSCs), which provide information on the initial conditions in the process of star formation. The low dust temperature (¡14 K) of Planck Galactic Cold Clumps (PGCCs) makes them likely to be pre-stellar objects or at the very initial stage of protostellar collapse. ”TOP-SCOPE” are joint survey programs targeting at Planck Cold Clumps. ”TOP”, standing for ”TRAO Observations of Planck cold clumps”, aims at an unbiased CO/13CO survey of 2000 Planck Galactic Cold Clumps with the Taeduk Radio Astronomy Observatory 14-meter telescope. ”SCOPE”, standing for ”SCUBA-2 Continuum Observations of Pre-protostellar Evolution”, is a legacy survey using SCUBA-2 onboard of the James Clerk Maxwell Telescope (JCMT) at East Asia Observatory (EAO) to survey 1000 Planck galactic cold clumps at 850 micron. We are also actively developing follow-up observations with other ground-based telescopes (NRO 45-m, Effelsberg 100-m, IRAM 30-m. SMT, KVN, SMA, ALMA). From these surveys, we identified a large number of massive filaments. Through detailed kinematics analysis, we found that those massive filaments are likely formed due to large-scale compression flows from HII regions, cloud-cloud collision and so on. I will also present dust polarization observations toward G035.39-00.33, which enable us to fully investigate the interplay between gas and magnetic fields in a filamentary infrared dark cloud.

[IT] **Tomoyuki Hanawa** – Chiba University

The linear stability of a filamentary cloud permeated by a perpendicular magnetic field

We examine the linear stability of a filamentary cloud permeated by a perpendicular magnetic field. The initial magnetic field is assumed to be perpendicular to the cloud axis and uniform for simplicity. The model cloud has a Plummer-like density profile and is assumed to be supported against the self-gravity by turbulence. The effects of turbulence are taken into account by enhancing an effective pressure of a low density gas. We derive the effective pressure as a function of the density from the condition of the hydrostatic balance. When the radial density profile is broader, i.e., the index is smaller, the model cloud is more unstable against radial collapse. When the magnetic field is mildly strong, the radial collapse is suppressed. If the displacement vanishes in the region very far from the cloud axis, the model cloud is stabilized by the mildly strong magnetic field. If rearrangement of the magnetic flux tubes is permitted, the model cloud is unstable even when the magnetic field is extremely strong. The stability depends on the outer boundary condition as in case of the isothermal cloud. The growth rate of the rearrangement mode is smaller for a lower index. The rearrangement instability is likely to grow more slowly than quasi-static evolution due to ambipolar diffusion.

[CT] **Anna Punanova** – Ural Federal University
with Paola Caselli, Jaime Pineda, Andy Pon, Mario Tafalla, Alvaro Hacar, Luca Bizzocchi

Kinematics of dense gas in L1495: from filament to core center

In this work, we study kinematics of the dense gas of starless and protostellar cores along the L1495 filament and the kinematic links between the cores and the surrounding molecular cloud. The chemical fractionation which takes place in the ISM makes various species tracers of different parts of the cores. While carbon-bearing species are abundant in the outer layers of the cores and depleted in the deeper parts, nitrogen-bearing species appear in the evolved gas and stay in the gas phase up to densities of 10^6 cm^{-3}. Rotational transitions of higher levels typically excited at higher densities and thus trace deeper areas of the dense cores. In this work, we use C18O(1-0) to trace the molecular cloud gas; H13CO+(1-0) and DCO+(2-1) to trace the core envelopes; and N2H+(1-0) and N2D+(2-1) to trace the central parts of the cores (including the neutral depletion zone). We measure velocity dispersions, local and total velocity gradients and estimate the specific angular momenta of 13 dense cores using on-the-fly maps of these species observed with IRAM 30m telescope and the C18O(1-0) FCRAO observations from the Hacar et al. 2013 survey. For one core, we study even denser gas using the N2H+(3-2) IRAM 30m map and p-NH2D(1,1) NOEMA observations. All cores of the 10-pc filament show very similar properties. The non-thermal contribution to the velocity dispersion increases from higher to lower density tracers. At the level of the cloud-core transition, the core's envelope is spinning up, consistent with conservation of angular momentum during core contraction. At small scales the core material is slowing down implying a loss of specific angular momentum at small scales. The cloud material stays unaffected by the presence of rotating cores.

[CT] **Yoshiaki Misugi** – Nagoya University
with Shu-ichiro Inutsuka, Doris Arzoumanian

An Origin of the Angular Momenta of Molecular Cloud Cores

The angular momentum of a molecular cloud core plays a key role in star formation, since it is directly related to the outflow and jet emanating from the new-born star and it eventually results in the formation of the protoplanetary disk. However, the origin of the core rotation and its time evolution are not well understood. On the other hand, recent observations, e.g., from Herschel reveal that molecular clouds exhibit a ubiquity of filamentary structures and that star forming cores are associated with the densest filaments. Since these results suggest that dense cores form primarily in filaments, the mechanism of core formation from filament fragmentation should explain not only the core mass spectrum, but also the distribution of the angular momentum of these cores. Therefore we analyze the relation between velocity fluctuations along the filament and the angular momenta of the cores formed in the filament. We first find that an isotropic velocity fluctuation that follows the Kolmogorov spectrum does not reproduce the observed angular momenta of molecular cloud cores. We then identify the need for a large power in small scales and study the case of anisotropic velocity fluctuations along the filament characterized with larger power in the direction perpendicular to the filament axis than the power in the parallel direction for short wave length modes. This seems to be consistent with available observational results, and we find that it reproduces the observed rotation properties of cores. Our results indicate that more detailed and systematic observations of both the velocity structure in filaments and the angular momentum distribution of molecular cloud cores will critically determine the validity of the mechanism of core formation from filamentary molecular clouds. We will present these results and discuss the time evolution of the angular momenta of cores.

[CT] **Kazuki Tokuda** – Osaka Prefecture University/NAOJ
with Toshikazu Onishi; Kazuya Saigo; Tomoaki Matsumoto; Tsuyoshi Inoue; Shu-ichiro Inutsuka; Yasuo Fukui; Masahiro N. Machida; Kengo Tomida; Takashi Hosokawa; Akiko Kawamura; Kengo Tachihara

Warm CO filamentary/clumpy gas generated by possible turbulent shocks in a highly dynamical dense core in Taurus resolved by ALMA

Interstellar turbulence is supposed to be one of the most important factors to regulate star formation activities. Shocks induced by supersonic turbulence dramatically increase the density and temperature in the post-shock layer and promote the structure formation, such as interstellar filaments, dense cores, and protostars. Recent interferometers, such as ALMA, have been resolving internal complex filamentary morphologies possibly formed by turbulent motions of dense cores in the early phase of low-mass star formation. Our recent ALMA observations toward the cold protostellar core, MC27/L1521F in Taurus (Onishi et al. 1999), revealed highly complex structures, such as arc-like structures and fragmentation of starless dense gas, with sizes of several tens to a few thousands of au, suggesting multiple protostar formation (Tokuda et al. 2014; 2016). Numerical simulations by Matsumoto et al. (2015) demonstrate that a dynamical interaction between formed protostar and surrounding dense condensations of a 100 au scale disturbs the envelope on a ~1000 au scale, reproducing the arc-like structure on that scale. We subsequently carried out the follow-up observations with an angular resolution of ~20 au, which is several times higher than the previous ALMA studies. The high-resolution 12CO (J=3-2) observations resolved for the first time complex warm (>15-60 K) filamentary/clumpy structures, which have not been observed in cold cores. We suggest that the warm CO gas may be a consequence of shock heating or turbulent dissipation induced by interactions among the different density/velocity components (Tokuda et al. 2018, ApJ in press). These facts shed a new light on the multiple low-mass star formation as well as the formation of the small-scale filaments/fragments.

[IT] **Yueh-Ning Lee** – IPGP
with Patrick Hennebelle, Gilles Chabrier

Hierarchical fragmentation of interstellar filaments: what leads to the core mass function?

The initial mass function (IMF) plays a central role in stellar cluster evolution. Much effort has been dedicated to the universality of the IMF by linking it to the core mass function (CMF), which describes the mass distribution of the star precursors. The hierarchical fragmentation of a molecular cloud into sheets, filaments, and finally cores is a behaviour expected from the nature of the self-gravitating fragmentation. We are therefore interested in whether the geometry plays a role in the outcome of fragmentation, or more precisely, the mass distribution into the cores. Observations have suggested formation of groups of cores along the filament. I will present an analytical model on the fragmentation of magnetised filaments, in which the filamentary geometry leads naturally to such behaviour.

[CT] **Sandra Patricia Treviño Morales** – Chalmers university of technology/ Onsala space observatory
with J. Kainulainen; H. Beuther; A. Stutz; J. Abreu-Vicente; M. Zhang

Evolutionary sequence for the fragmentation of high line-mass filaments

High line-mass filaments are birthplaces of massive stars and star clusters and thus important for Galactic scale star formation. However, their fragmentation, collapse, and dynamics remain to be well understood. One key open question is how the evolution of fragmentation proceeds. Our team has performed a sensitive fragmentation study of two high line-mass filaments presenting different evolutionary states. The dense integral-shape filament (ISF) in Orion A, and the more quiescent infrared-dark cloud G357. The comparison of fragmentation in both filaments provide the first observational constraints for the evolutionary sequence of fragmentation in massive filaments. For the ISF, we identify fragmentation and clustering in different scales along the filament, with cores strongly grouped along the filament with separations of about 0.25 pc. On the other hand, G357 has a lower number of fragments, with similar intensities/masses as those found in ISF, but distributed in more compact and smaller groups along the filament separated by larger distances (about 1.5 pc).

[CT] **Bilal Ladjelate** – IRAM Granada
with Philippe André, Vera Könyves, Yoshito Shimajiri, Andrea Bracco, Pedro Palmeirim, Arabindo Roy, Doris Arzoumanian

Star-formation in the Ophiuchus Molecular Cloud: from filaments to brown-dwarfs formation
From molecular clouds to stars, every step of the evolution of young stars can be observed in the submillimetric range. The Herschel Space Telescope observed, as part of the Herschel Gould Belt Survey, many molecular clouds. When these molecular clouds are fragmenting, dense prestellar cores accumulating dust and gaz are forming and contracting. We performed a census of prestellar dense cores in the Ophiuchus Molecular Cloud, which appear to be coupled with filamentary structures, as part of the paradigm of star-formation inside insterstellar filaments. The region was not previously known as filamentary, despite the observation of protostellar alignments. This molecular cloud is under the heavy feedback of active stars nearby seen in the structure of the molecular cloud. Oph B-11, detected with interferometric observations, is a brown dwarf precursor, which final mass will not be important enough for the final star to burn hydrogen. Their formation mechanism is not well constrained, we must find and characterize a first candidate pre-brown dwarf. Oph B-11 was detected along a nearby shock, we characterize chemically. Moreover, higher resolution studies with ALMA show a structured molecular environment, and help us constrain the mechanism of formation of this kind of objects. These observations show a series of shocks in differents tracers, spatially coincident with the detected position of the pre-brown dwarf, in favor of the gravo-turbulent scenario for the formation of brown dwarfs. I will discuss the legacy of Herschel in the Ophiuchus region in the filament paradigm of star-formation, and the future of these studies with the advent of new instruments, like NIKA2 and its polarimetry facility.

Day 5: Friday, November 9

[CT] **Yasuo Fukui** – Nagoya University
with K. Tokuda, T. Onishi, R. Harada, K. Saigo, M. Meixner, R. Indebetouw, M. Sewilo, et al.

Spatially resolved filamentary clouds in the Large Magellanic Cloud
We present the ALMA Band 6 observations of CO isotopes and 1.3 mm continuum emission toward the N159 region, which is the most intense and massive molecular cloud as shown by the brightest CO J=3-2 emission in the Large Magellanic Cloud (LMC). The spatial resolution is 0.25-0.28 arcsec (0.060-0.067 pc), which is a factor of 3 higher than the previous ALMA observations in this region. Although the typical width of the previously identified filaments of the filaments was ~1 pc, the high resolution allowed us to resolve the typical width (full width half maximum) to be ~0.1 pc with line mass of a few × 100 $M_{\odot}$/pc. We discovered in N159W that there are multiple protostellar sources with bipolar outflows along the massive filament. Based on the previous papers on colliding clouds/filaments (Fukui et al. 2016; 2017), we present a scenario that a supersonically colliding gas flow triggered the formation of the massive filament and protostars. A recent theoretical study of the shock compression in colliding molecular flows (Inoue et al. 2018) demonstrates that the formation of filaments with hub-structure is a usual outcome of the collision. Toward N159E, the CO observations also revealed striking pillar-like features around the Papillon Nebula. The HII region and the CO pillars clearly show the complementary distributions with each other and the column density of the pillars is an order of magnitude higher than that of the pillars in the Eagle nebula (M16), suggesting that we are witnessing an early stage of "pillar creation".

[CT] **Catherine Zucker** – Harvard-Smithsonian Center for Astrophysics
with Cara Battersby, Alyssa Goodman, Rowan Smith

A Systematic Comparison of the Physical Properties of Observed and Synthetic Large-Scale Galactic Filaments
The discovery of the highly elongated (100+ pc long, <1 pc wide) Nessie filament?s potential association with the Scutum-Centaurus arm is a tantalizing case in point for how our Galaxy?s longest, high-density features might be shaped by the global gas dynamics of spiral galaxies (e.g. Galactic shear, compression of gas upon entering a spiral arm potential well). We now have a sample of 45 large-scale (11-269 pc) molecular filaments from the literature (derived using different data sets, selection criteria, and methodology) and in this talk we present the first comprehensive, uniform analysis of their physical properties. Do all large-scale filaments have the same

formation mechanism? How do their properties compare to smaller-scale filaments (widths ~ 0.1 pc, lengths ~ a few parsecs) in nearby molecular clouds (e.g. Arzoumanian et al. 2011)? We find significant variation in the physical properties of large-scale filaments, suggesting that different filament finding techniques are uncovering a wide range of physical structures. Our results suggest that especially elongated (aspect ratio > 20 : 1) and high-density ($N_{H2} > 10^{22}$ cm^{-2}) "Bone-like" filaments may preferentially trace the gross structure (e.g. spiral arms, the gravitational midplane) of our Galaxy, while others could simply be large concentrations of molecular gas (GMCs, core complexes). We discuss our large-scale filament sample in the context of the latest spiral arm models in longitude-latitude-velocity space. Finally, we present results from our ongoing work performing a comparison between observational and synthetic large-scale filament samples, the latter of which is extracted from a high-resolution swath of a spiral galaxy simulated with AREPO (see Smith et al. 2014). Early results from numerical simulations suggest that large-scale filaments are relatively rare ($\lesssim$ 1 filament per square kpc), that they form in both the arm and interarm regions, and that there are systematic differences in their properties based on Galactic environment.

[CT] **Marina Kounkel** – Western Washington University
with Kevin Covey, Genaro Suarez, Carlos Roman-Zuniga, Jesus Hernandez, APOGEE Collaboration

Six-dimensional structure of the Orion Complex

We present an analysis of spectroscopic and astrometric data from APOGEE-2 and Gaia DR2 to identify structures towards the Orion Complex. By applying a custom hierarchical clustering algorithm to the 6-dimensional stellar data, we identify spatially and/or kinematically distinct groups of young stellar objects with ages ranging from 1 to 12 Myr. We also investigate the star forming history within the Orion Complex, and identify peculiar sub-clusters. With this technique we map the kinematics, structure, and ages of the stars within the Orion A and B molecular clouds, and λ Ori. We also reconstruct the older populations in the regions that are presently largely devoid of molecular gas, such as Orion C (which includes the λ Ori cluster), and Orion D (the population that traces Ori OB1a, OB1b, and Orion X). These structures can be used to reconstruct the properties of the molecular clouds that have produced them, and they represent an example of potential evolution of their younger counterparts. Together these data represent a major step forward in terms of understanding the dynamical evolution within the young star-forming regions. This will be instrumental for the modeling efforts of the assembly and dispersal of molecular clouds and the stars that form within them.

[CT] **Ana Duarte Cabral** – Cardiff University

Travelling through the galactic potential: Giant Molecular Filaments

Molecular clouds are the result of the interchange and evolution of gas as it travels through the galaxy through a wide range of conditions, densities and scales. It is therefore essential that we understand the galactic journey of the molecular gas, if we want to determine the global galactic processes which regulate how molecular clouds are formed, shaped, and able to form stars. In this talk, I will focus on a particularly striking type of clouds, the so-called giant molecular filaments, which are extremely elongated clouds, some reaching more than 100pc in length. Giant molecular filaments have been observed in both the Milky Way and nearby spiral galaxies, and are thought to be tightly linked to the larger-scale motions of spiral galaxies. It is not clear, however, if these extreme clouds trace any particular region in spiral galaxies and/or if they represent an important step on the evolution of molecular clouds in general. Here I will follow the formation and evolution of giant molecular filaments within our galaxy-scale simulations, and explore how different galactic environments can affect the observable properties of clouds, by following them as they travel from the shear-dominated inter-arm regions into and through spiral arms. I will explore our findings and their consequences in light of both Galactic and extragalactic observations.

[CT] **Miaomiao Zhang** – Max Planck Institute for Astronomy
Jouni Kainulainen, Min Fang, Michael Mattern, Thomas Henning

Star-forming content of the Galactic giant molecular filaments

Observations have discovered numerous giant molecular filaments (GMFs) in the Milky Way and suggested them to occupy a special role in the Galaxy-scale star formation pattern. However, the studies so far have not confronted this suggestion with an analysis of star formation within the GMFs; the star formation activities of GMFs remain unknown. In this contribution, we present a systematic study of physical properties and star formation within all currently known GMFs. We first analyse gas properties, such as dense gas masses, using a homogenous approach for all GMFs. We then identify and classify the young stellar object (YSO) populations within each GMF using multi-wavelength photometry from near- to far-infrared. This allows us to estimate the star formation rates (SFRs) of the GMFs and to establish relationships between the SFRs and the GMF properties. We find that the median SFR surface density and star formation efficiency are similar to the nearby star-forming clouds, which indicates that the GMFs are not special objects from the perspective of star formation. We find no correlation between the SFR surface density and gas surface density, nor between SFR surface density and gas surface density per free-fall time. However, we find a significant correlation between SFR and dense gas mass and also a strong correlation between the SFR per unit length and line mass. Overall, our results discourage the use of gas surface densities as a predictor of SFR. The SFRs are more strongly linked to the dense gas mass and, in the case of filamentary clouds, to the line mass.

[CT] **Toshikazu Onishi** – Osaka Prefecture University
with K. Tokuda, Y. Fukui, A. Kawamura, K. Muraoka, R. Harada, S. Zahorecz, K. Saigo, M. Meixner, R. Indebetouw, M. Sewilo, T. Wong et al.

Molecular gas distribution in the GMCs in the Magellanic Clouds

It is generally thought that most stars are born as clusters in Giant Molecular Clouds (hereafter GMCs), and, therefore, the understanding of the evolution of GMCs in a galaxy is one of the key issues to investigate the evolution of a galaxy. The recent state-of-the-art radio telescopes have enabled us to reveal the distribution of GMCs extensively in the Galaxy as well as in the nearby galaxies, and the physical properties and the evolution of the GMCs leading to the cluster formation are being uncovered. Here we present studies of spatially resolved GMCs in the Magellanic Clouds(LMC/SMC), aiming at determining the origins of the observed turbulence and assessing the role of gas interaction in triggering star formation by the observations spanning a large range of scales from 0.1 pc to 100 pc and environmental conditions.

We have carried out ALMA observations toward ~ 10 GMCs located across the LMC by using ALMA mainly in the CO isotopologue lines of J=1-0 and 2-1 and continuum bands. The typical angular resolution is 1-3 arcsecs; 1 arcsec corresponds to 0.24pc at the distance of the LMC. These clouds have different evolutionary stages showing a variety of star formation activity. The observations revealed the complex nature of the molecular gas in the LMC, which are full with filaments and clumps; we also quantify their density structure and velocity-size correlations. A comparison with the Galactic GMCs indicates similarity of multiple filaments entangled toward the region where high-mass stars are forming. We have also carried out 0.3pc resolution observations of N83C, a high mass star-forming region in the SMC. A radiative transfer analysis suggests that the kinetic temperature is ~40K and the density is a few $\times 10^4 cm^{-3}$, which is consistent with the virial analysis. This high-density, implying a lack of lower-density envelope, and the high temperature indicates that UV radiation deeply penetrates into the clump and CO molecule is heavily photodissociated in the low-metalicity environment.
