Journée IRAM France
31 janvier 2019
Paris

L'interféromètre NOEMA, en 2018 avec 10 de ses futures 12 antennes

credit:F. Gueth/IRAM

Le telescope de 30-mètres - credit: DiVertiCimes/IRAM

Programme

9h00-09h30: Welcome coffee

Chair: Jean-Loup Puget
09h30-09h40: Introduction, Guy Perrin (INSU)
09h40-10h30: IRAM (NOEMA & 30m), Karl Schuster & Frédéric Gueth (IRAM)
10h30-10h35: Chiara Ferrari (SKA-France), SKA/IRAM synergy
10h35-10h45: Thierry Contini (IRAP), MUSE/IRAM synergy
10h45-11h00: Discussion animated by Raphael Moreno and Fabienne Casoli

11h00-11h15: Café

Chair: Nicole Nesvadba
11h15-11h30: Cosmology & SZ, Juan Macias-Pérez (LPSC)
11h30-11h45: Evolution of galaxies and AGN, Françoise Combes (LERMA)
11h45-12h05: 4 Flash-talks of 5 minutes
- Jean-Baptiste Melin (CEA), Le fond diffus cosmologique en haute définition
- Chiara Deugenio (CEA), Dead and Dusty ETGs at z~3
- Hervé Dole (IAS), Towards a NOEMA survey of z>2 protoclusters ?
- Benoit Cerutti (IPAG), Simulations numériques ab-initio de magnétosphères de trous noirs

12h05-12h25: Discussion animated by David Elbaz and Alexandre Beelen

12h25-13h25: Buffet

Chair: Antoine Gusdorf
13h25-13h40: ISM in nearby galaxies, Annie Hughes (IRAP)
13h40-13h55: ISM structures, Marc-Antoine Miville-Deschênes (AIM)
13h50-14h05: Star formation, Frédérique Motte (IPAG)
14h05-14h40: 7 Flash-talks of 5 minutes
- Philippe Salome (LERMA), Molecular gas in Brightest Cluster Galaxies
- Diane Cormier (CEA), Propriétés du gaz dense et formation d'étoiles dans les galaxies proches avec le programme EMPIRE
- Katharina Lutz (Strasbourg), Millimeter-centimeter emission excess in nearby galaxies
- Pierre Dell'Ova (LERMA), The molecular cloud interacting with cosmic rays in IC443G
- Julien Montillaud (UTINAM), Colliding filaments in the Monoceros OB 1 molecular cloud
- Maud Galametz (CEA), ALMA, SMA and PdBI interferometric observations observations of the youngest solar-type protostars
- Philippe Andre (CEA), Searching for pre-brown dwarf cores in nearby starforming clouds with NIKA2 and NOEMA

14h40-15h10 Discussion animated by Karine Demyk and Pierre Guillard
15h10-15h25: Dying star enveloppes, Fabrice Herpin (LAB)
15h25-15h40: Protoplanetary disks and jets, Anne Dutrey (LAB)

15h40-15h55 café

Chair: Maryvonne Gerin
15h55-16h10: Astrochemistry (dust and molecules) and its link with exobiology, Charlotte Vastel (IRAP)
16h10-16h30: 4 Flash-talks of 5 minutes
- Miguel Montarges (Leuven), Reconstruction 3D de l'environnement de la supergéante rouge µ Cep à partir d'observations NOEMA de la raie CO J = 2-1
- Victor deSouza (IRAM), A survey of the HCN and HNC C and N isotopic ratios in nearby star formation regions
- Eleonora Bianchi (IPAG), Hot corino aging: molecular complexity and deuteration towards the Class I source SVS13-A
- Marta de Simone (IPAG), Complex Organics in the NGC 1333 IRAS 4A Outflows

16h30-16h50: Discussion animated by Agnès Lebre and Cecilia Ceccarelli

16h50-17h05: Disque de débris, Jean-François Lestrade (LERMA)
17h05-17h20: Solar system, Nicolas Biver (LESIA)
17h20-17h30: 2 Flash-talks of 5 minutes
- Thibault Cavalie (LAB), Long-term monitoring and chemical inventory in Jupiter and Saturn's atmospheres
- Lea Bonnefoy (LATMOS), Probing the subsurface of Iapetus two faces

17h30-17h40: Discussion animated by Thierry Fouchet and Emmanuel Lellouch
17h40-18h00: Conclusions

Session # 1
IRAM and its environment

Synergies SKA/IRAM

Chiara Ferrari

[1] *Maison SKA France/OCA*

Abstract: Avec le début de la construction du Square Kilometre Array (SKA) prévue pour 2021, la communauté française continue sa reflexion et sa préparation à l'exploitation de cet Observatoire majeur des 50 prochaines années. Je donnerai un aperçu rapide des synergies entre le SKA et les instruments de l'IRAM dans différents domaines de l'astrophysique.

Probing the molecular gas content of galaxies in an over-dense group at z~0.7 with NOEMA: a test case for environmental quenching

T. Contini[1], J. Freundlich[2], B. Epinat[3], P. Salomé[4], et al.

[1]IRAP, Toulouse - France
[2]Racah Institute of Physics, Jerusalem - Israel
[3]LAM, Marseille - France
[4]LERMA, Paris - France

How do dense environments, such as groups and clusters, affect star formation efficiency and galaxy growth? What are the physical processes responsible for star formation quenching in these structures? We started a program with NOEMA to adress these questions by probing the molecular gas content of galaxies living in an over-dense region of a galaxy group at z~0.7. This redshift corresponds to a crucial period for galaxy evolution where the environmental quenching processes can be caught in the act in such dense environments. For this pilot program, we target the group COSMOS-Gr30 which is part of a larger sample of z~0.3-1 groups drawn from an ongoing VLT/MUSE-GTO program aimed to study environmental quenching over the last 8 Gyr. Deep MUSE observations revelead a huge, unique, and unexpected ionized gas structure in this group, wrapping about eight galaxies in an over-dense region [1]. This gas could have been expelled recently from the galaxies due to outflows, tidal interactions or stripping. The goal of this program is to test this hypothesis and thus gain into our understanding of environmental quenching.

Références:

[1] Epinat, B., Contini, T., Finley, H., et al., A&A 609, 40 (2018)

Supplementary material for discussion

IMAGER : une alternative à MAPPING pour les grands jeux de données

E. Di Folco[1], S. Guilloteau[1], T. Jacq[1]

[1] Laboratoire d'Astrophysique de Bordeaux, Université de Bordeaux, CNRS, UMR5804,
B18N, Allée Geoffroy Saint-Hilaire, F-33615 Pessac - France

Dans le cadre du Service National d'Observation, nous avons développé un logiciel d'imagerie optimisé pour les données multi-spectrales large bande telles que produites par NOEMA et ALMA. Cette suite est offerte sous forme d'une contribution documentée à GILDAS. Sa philosophie est basée sur une interface simplifiée et une implémentation intégrée des fonctionnalités d'imagerie, et permet de réduire notablement le temps de traitement pour les champs uniques comme pour les mosaïques. IMAGER a été développé et optimisé pour traiter de grands jeux de données, avec une stratégie reposant sur des buffers internes, évitant ainsi les étapes de lecture/écriture de multiples fichiers intermédiaires. IMAGER offre également des outils optimisés de manipulation et visualisation des grands cubes spectraux et de déconvolution. Enfin, un algorithme de self-calibration (en phase et amplitude) éprouvé propose une stratégie d'analyse assistée pour tenter d'améliorer la dynamique des images en imposant des contraintes cohérentes sur la calibration des données interférométriques.

Session # 2
Cosmology and redshifted galaxies

Le fond diffus cosmologique en haute définition

J.-B. Melin[1], J. G. Bartlett[2]

[1]IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France

*[2]APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3,
CEA/lrfu, Observatoire de Paris, Sorbonne Paris Cité, 10 rue Alice Domon et Léonie
Duquet, 75205 Paris Cedex 13, France*

Les récents sondages à grand champ du fond diffus cosmologique Planck[1], SPT[2] et ACT[3] ont permis de faire des avancées majeures en cosmologie (mesures actuelles les plus précises des paramètres cosmologiques) et en astrophysique (catalogue de galaxies et d'amas de galaxies, physique de la Voie Lactée,…). Les futurs générations d'instruments LiteBIRD[4], Simons Observatory[5] puis CMB-S4[6] se concentreront sur la recherche du signal de polarisation « mode B » qui signe l'inflation. Pour cela, elles observeront exclusivement les échelles angulaires allant de quelques arcmin à l'ensemble du ciel. L'observation du fond diffus cosmologique aux petites et très petites échelles (inférieures à l'arcmin) n'est pour l'instant pas envisagée dans le design de ces instruments. Pourtant la science pouvant être couverte par l'étude du fond diffus cosmologique à ces échelles, intimement liée à la formation des structures dans l'Univers, est vaste.

NIKA2 installée au télescope de 30m commence à la défricher grâce à ses avancées sur la physique des amas de galaxies. Pour aller plus loin, il faudra disposer d'un instrument ayant la même résolution mais beaucoup plus sensible et avec un champ de vue plus grand. Au niveau international, la réflexion débute[7] : résolution de 20 arcsec (à 150GHz) avec une sensibilité de 0.1 μK.arcmin (dix fois meilleure que la sensibilité annoncée pour l'expérience CMB-S4).

Dans cette contribution, nous proposons de présenter le cas scientifique qui motive la construction d'un tel instrument et d'ouvrir la discussion sur les contraintes techniques associées.

Références

[1] http://sci.esa.int/planck/
[2] https://pole.uchicago.edu/
[3] https://act.princeton.edu/
[4] http://litebird.jp/eng/
[5] https://simonsobservatory.org/
[6] https://cmb-s4.org/
[7] https://www.simonsfoundation.org/event/the-cmb-in-hd-the-low-noise-high-resolution-frontier/

Dead and Dusty ETGs at z~3

C. D'Eugenio[1], E. Daddi[1], R. Gobat[2], V. Strazzullo[3], S. Jin[4]

[1] *CEA, IRFU, DAp, AIM, Université Paris-Saclay, Université Paris Diderot, F-91191 Gif-sur-Yvette, France*

[2] *Instituto de Física, Pontificia Universidad Católica de Valparaíso, Casilla 4059, Valparaíso, Chile*

[3] *Department of Physics, Ludwig-Maximilians-Universitat, Scheinerstr. 1, D-81679 Munchen, Germany*

[4] *School of Astronomy and Space Science, Nanjing University, Nanjing 210093, China*

The formation of quiescent early-type galaxies (ETGs) is still an unsolved mystery in galaxy evolution, together with their quenching mechanism(s). Its solution lies in the study of the most distant passive objects known so far, closer and closer to their formation event; and in the understanding the evolution of their interstellar medium across cosmic time. We take advantage of one of the first statistical samples of spectroscopically confirmed quiescent galaxies at z=3, obtained from HST grism spectroscopy. We will exploit NOEMA time (grade B) to probe the optically thin Rayleigh-Jeans tail of thermal dust continuum [1] at 1.1mm of one of our most distant targets ($z=3.118\pm 0.002$) (Fig.1), in order to measure M_{dust} and constrain M_{gas}. This is to clarify whether the strong evolution in $M_{dust}/M_\star$ observed for passive ellipticals from z=0 to z=1.76 as fast as $(1+z)^\alpha$ with $\alpha \geqslant 4-5$ [2] continues (case 1a in Fig.2), gets milder ($\alpha \sim 2.2$, case 1b), flattens (case 2) or actually inverts towards z=3 (case 3). In this sense, NOEMA data will help in the exploration of dust enrichment scenarios and, ultimately, in disentangling the elusive quenching mechanisms that led to the formation of such galaxies.

References:

[1] Magdis et al. 2011, ApJL, 740, L15

[2] Gobat et al. 2018, NatAstr, 2, 239

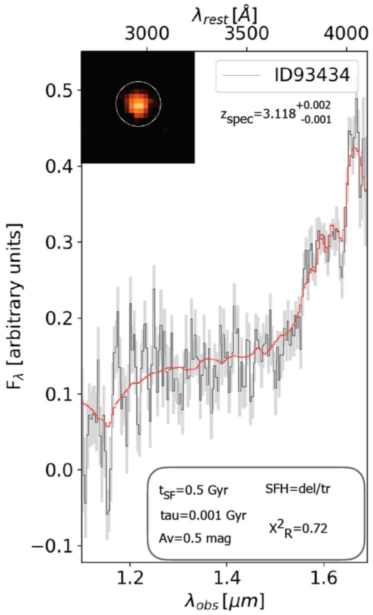


Fig.1: HST spectra of ID93434. Red curve: best fit Composite Stellar Population from Bruzual and Charlot 2003. The HST/WFC3 F160W imaging is reported, marked by a region of radius=0.6”.

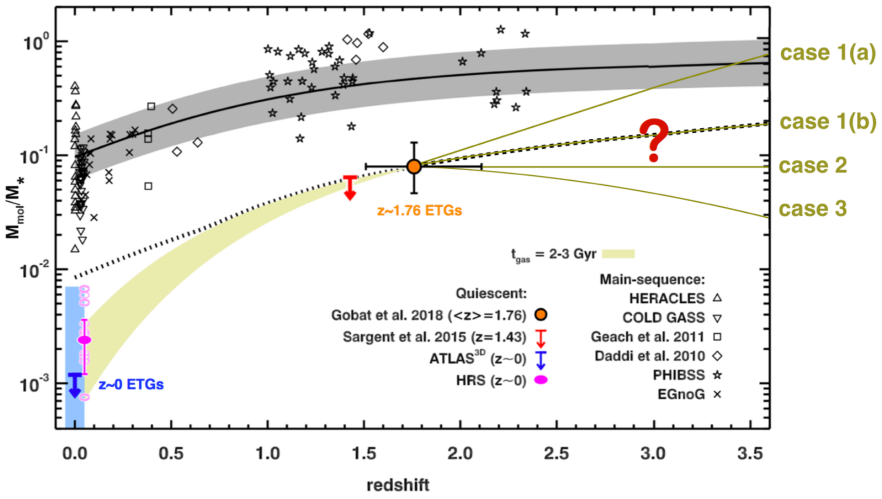


Fig. 2: Evolution of molecular gas fraction $M_{mol}/M_\star$ as a function of redshift for main-sequence (MS) and quiescent galaxies. The reference sample of 977 ETGs at $< z >\sim 1.76$ is marked as an orange dot. The solid line shows the the evolution of an average MS galaxy with stellar mass $5\times10^{10}M_\odot$. The dashed line shows the rise of the dust fraction (traced by molecular gas) with respect to local counterparts. Even when accounting for offsets in $M_\star$ between local and high-z samples there is an increase by more than two orders of magnitudes in $M_{mol}/M_\star$ which grows faster than what is happening in MS galaxies. The situation for more distant passive galaxies is currently unknown. Adapted from Gobat et al. 2018.

Towards a NOEMA survey of z>2 protoclusters ?

Hervé Dole, IAS, univ. Paris-Sud, univ. Paris-Saclay, CNRS
et al.

Understanding of the most distant galaxy clusters and proto-clusters at z>2, the epoch of the peak star formation is a hot topic of current research (e.g. Overzier 2016), providing an opportunity to investigate key physical processes in galaxy formation and cosmology. Many teams (see references) start having significant data.

Among those structures detected, a few exhibit very strong star formation rates (e.g. Wang et al., 2016, Planck Collab XXVII 2015). Understanding the processes of star formation, gas consumption, as a function of redshift and environment become thus possible in a cosmological context.

With 2160 Planck protoclusters candidates, selected on the whole sky on the cleanest 30% of the sky, we have a major homogeneous sample to study. These structures are color-selected to have very high star-formation rate. We followed-up about 230 of those with Herschel SPIRE, and about 80 with Spitzer (SPHerIC sample, the Spitzer Planck Herschel Infrared Clusters, Martinache et al., 2018). Few have already confirmed redshifts, and are above redshift 2. In addition, extremely intriguing structures show also high SFR e.g. in the COSMOS field.

NOEMA has the unique capability in the Northern hemisphere to quickly measure redshifts and measure many CO transitions as well as CII in this key redshift range z~2-4. Measuring the molecular gas content and excitation, identifying the gas reservoirs is a major scientific driver.

We propose the idea of a large program targeting an homogeneous sample of high SFR z>2 protocluster structures to address those questions.

References

Chiang, Y.-K. et al. 2014 ApJL 783 3
Daddi E., et al., 2016, ApJ, 829, 53
Daddi et al 2017 ApJ 846 L31;
Flores-Cacho et al., 2016, https://arxiv.org/abs/1510.01585
Gobat, R., Daddi E., et al. 2011 A&A 526 133
Galametz A., et al., 2012 ApJ 749 169
Hatch, N.A. et al. 2014 MNRAS 445 280
Muldrew et al. 2015 MNRAS 452 2528
Noirot, G. et al. 2016, ApJ, 830, 90
Noirot et al 2018, ApJ, 858, 39
Overzier R.A., 2016, AARv, 24, 14
Planck Collaboration. XXXIX, 2016 A&A 596 A100
Planck Collaboration. XXVII 2015 A&A 582 A30
Strazzullo, V., et al 2018 ApJ 862 64
Valentino F., Daddi E., et al., 2015, ApJ, 801, 132
Valentino F.
Wang T., et al., 2016, ApJ, 828, 56
Wylezalek et al 2013 ApJ 769 79.

Simulations numériques ab-initio de magnétosphères de trous noirs

Benoît Cerutti

Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France

L'environnement proche d'un trou noir en rotation rapide plongé dans un champ magnétique externe (la magnétosphère) est propice à l'accélération de particules à haute énergie et engendrer un rayonnement synchrotron de la radio aux rayons gamma. Le processus d'accélération reste encore très mal compris car la magnétosphère est difficile à modéliser. Pourtant, cette question n'a jamais été aussi pressante qu'aujourd'hui avec l'arrivée imminente des premières observations du Event Horizon Telescope (EHT) capables de résoudre l'horizon des événements, entre autres, du trou noir supermassif de la galaxie Sagittarius A*. A ce jour, seules les méthodes fluides de type magnétohydrodynamique ont été utilisées pour prédire les images attendues. Bien que cette approche soit suffisante pour rendre compte de la dynamique globale du flot de matière, elle s'avère incapable de modéliser l'accélération des particules et le rayonnement non-thermique associé. Je présenterai le tout premier modèle numérique ab-initio de type « particle-in-cell » d'une magnétosphère de trou noir et je décrirai quelques directions futures de nos travaux en lien avec les résultats de l'EHT.

Références

[1] Parfrey, K., Philippov, A., & Cerutti, B., accepté pour publication dans Phys. Rev. Lett. (2018)

Supplementary material for discussion

Investigating the nature of high redshift starbursts: new insights from their dust obscuration

Antonello Calabrò[1], Emanuele Daddi[1]

[1] *CEA, IRFU, DAp, AIM, Université Paris-Saclay, Université Paris-Diderot, Sorbonne Paris Cité, CNRS, F-91191 Gif-sur-Yvette, France*

A long standing problem in galaxy evolution is whether high-redshift starbursts (selected by their SFR(IR) excess compared to the star-forming Main Sequence) are gas rich galaxies or merger systems experiencing a larger star-formation efficiency. In order to study this highly embedded galaxies, it is more convenient to observe them in the near-IR rest-frame than in the optical, which is currently possible with ground-based telescopes only below redshift 0.9. I will present new results obtained for a representative sample of 25 Herschel-detected starbursts at $z\sim0.7$, observed with the Magellan-FIRE spectrograph. I will show that their dust attenuation pattern (derived by comparing Paβ, Hα and bolometric IR luminosities) is consistent with an optically thick mixed model with average total optical depth of 9 magnitudes in V band, indicating the presence of highly embedded cores, as seen in local ULIRGs. We argue this provides a strong evidence for a merger-induced starburst scenario at high redshift. In addition, I will show that the same galaxies follow relatively tight correlations between total obscuration, emission line ionization, starburst core size and effective age (as traced by line EWs), which are interpreted as a time-evolutionary sequence of merger stages. Intriguingly, X-ray emission is detected only for a subset of later-stage mergers, suggesting emergent AGNs leading to a final bright QSO and a passive spheroidal system. Within this year, IRAM-NOEMA observations for the same starbursts will allow to put tighter constraints on their core obscuration and further characterize the merger sequence by measuring their instantaneous total SFR activity. The sample presented here is almost unique in terms of spectral coverage, and paves the road for future investigations with JWST, which will probe fainter near-IR lines up to redshift 7.

Molecular gas content in galaxies with vs without a radio AGN

Delvecchio, I.[1], Daddi, E.[1]

[1]*Département d'Astrophysique, CEA-Saclay*

I will present on-going observing strategies at CEA-Saclay for measuring the molecular gas content within a carefully-selected sample of radio AGN in the COSMOS field. We have exploited very deep (rms~2.3uJy/beam) VLA 3 GHz observations in COSMOS, finding over 1300 radio AGN at redshift $0.6<z<5$. Radio AGN are key laboratories for testing the impact of AGN-driven feedback on galaxy growth. In a recent study [1] we found that the fraction of radio AGN - at fixed radio power and redshift – that live inside star-forming galaxies, is strikingly similar to that displayed by a control sample of galaxies without a radio AGN, matched in redshift and stellar mass. No difference is found at any radio power and redshift. This might suggest that the presence of a radio AGN does not strongly influence the overall star-forming content of the host galaxy.

Further observations are needed for exploring the molecular gas content of galaxies between galaxies with VS without a radio AGN, matched in mass, redshift, and star formation rate. Comparing the molecular gas mass inferred with NOEMA observations might give us clues on the star-formation efficiency and gas depletion timescales when a radio AGN is active or not.

NOEMA is the ideal instrument for carrying out this study. I will quickly describe our proposed target sample, observing strategy and possible implications of this analysis.

Références

[1] Delvecchio, I., et al., MNRAS, 481, 4971 (2018)

The extension of the cold gas in z>1 galaxies as seen with ALMA

Annagrazia PUGLISI[1]

Laboratoire AIM-Paris-Saclay, CEA/DSM-CNRS-Universit Paris Diderot,

Irfu/Service dAstrophysique, CEA Saclay, Orme des Merisiers, 91191 Gif sur Yvette, France

Studying the structure of the molecular gas in high-redshift galaxies is a key ingredient for understanding their star formation properties. Current studies show that massive star forming galaxies and SMGs in the distant Universe host compact concentrations of molecular gas, as traced by their CO and dust continuum emission. The question of whether more typical star-forming galaxies at $z>1$ host compact molecular gas reservoirs remains open. With our ALMA surveys targeting the CO(5-4) and CO(2-1) transitions and the 1.3 mm dust continuum in more than 100 objects at $1.1<z<1.7$ we can now measure the sizes of gas and dust in a wide dynamic range of stellar mass and SFR. This allows us to probe the extension of the molecular gas in different phases as well as explore its relation with galaxy integrated properties. I will present new results from these surveys discussing potential interest for exploring the spatial resolution capabilities of NOEMA phase-2.

Towards low surface brightness observations of gas accretion and cold gas recycling in high-redshift galaxies

P. Guillard[1], M. D. Lehnert[1], F. Boulanger[2,1] C, G. Pineau des Forêts[2,3], P. Cox[1].

[1] Sorbonne Université, CNRS, UMR 7095, Institut d'Astrophysique de Paris, 98bis bd Arago, 75014 Paris

[2]LERMA, UMR 8112, CNRS, Observatoire de Paris, 61 Avenue de l'Observatoire, 75014 Paris

[3]Institut d'Astrophysique Spatiale, CNRS UMR 8617, Université Paris-Sud, 91405 Orsay, France

The nature of the circum-galactic medium, and the dynamical interaction between the different gas phases flowing in and through the CGM, drive the baryon cycle of galaxies, and therefore regulate their baryonic content. Observations of gas in halos of galaxies, as well as in- and out-flows around them, start to show evidence that the (CGM) around galaxies is multiphase and turbulent (e.g., Emonts et al. 2016), but observationally tracking this baryon cycle at high redshift is still very challenging. I will discuss prospects of low-surface observations of cold gas around galaxies opened up by IRAM and ALMA, as well as the future JWST telescope. Those two slides present the discovery of a very massive (a few 1e10 solar masses) and extended (80 kpc) reservoir of CO gas in the halo of the Spiderweb protocluster at z=2, and the extremely bright [CII] line detections in a growing number of sources, which may be the sigh of the dissipation of turbulent-driven accretion (Guillard et al. 2019). This will hopefully provide food for thought for the discussions.

Références

[1] Emonts et al. 2016, Science

[2] Guillard et al., 2019, sub. to A&A.

Session # 3
ISM and star formation

Molecular gas in Brightest Cluster Galaxies

Salomé P[1], Olivares, V[1], Polles, F[1], Beckman R[2], Guillard, P[2], Dubois, Y[2], Godard B[1], Hamer, S[3], Combes F[1], Lehnert, M[1], Pineau des Forêts G[1] Boulanger F[1]

[1]*LERMA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, École normale supérieure, F-75014 , Paris, France*

[2]*IAP, Sorbonne Universités, UPMC Univ. Paris 6 et CNRS, UMR 7095, Institut d'Astrophysique de Paris, 98 bis Bd Arago, F-75014 Paris, France*

[3]*IOA, Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB1 0HA, UK*

Nearby Brightest Cluster Galaxies (BCGs) lying in cool core clusters have been discovered to host large amounts of molecular gas. This gas in organized in gigantic filamentary structures of several tens of kpc that are spread all around the central galaxy. Those objects harbor radio-AGNs that interact with the Intra-Cluster Medium (ICM) by inflating enormous gas cavities inside the cluster hot X-ray gas. Those bubbles are claimed to be an important actor of feedback, preventing the ICM to cool dramatically. NOEMA and ALMA bring a new piece in this picture : the detailed morphology and kinematics of the cold molecular filaments. The origin and the fate of these filaments is still debated. With the help of gas properties modeling, numerical simulations and new observations, we use those structure to probe their role in the gas life cycle around galaxies in the presence of an AGN.

Références:

[1] Tremblay G., et al., ApJ, 865, 13T (2018)
[2] Vantyghem, A. N, et al., arXiv181109653V (2018)

Propriétés du gaz dense et formation d'étoiles dans les galaxies proches avec le programme EMPIRE

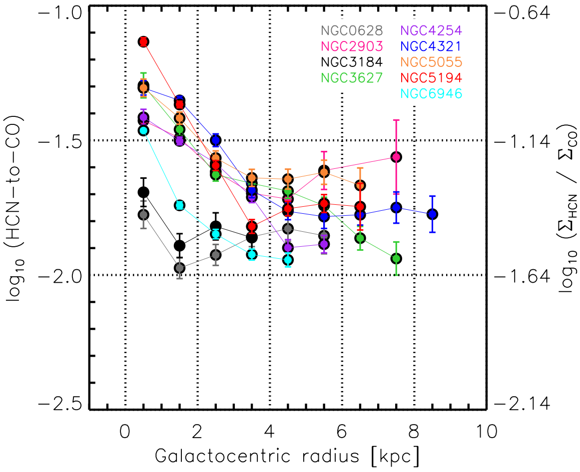
Diane Cormier[1], Frank Bigiel, María Jesús Jiménez-Donaire, Adam Leroy, Molly Gallagher, Antonio Usero, Annie Hughes, Jérôme Pety, et al.

[1] Laboratoire AIM, CEA/DSM - CNRS - Université Paris Diderot, Irfu/Service d'Astrophysique, CEA Saclay, 91191, Gif-sur-Yvette, France

Le gaz dense est un ingrédient majeur pour former des étoiles. Si certaines études indiquent qu'au-delà d'un certain seuil en densité, la quantité de gaz qui se transforme en étoile est quasiment universelle (ex : [1]), des études récentes du gaz dense – vu par HCN, HCO^+, ^{13}CO, maintenant accessibles à l'observation dans les galaxies proches – dressent un tableau plus complexe. En effet, la fraction de gaz dense (HCN/CO) et l'efficacité de formation d'étoiles (HCN/IR) semblent montrer des variations systématiques en fonction du rayon des galaxies, mettant en avant le rôle de l'environnement galactique pour contrôler ces quantités. Dans ce talk, je vais présenter les résultats initiaux du programme du 30-m EMPIRE (PI Bigiel) qui a cartographié entièrement les traceurs du gaz dense dans 9 galaxies spirales proches ([2,3,4,5]), et les perspectives de suivis à haute résolution pour tester le rôle de la densité dans la formation stellaire.

Références

[1] Evans et al., ApJ, 782, 114 (2014)
[2] Bigiel et al., ApJ, 822, 26 (2016)
[3] Cormier et al., MNRAS, 475, 3909 (2018)
[4] Gallagher et al., ApJ , 858, 90 (2018)
[5] Jiménez-Donaire et al. in prep



Millimeter-centimeter emission excess in nearby galaxies

K. Lutz[1], C. Bot[1]
[1] *Université de Strasbourg, CNRS, Observatoire astronomique de Strasbourg, UMR 7550, F-67000 Strasbourg, France*

The multi-wavelength emission of galaxies is a composite emission: stellar emission in the UV and optical, dust emission in the IR, free-free emission and synchrotron in the radio. At microwave frequencies, all these radiations from a galaxy will be superimposed on the background emission from the cosmic microwave background (CMB) fluctuations.

Studies of nearby galaxies with the Planck satellite ([1] and [2] for the Magellanic Clouds; [3] for NGC4214, [4] for M31 and [5], [6] for M33) have shown that the dust emission of nearby galaxies at millimeter wavelengths is flatter than what was expected. In other words, there is an excess emission at millimeter wavelengths above that expected from dust, free-free, synchrotron and CMB fluctuations. This millimeter excess is probably due to a change of dust properties and different dust models can account for it (different dust emissivity slope, different dust properties, different emission mechanism).

Another result of these studies stems out only if we put them all together: in order to reproduce the spectral energy distribution of these galaxies, CMB fluctuations had to be removed. These fluctuations can be either positive or negative, but in the direction of these nearby galaxies, all the fluctuations were systematically taken to be positive. This is highly surprising: why would all these galaxies lie on hot spots of CMB fluctuations? Instead, it is possible that part of the millimeter excess emission is taken into account as CMB fluctuations at the moment and that the excess may be higher than what has presently been reported.

New observations of nearby galaxies at higher resolution with IRAM would enable more detailed studies of this millimeter-centimeter excess in nearby galaxies and to probe its origin and environmental dependencies.

References:

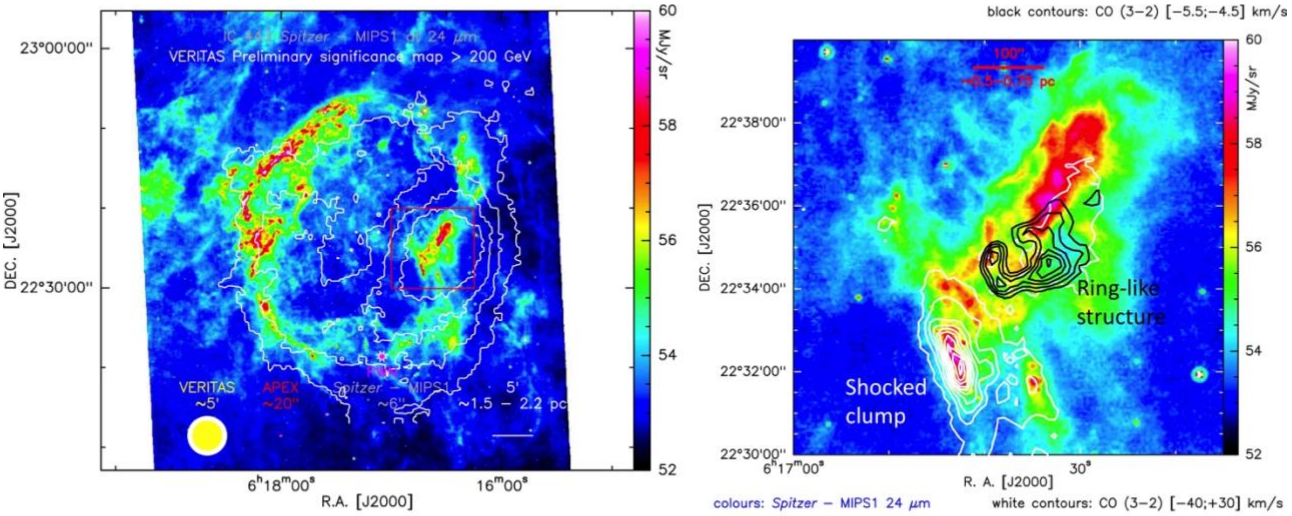
[1] Bot, C., Ysard, N., Paradis, D., et al. 2010b, A&A, 523, A20
[2] Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2011, A&A, 536, A17
[3] Hermelo I., Lisenfel U., Relano M., Tuffs R., Popescu C., Groves B., 2013, A&A, 549, A70
[4] Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2015b, A&A, 582, A28
[5] Hermelo I., Relano M., Lisenfeld U., Verley S., Kramer C., et al., 2016, A&A, 590 A56
[6] Tibbs C. T., Israel F. P., Laureijs R. J., Tauber J.A., et al., 2018, MNRAS, 477, 4968

The molecular cloud interacting with cosmic rays in IC443G

P. Dell'Ova[1,2], A. Gusdorf[1,2], M. Gerin[1,2]

[1]LERMA, UMR 8112 du CNRS, Observatoire de Paris, École Normale Supérieure, 24 rue Lhomond, F75231 Paris Cedex 05, France.
[2]Sorbonne Universités, UPMC Université Paris 6, Paris, France.

Context. Supernova remnants (SNRs) account for a major feedback source of stars on the galactic interstellar medium. During the latest stage of supernovae explosions, shock waves produced by the blast modify the chemistry of gas and dust, inject kinetic energy in the surroundings, and may enhance or trigger star formation. Simultaneously, cosmic rays accelerated in the early stages interact with the ambient gas, generating gamma ray photons.
Aims. We study the properties of the gas in IC443, a shell type SNR at a distance of 1-1,5 kpc. Located within the peak of gamma emission, IC443G is the best suited molecular cloud to investigate star formation, as well as gas and dust evolution under the influence of cosmic rays.
Methods. We used 10'×10' maps of CO(2-1) and CO(3-2) transitions obtained with APEX over the whole extent of the gamma ray peak to reveal the molecular structure of the region. We measured optical depths of the ^{12}CO(2-1) and (3-2) transitions, then we used an excitation diagram analysis and/or LVG analysis to measure the mass and constrain the kinetic temperature of the gas.
Results. Two molecular clouds are detected: one shocked molecular clump associated with linewidths extending between -30 km/s and 20 km/s and a quiescent, denser one associated with a linewidth of 2 km/s having a ring-like structure. We used complementary data (tracing the stars, gas and dust) at multiple wavelengths to understand the association of these two structures with the very peak of gamma emission detected by VERITAS and FERMI. We postulate that the interaction between cosmic rays and both clouds might contribute to the gamma ray emission.



Left: The IC443 supernova remnant seen by *Spitzer*/MIPS at 24 µm (colours), overlaid with the sgnificance map above 200 GeV obtained from the VERITAS gamma-ray telescope (white contours). The red rectangle is the region we mapped in CO (2-1) and (3-2) with APEX. It corresponds to the peak of gamma-ray emission. *Right:* a zoom-in on the red rectangle image, showing the *Spitzer*/MIPS emission at 24 µm (colours), and our 12CO (3-2) observations (contours). The white contours show the shocked clump (integrated between -40 and +30 km/s), while the black ones show a ring-like structure (between -5.5 and -4.5 km/s).

Colliding filaments in the Monoceros OB 1 molecular cloud

J. Montillaud[1], M. Juvela[2], C. Vastel[3] et al.

[1]Institut UTINAM - UMR 6213 - CNRS - Univ BFC, OSU THETA, Besançon, France
[2]Department of Physics, P.O.Box 64, FI-00014, University of Helsinki, Finland
[3]Université de Toulouse; UPS-OMP; IRAP; Toulouse, France

Current theories and models attempt to explain star formation globally, from core scales to giant molecular cloud scales. A multi-scale observational characterisation of an entire molecular complex is necessary to constrain them. The *Galactic cold cores* (GCC) programme has built an unbiased sample of star-formation (SF) regions with various physical characteristics (e.g. size, mass, temperature, ...) and environments (e.g. quiet vs. close to an expanding HII region), where large-scale submillimetre dust emission was mapped [1,2]. This makes an excellent sample to study the connection between (i) the evolution of cores and filaments in a star-forming cloud and (ii) the global evolution of the cloud, as well as to identify the engines of the cloud dynamics.

As a first step in the multi-scale analysis, we investigated the star formation activity in G202+2.8 [3], a sub-region of the Monoceros OB1 cloud with a complex morphology harbouring interconnected filamentary structures. We characterised the properties of the structures and sources in this field using both infrared observations from the *Herschel* and WISE telescopes and molecular tracers observed with the IRAM 30m and TRAO 14m telescopes. The SF activity was evaluated by surveying the distributions of dense cores and protostars, and their evolutionary state. The velocity field of the cloud was examined and velocity-coherent structures were identified and characterised to analyse the dynamics of the filaments. We found evidence for a local peak in star-formation activity around the centre of G202+2.8, where several protostars are found, including a Class 0/I protostar that may be responsible for two crossed outflows. Two main velocity components in molecular tracers were revealed, well separated in radial velocities in the north and merged around the location of an intense N_2H^+ emission in the centre of G202+2.8. We showed that the relative position of the two components along the sightline, and the velocity gradient of the N_2H^+ emission imply that the components have been undergoing collision for 10^5 yrs, although it remains unclear whether the gas mainly moves along or across the filament axes. The dense gas where N_2H^+ is detected (Fig.1) was interpreted as the compressed region between the two filaments, corresponding to a high mass-inflow rate of $\sim 1\mathrm{x}10^{-3}$ M_{sun}/yr for this region and possibly leading to a significant increase in its star-formation efficiency. We showed that the HII region around the nearby cluster NCG 2264 is still expanding and its role in the collision was examined. However, we could not rule out the idea that the collision arises mostly from the possible global collapse of the cloud.

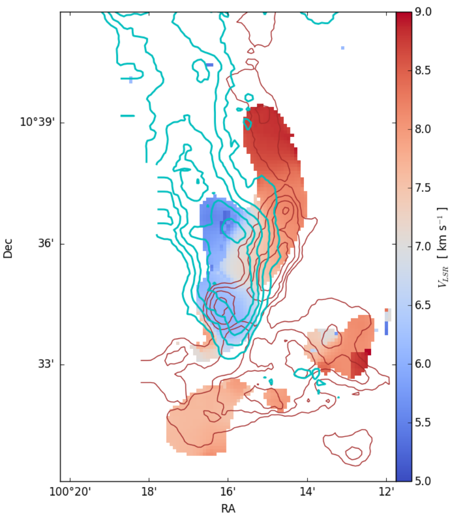


Fig. 1: Centroid velocity of the N_2H^+ isolated component at the junction point between the colliding filaments (color scale). The blue and red lines show the contours of the ^{13}CO emission from the north filament (~5 km/s), and the south filament (~8 km/s).

The Monoceros OB1 cloud appears as a valuable test case for star-formation theories. As a second step in our multi-scale approach, a large-scale study of this region is now necessary to investigate the scenario of a global collapse and its origin. The IRAM 30m telescope is an excellent tool to continue the characterisation of both the dense gas and the large-scale dynamics in the GCC fields.

Références

[1] Juvela M., Ristorcelli I., Pagani L. et al., A&A, 541, A12 (2012)
[2] Montillaud J., Juvela M., Rivera-Ingraham et al., A&A, 584, A92 (2015)
[3] Montillaud J., Juvela M., Vastel C. et al., submitted to A&A

ALMA, SMA and PdBI interferometric observations observations of the youngest solar-type protostars

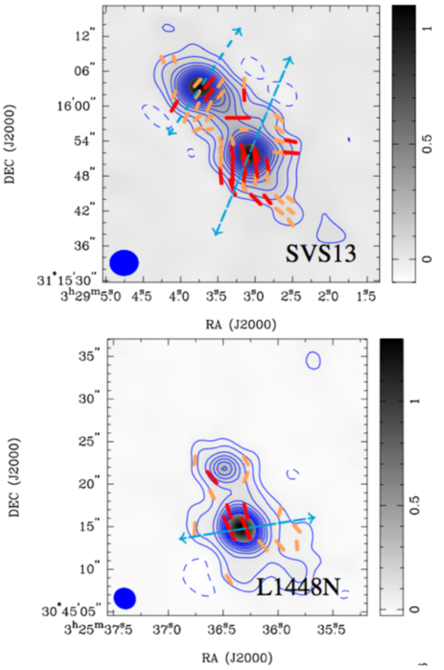
M. Galametz [1], A. Maury [1] et al.

[1] Astrophysics department, CEA/DRF/IRFU/DAp, Universit\'{e} Paris Saclay, UMR AIM, F-91191 Gif-sur-Yvette, France

The Class 0 population is key to understand stellar evolution because it is the protostellar phase during which most of the accretion takes place, i.e. when most of the stellar material is collected into the protostellar embryo.

Orientation of the magnetic fields in the envelope:

Magnetic fields (B) are believed to redistribute angular momentum efficiently during the accretion process but the role of B during the Class 0 stage is still unclear. In order to study the structure of B on 1000-2000 AU scales, we have acquired polarization observations of 9 low-mass protostellar cores with the SMA interferometers. Our sample contains 9 Class 0 protostars and includes single objects as well as close and wide multiples. Polarization is detected in all objects. I will show how the magnetic field lines align or not with the object outflow and that a relation seems to exist between the orientation of the magnetic field, the presence of fragmentation and the rotational energy at the envelope scale [1].



SMA 850µm continuum maps of two Class 0 protostars. The blue arrows indicate the outflow orientations. B-field vectors are overlaid with orange and red (2 and 3-σ detections)

Orientation of the magnetic fields on small scales:

One of the objects, B335, was followed-up with ALMA. I will present the complex morphology of its small-scale B structure, with a large-scale poloidal B in the outflow direction and a strongly pinched B in the equatorial direction. Our results suggest that the magnetized collapse has a high level of organization down to 50 AU scales [2].

Dust composition and evolution:

We are currently using 1 and 3mm observations of Class 0 protostars observed with PdBI (CALYPSO survey) to investigate potential variations of the grain size in their envelopes. We are comparing our interferometric observations with predictions from synthetic observations derived from MHD simulations of collapsing cores (Galametz et al. in prep). I will present some preliminary results.

References

[1] Galametz M. et al., 2018, A&A, 616A, 139 [2] Maury A. J. et al., MNRAS, 477, 2760

Searching for pre-brown dwarf cores in nearby star-forming clouds with NIKA2 and NOEMA

Ph. André[1], B. Ladjelate[1], Y. Shimajiri[1], N. Peretto[2], D. Ward-Thompson[3]

[1]*AIM, Laboratoire d'Astrophysique-Instrumentation-Modélisation, UMR7158*
CEA-Université Paris-Diderot-CNRS, C.E. Saclay, Orme des Merisiers - Bât. 709, 91191
Gif-sur-Yvette Cedex – France

[2] *School of Physics and Astronomy, Cardiff University – UK*

[3] *Jeremiah Horrocks Institute, University of Central Lancashire, Preston – UK*

The origin of brown dwarfs (BDs) is an important astrophysical problem because its solution can also shed light on how a broad range of objects, from typical stars to giant planets, are formed and gain their masses. Using PdBI/NOEMA at 3.2 mm and ALMA at 1.3 mm, we identified a good example of a pre-brown dwarf core (Oph B-11), a self-gravitating starless condensation of gas and dust in the BD mass regime, possibly formed by shock compression [1]. Our results on Oph B-11 tend to support models according to which brown dwarfs form in a similar manner to normal stars, from the direct collapse of a prestellar core. However, it does not yet prove that pre-brown dwarfs are the main channel of brown dwarf formation. A full assessment of the « pre-brown dwarf hypothesis » for brown dwarf formation requires a deep single-dish census of candidate brown-dwarf cores in nearby star-forming regions such as Ophiuchus and Taurus, followed up by interferometric observations to determine whether these candidates are compact/dense enough to be self-gravitating, hence bona-fide pre-brown dwarfs. The high mapping speed provided by NIKA2 on the 30m telescope for 1.2mm/2mm dust continuum observations, combined with the enhanced capabilities of NOEMA (e.g. much better sensitivity than PdBI), offer a unique opportunity to take a big step forward on this science topic in the coming years.

References

[1] André, Ph., Ward-Thompson, D., Greaves, J.S. 2012, Science, 337, 69

Supplementary material
for discussion

Rotation of Molecular Clouds

Jonathan Braine

Laboratoire d'Astrophysique de Bordeaux
CNRS / University of Bordeaux
Bordeaux, France

Systematic rotation of molecular clouds was detected for the first time in the Local Group spiral Messier 33, where a sample of 566 molecular clouds is available. There is a clear preference for prograde rotation (i.e. same direction as the galaxy as a whole). This preference is even stronger when the high signal-to-noise sample is used, reducing the effect of noise. The M33 results were presented by Braine et al. (2018, A&A 612, 51).

We have now analyzed the results for Messier 51, observed at high resolution with the Plateau de Bure interferometer as part of the PAWS project. M33 is a rather flocculent galaxy (without strong spiral arms) whereas M51 has very strong spiral arms. The arms provide a new environment, with a non-axisymmetric potential. As for M33, the clouds rotate mostly prograde. However, the fraction of prograde rotators is lower in the arms than outside of the arms (i.e. more retrograde rotators in the arms). The PAWS observations cover the region within corotation, so the clouds "catch up" to the arms and then leave them. Dividing the arm clouds into "entering" and "leaving" clouds, we find that while a large majority of the clouds enter the arms prograde, the majority leave with retrograde rotation!! Over the region observed, the time for the clouds to cross the arm is less than a cloud lifetime. Rotation direction has thus been reversed within the arms...

By the time of the conference, we should be able to present not only the M33 and M51 results but also those of a strongly barred galaxy, M83, observed with ALMA and enabling a new non-axisymmetric environment (bar) to be studied. This project was initiated following the observation that molecular gas was transformed more quickly into stars in sub-solar metallicity galaxies, and that cloud linewidths were systematically lower (at equivalent cloud size) in sub-solar metallicity galaxies as compared to large spirals. Cloud line widths are dominated by turbulence with a contribution from rotation. A major field of study for SPICA is the dissipation of turbulence through low-velocity shocks. Turbulence and angular momentum reversal are prime subjects for the study of low-velocity shocks with SPICA, typically through spectroscopy of the OI and H2 lines but not limited to that.

Kinematic studies of protostellar envelopes at high angular resolution with CALYPSO

M.Gaudel[1], A. Maury[1], A. Belloche[2] et Ph. André[1]

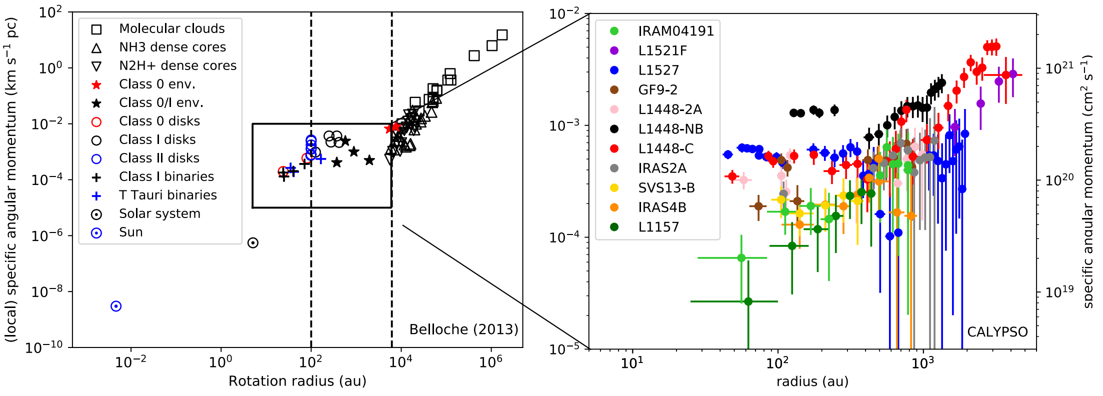
[1]AIM, CEA/DRF-CNRS-Université Paris Diderot, IRFU/Département d'Astrophysique, CEA Saclay, 91191 Gif-sur-Yvette - France

[2]Max-Planck-Institut fuer Radioastronomie, Auf dem Huegel 69, D-53121 Bonn - Germany

One of the main challenges to the formation of solar-like stars is the "angular momentum problem": if the angular momentum of the protostellar envelope is totally transferred to the central embryo during the main accretion phase, the gravitational force cannot counteract the centrifugal force and the stellar embryo fragments prematurely before reaching the main sequence. Thus, the rotating envelope needs to reduce its angular momentum by 5 to 10 orders of magnitude.

In order to quantify the amplitude of this problem and identify the mechanisms responsible for the angular momentum redistribution, we used high angular resolution observations (0.5'', i.e. ~100 au) from the CALYPSO (Continuum and Lines in Young Protostellar Objects, PI: Ph. André) IRAM large program for a sample of 11 Class 0 protostars with d<250 pc. Combining the molecular line emission from $C^{18}O$ and N_2H^+ as well as spatial information of the PdBI and 30m, we probed the kinematics and established, for the first time in a large sample, robust constraints on the radial distributions of specific angular momentum within protostellar envelopes in a large range of scales from ~100 to 5000 au. Two distinct regimes are revealed: a relatively constant profile at small scales (<1000 au) and an increasing of the angular momentum at larger radii (1000-5000 au).

The constant profile shows that the specific angular momentum of the material directly involved in the star formation (<1000 au) is "only" 3 orders of magnitude larger than the typical one of T-Tauri stars. Furthemore, velocity gradients observed on large scales (>3000 au) - that are historically used to measure the rotation of the core and quantify the angular momentum problem - are not due to pure envelope rotation but can be the signature of the turbulent cascade from 10^6 to 1000 au or a contamination from the interstellar filament dynamics on the light of sight.



Witnessing the fragmentation of filament into prestellar cores in Orion B/NGC 2024

Y. Shimajiri[1], Ph. Andre[1], N. Peretto[2], D. Arzoumanian[3],
and K Konyves[1]

[1] Laboratoire AIM, CEA/DRF-CNRS-Université Paris Diderot, IRFU/Département d'Astrophysique, C.E. Saclay, 91191 Gif-sur-Yvette, France
[2] School of Physics & Astronomy, Cardiff University, Queen's building, The parade, Cardiff, CF24 3AA, UK
[3]Department of Physics, Graduate School of Science, Nagoya University Nagoya 464-8602, Japan

Recent *Herschel* observations of nearby molecular clouds revealed that filamentary structures are ubiquitous and that most prestellar cores form in dense filaments. Thus, revealing that the dense filaments are fragmenting into cores from the kinematic viewpoint observationally is crucial to understand the star formation in filaments. We aimed to investigate whether the observed filaments are fragmenting into cores. We observed NGC2024 of the Orion B molecular cloud in the ^{12}CO (1--0), ^{13}CO (1--0), C^{18}O (1--0), and H^{13}CO^{+}(1--0) molecular lines with Nobeyama 45m telescope and in H^{13}CO^{+} (1--0) with NOEMA. The distributions of the ^{13}CO, C^{18}O, and H^{13}CO^{+} emission show the filamentary structure. The mean radial column density profile in *Herschel* shows the 0.06 pc filament width which is consistent with the previous *Herschel* studies. On the other hand, the filament widths in ^{13}CO and C^{18}O are larger than that in *Herschel*, while the width in H^{13}CO^{+} is narrower. These results suggest the ^{13}CO and C^{18}O emission trace only the outer (lower density) part of the *Herschel* filament and the H^{13}CO^{+} emission traces only the inner (denser) part. To identify cores embedded in the filament, we performed the *dendrogram* analysis on the *Herschel* column density and NOEMA H^{13}CO^{+} cube maps. As a result, we detected fours cores in the *Herschel* map toward the area covered with the NOEMA and found that each core detected in *Herschel* corresponds to one core detected in the NOEMA H^{13}CO^{+} cube map. The Nobeyama H^{13}CO^{+} centroid velocity map shows the velocity gradient along both axes of the filament and velocity oscillation along the major axis. A comparison between centroid velocity and density distributions revealed that there is a lambda/4 phase shift between two distributions around the core associated with a protostar. The velocity structure function of our toy model of the fragmenting filament also has a good agreement with the observed velocity structure function. These results can be explained that the filament in NGC2024 fragments into cores.

Références

[1] André, P., Men'shchikov, A., Bontempts, S., e al. 2010, A&A, 518, L102

[2] Konyves, V., André, P., Men'shchikov, A., et al. 2015, A&A, 54, A91

Synergy between observations and numerical simulations in the context of low-mass star formation.

Valeska Valdivia[1], Anaëlle Maury[1], Patrick Hennebelle[1], Maud Galametz[1],
Robert Brauer[1] & Stefan Reissl[2]

[1] Laboratoire AIM, Paris-Saclay, CEA/IRFU/DAp - CNRS - Université Paris Diderot, 91191 Gif-sur-Yvette Cedex, France

[2] Universität Heidelberg, Zentrum für Astronomie, Institut für Theoretische Astrophysik, Albert-Ueberle-Str. 2, 69120 Heidelberg, Germany

Star formation takes place in the densest regions of filamentary molecular clouds. The gravitational collapse of the protostellar envelope transports not only the mass that builds up the star, but also carry a load of angular momentum which, if totally transferred to the accreting protostar, can accelerate the protostar up to break-up speeds, ultimately preventing the star formation. Observations of Class 0 protostars suggest that large circumstellar disks and multiple systems are quite rare during this phase, questioning the standard scenario in which they form because of conservation of angular momentum of the rotating envelope [1]. Numerical simulations have shown that magnetic fields play a key role in the transport of angular momentum [2,3,4]. In magnetized models the magnetic braking redistributes efficiently most of the envelope's angular momentum, hence predicting the formation of smaller circumstellar disks. Using the polarization capabilities of the SMA we have observed 12 low-mass proto-stars at 870 µm [5], and we have detected dust polarized emission in all the objects of the sample. The sample shows a depolarization towards high density regions, and the orientation of the inferred magnetic field vectors with respect to the outflow direction shows a bimodal distribution. Non-ideal MHD numerical simulations are helping us to study the evolution of the magnetic field during the gravitational collapse. To compare with observational data, we postprocessed a snapshot from the simulation with the state-of-the-art radiative transfer code POLARIS [6] to compute the Stokes parameters and produce synthetic observations of mm/submm polarized dust emission. We compare the results obtained using the radiative torques (RAT) mechanism to the results obtained by assuming that grains are perfectly aligned to constrain how well polarized dust emission traces the magnetic field orientation. We find that the RAT mechanism traces the magnetic field as long as: 1) the radiation source is strong enough, 2) the dust grains are big enough to be aligned, and 3) the magnetic field remains well organized.

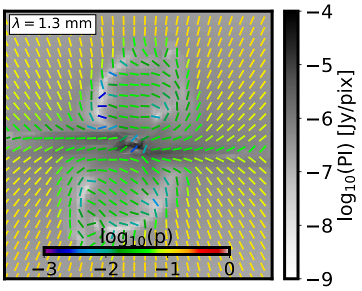


Fig. 1: Synthetic polarized dust emission from a protostellar envelope collapse (RAMSES niMHD simulation + POLARIS radiative transfer) at a scale of 2000 au (background gray scale) showing the magnetic field orientation and polarization fraction (color scale) inferred from the Stokes parameters.

References

[1] Maury A. J. et al., 2010, A&A, 512, A40
[2] Joos M. et al., 2012, A&A, 543, A128
[3] Seifried D. et al, 2013, MNRAS, 432, 3320
[4] Li Z.-Y. et al., 2013, ApJ, 774, 82
[5] Galametz, M. et al. 2018, A&A, 616, A139
[6] Reissl, S. et al 2016, A&A, 593, A87

Session # 4

Dying stars, Young Stellar Objects, and Astrochemistry

Reconstruction 3D de l'environnement de la supergéante rouge μ Cep à partir d'observations NOEMA de la raie CO J = 2-1

M. Montargès[1], W. Homan[1], D. Keller[1], L. Decin[1], G. Harper[2], J. M. Winters[3],
A. Castro-Carrizo[3] et T. Le Bertre[4, 5].

[1] Institute of Astronomy, KU Leuven, Celestijnenlaan 200D B2401, 3001 Leuven, Belgium
[2] Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309, USA
[3] Institut de Radioastronomie Millimétrique, 300 rue de la Piscine, 38406, Saint Martin d'Hères, France
[4] LERMA, Observatoire de Paris, PSL Research University, CNRS, UMR 8112, 75014, Paris, France
[5] Sorbonne Universités, UPMC Univ. Paris 06, UMR 8112, LERMA, 75005, Paris, France

Les étoiles supergéantes rouges sont entourées d'un environnement circumstellaire composé de gaz et de poussières. Il est alimenté par leur perte de masse qui permet à l'étoile de disperser des éléments lourds dans le milieu interstellaire. Mieux connaître la structure et la dynamique de cette enveloppe est crucial pour comprendre les processus à l'origine de la perte de masse des supergéantes rouges, perte de masse qui contribue fortement à façonner l'éjecta initial de la supernova.

Nous avons observé l'émission de la raie CO J=2-1 de la supergéante rouge μ Cep avec l'interféromètre NOEMA. Le *beam* de l'interféromètre est de 0.92 x 0.72 arcsec (590 x 462 au à la distance de μ Cep). Les cartes de continuum ne montrent pas d'autre signal que l'émission de la source centrale. Soustraites du continuum, les cartes par canaux montrent un environnement circumstellaire très inhomogène et constitué de nombreux *clumps.*

Nous avons effectué une déprojection 3D de l'ensemble des données en faisant l'hypothèse d'un champ de vitesse constant dans l'environnement circumstellaire. Cette déprojection nous a permis d'effectuer une modélisation 3D grâce au code de transfert radiatif LIME. Nous avons pu déterminer le taux de perte de masse de μ Cep dont seule une faible fraction est due aux *clumps*. Le reste est dû à un flux continu dont nous ne pouvons pas assurer qu'il ne soit pas lui-même composé de *clumps* non résolus par nos observations.

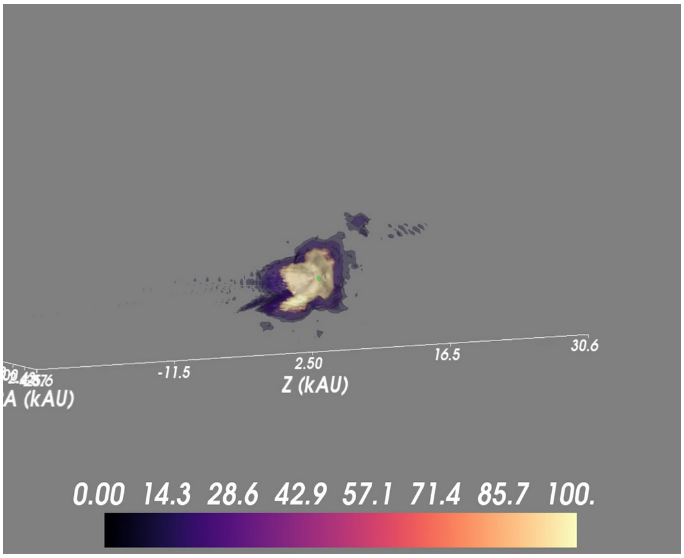


Fig. 1: *Illustration de la déprojection 3D de l'environnement de μ Cep.*

A survey of the HCN and HNC C and N isotopic ratios in nearby star formation regions

Victor S. Magalhães[1], Pierre Hily-Blant[2], Alexandre Faure[2]

[1] IRAM, 300 rue de la Piscine, 38406 Grenoble Cedex, France
[2] IPAG, 414 rue de la Piscine, 38406 Grenoble Cedex, France

The nitrogen isotopic ratio ($^{14}N/^{15}N$) varies in the Solar system, it can be as low as 50 (meteorites[1]) and as high as 441 (in the Sun[2]). The origin of this variation is however not known. Elucidating the origin of this variation might bring about new understanding in the inheritance of volatiles by planetary systems. A tantalizing hint was uncovered with the detection of a fractionated reservoir of HCN in protoplanetary disks[1,3]. This fractionated reservoir presented a nitrogen isotopic ratio of ~110, which is a third of the isotopic ratio of the bulk of the ISM, ~330[1]. With this result in mind we set out on the goal of obtaining the first direct measurement of the nitrogen isotopic ratio in HCN in the dense ISM. We succeeded in this endeavor through the use of spectra obtained with the IRAM-30m telescope, which were fitted using a MCMC technique coupled to our non-local 1D radiative transfer code, ALICO[4-6]. From this fit we obtained a nitrogen isotopic ratio of HCN in L1498 of 338(29)[6], which is in agreement with the bulk of the ISM, but also found that HCN was heavily fractionated in carbon with $H^{12}CN/H^{13}CN = 45(3)$[6], much lower than that the bulk ($^{12}C/^{13}C$~70[7]). The mixed isotopic ratio $H^{13}CN/HC^{15}N$ was measured to be 7.5(0.8), which is in good agreement with previous measurements in L1498 using escape probability methods (7.9(0.9)[8]). From this, we can assume that the previously measured $H^{13}CN/HC^{15}N$ ratios in other sources using escape probability methods are reliable. We find however, that the already measured ratios are not in agreement with the value measured in L1498: $H^{13}CN/HC^{15}N$=2.0-4.5 in L1544, 2.0-3.7 in L183, and 5.5(0.8) in B1 [9, 10]. These discrepancies open up the intriguing possibility of source-to-source variations on the C and/or N isotopic ratios in HCN, which may implicate new constraints in nitrogen chemistry in the ISM.

With this tantalizing possibility in mind we have set out to redo the work done with L1498 to two more prestellar cores: L1512 and L183. We have also decided to include one more species, HNC, a sister molecule to HCN. To be able to unambiguously derive the abundances of HCN and HNC we plan to use density profiles derived from continuum observations and two rotational transitions of the main isotopologues, J=1-0 and J=3-2. The J=1-0 observations of HCN, HNC and their rare isotopologues have been realized in September 2018 in the 30m telescope while the J=3-2 observations shall be carried out during this semester, also on the 30m telescope. This project is only possible due to great sensitivity of the IRAM-30m telescope which enables fast observation of the rare isotopologues and higher J transitions (less than an hour per position on the sky). The large bandwidth provided by the EMIR receiver also enables us to have the $H^{13}CN$ and $HC^{15}N$ J=1-0 transitions simultaneously, greatly reducing the integration times needed.

[1] Hily-Blant, P., Magalhaes, V., Kastner, J., et al. 2017, A&A, 603, L6
[2] Füri, E. & Marty, B. Nature Geoscience 2015, 8, 515–522.
[3] Guzmán, V. V., Öberg, K. I., Huang, J., Loomis, R., & Qi, C. 2017, ApJ, 836, 30
[4] Daniel, F., & Cernicharo, J. 2008, A&A, 488, 1237
[5] Magalhães, V. S. Ph.D. thesis, Université Grenoble Alpes, 2017.
[6] Magalhães, V. S.; Hily-Blant, P.; Faure, A.; Hernandez-Vera, M.; Lique, F. A&A 2018, 615, A52.
[7] Milam, S. N., Savage, C., Brewster, M. A., Ziurys, L. M., & Wyckoff, S. 2005, ApJ, 634, 1126
[8] Ikeda, M., Hirota, T., & Yamamoto, S. 2002, ApJ, 575, 250
[9] Hily-Blant, P., Bonal, L., Faure, A., & Quirico, E. 2013a, Icarus, 223, 582
[10] Daniel, F., Gérin, M., Roueff, E., et al. 2013, A&A, 560, A3

Hot corino aging: molecular complexity and deuteration towards the Class I source SVS13-A

E. Bianchi[1], C. Ceccarelli[1, 2], C. Codella[3, 1], M. Bouvier[1], A. Dehghanfar[1], M. De Simone[1], J. Enrique-Romero[1], A. Jaber Al-Edhari[1], C. Kahane[1, 2], B. Lefloch[1, 2], A. López-Sepulcre[4, 1], J. Ospina-Zamudio[1], F. Vazart[1], N. Balucani[5], R. Neri[4], C. Vastel[6]

[1] *Univ. Grenoble Alpes, IPAG, F-38000 Grenoble, France*

[2] *CNRS, IPAG, F-38000 Grenoble, France*

[3] *INAF-Osservatorio Astrofisico di Arcetri, 50125 Firenze, Italy*

[4] *Institut de Radioastronomie Millimtrique (IRAM), 38406 Saint-Martin-d'Hères, France*

[5] *Dipartimento di Chimica, Biologia e Biotecnologie, Università degli studi di Perugia, 06123 Perugia, Italy*

[6] *IRAP, Université de Toulouse, CNRS, UPS, CNES, Toulouse, France*

The measurement of the abundance of both deuterated molecules and interstellar Complex Organic Molecules (iCOMs; C-bearing molecules containing at least six atoms) is a crucial step in understanding the formation of pre-biotic molecules in the interstellar medium and their possible delivery onto planetary systems around Sun-like stars. In addition, the D/H ratio can be used as fossil record of the physical conditions at the moment of the icy water and organics formation. Typical laboratories where to study both iCOMs and deuterium fractionation are the so-called hot-corinos, i.e. the inner 100 au envelope of Sun-like protostars. These regions are heated at temperatures larger than 100 K, so that dust mantles products enrich the chemical composition of the gas and trigger subsequent chemical gas-phase reactions. While hot-corinos in Class 0 sources are relatively well-known, very little has been done so far to study the overall composition of those of more evolved Class I sources.

We present a chemical systematic study of the Class I object SVS13-A [1,2] obtained in the framework of two IRAM Large Programs: ASAI (Astrochemical Survey At IRAM-30m: [3]) with the 30m and SOLIS (Seeds Of Life In Space: [4]) with NOEMA.

Thanks to the ASAI high-sensitivity unbiased spectral survey of the 3, 2 and 1.3 mm bands (rms of few mK in channels of 0.6-0.2 km s^{-1}), we detected and analysed several emission lines from deuterated species and iCOMs (Fig. 1). Within SOLIS, we obtained spectacular high-sensitivity and high-spatial resolution maps of crucial iCOMs (Fig. 2,3) and many other species, thanks to the large spectral coverage of the new Polyfix correlator.

These new observations are the first step to fill in the gap between prestellar cores and protoplanetary disks, showing how the gas chemical content is modified during the early evolutionary stages of Sun-like star forming regions.

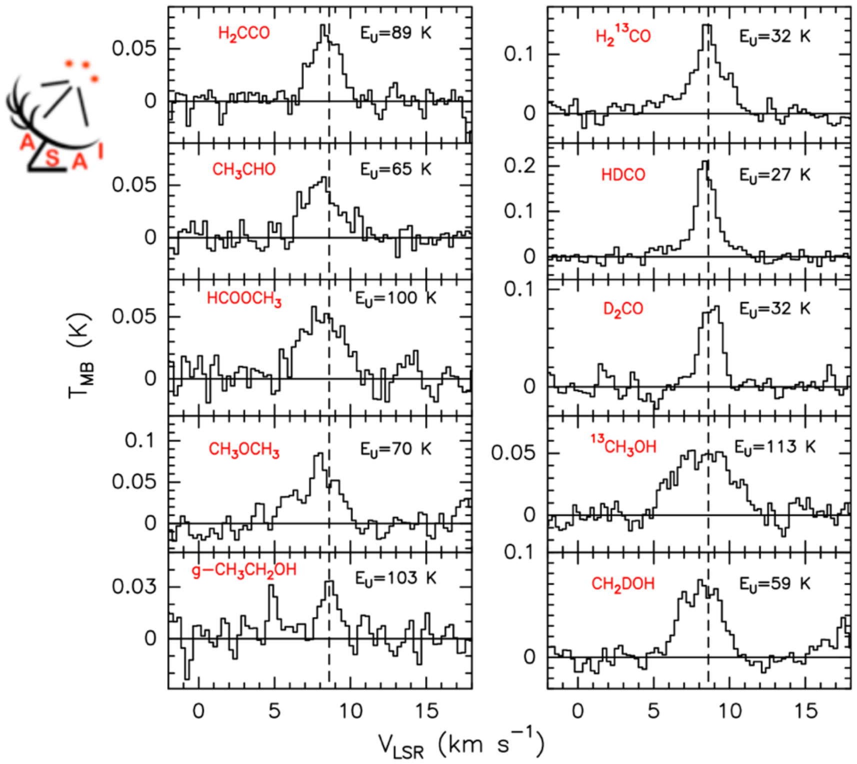
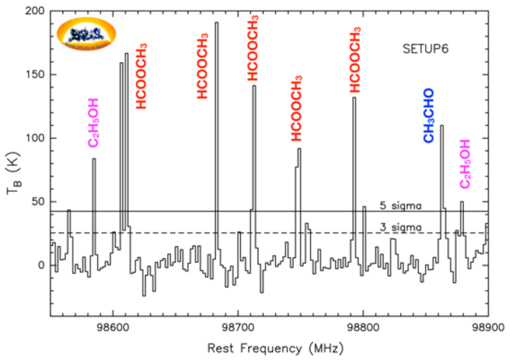


Figure 1: iCOMs and deuterated species detected with the ASAI IRAM-30m spectral survey.



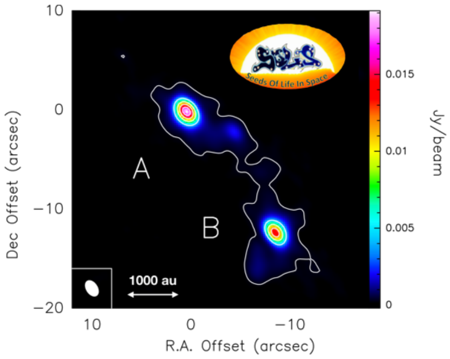


Figure 2: Selected windows from the new SOLIS NOEMA (Polyfix) observations.

Figure 3: Continuum emission of the SVS13 system as observed by SOLIS NOEMA at 82 GHz.

Références

[1] Bianchi E. et al., MNRAS, 467, 3011 (2017)
[2] Bianchi E. et al, MNRAS (2018)
[3] Lefloch B. et al., MNRAS, 477, 4792 (2018)
[4] Ceccarelli C. et al., ApJ, 850, 176 (2017)

Complex Organics in the NGC 1333 IRAS 4A Outflows

M. De Simone[1], C. Ceccarelli[1,2], C. Codella[3,1], E. Bianchi[1], M. Bouvier[1], A. Dehghanfar[1], J. Enrique-Romero[1], A. Jaber Al-Edhari[1], C. Kahane[1,2], B. Lefloch[1,2], A. López Sepulcre[4,1], J. Ospina-Zamudio[1], F. Vazart[1], N. Balucani[5,1], C. Favre[3], R. Neri[4], C. Vastel[6]

[1] Université Grenoble Alpes, IPAG, F-38000 Grenoble, France

[2] CNRS, IPAG, F-38000 Grenoble, France

[3] INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125, Florence, Italy

[4] Institut de Radioastronomie Millimétrique, 300 Rue de la Piscine, F-38406, Saint Martin d'Hères, France

[5] Dipartimento di Chimica, Biologia e Biotecnologie, Università degli Studi di Perugia, 06123, Perugia, Italy

[6]IRAP, Université de Toulouse, CNRS, UPS, CNES, Toulouse, France

Interstellar Complex Organic Molecules (iCOMs) are often considered as the small bricks from which more complex and prebiotic molecules may build up. As part of the SOLIS (Seeds Of Life in Space; [1]) Large Program with the IRAM-NOEMA (NOrthern Extended Millimeter Array) interferometer, we have obtained high angular resolution maps of several iCOMs towards the binary Class 0 protostar NGC 1333 IRAS 4A. This system is associated with a spectacular large-scale (≥1' in size) bipolar outflows previously studied with several tracers (e.g. SO, SO_2, HCN, H_2CO) [3,5].

The new SOLIS observations show iCOMs emission on scales of 2"-1' in these outflows, where the interaction of the violently ejected material with the surrounding quiescent gas creates shocked regions, as shown in Figure 1. This is the second ever outflow, after L1157-B1 [2,4], where iCOMs have been detected and imaged their spatial distributions. Furthermore, we observe a spatial segregation between different iCOMs, which could be caused by an abundance time-dependence effect, due to the release into the gas phase of the precursors of the detected species. We will discuss how the observed chemical segregation provides severe constraints on the iCOMs formation routes.

References

[1] Ceccarelli, C., Caselli, P., Fontani F., et al. 2017, ApJ, 850:176;

[2] Codella, C., Ceccarelli, C., Caselli, P., et al. 2017, A&A, 605, L3;

[3] Choi, M., Kang, M., Tatematsu, K., et al. 2011, PASJ, 63, 1281:1291;

[4] Lefloch, B., Ceccarelli, C., Codella, C., et al. 2017, MNRAS, 469, L73-L77;

[5] Santangelo, G., Codella, C., Cabrit, S., et al. 2015, A&A, 584, A126;

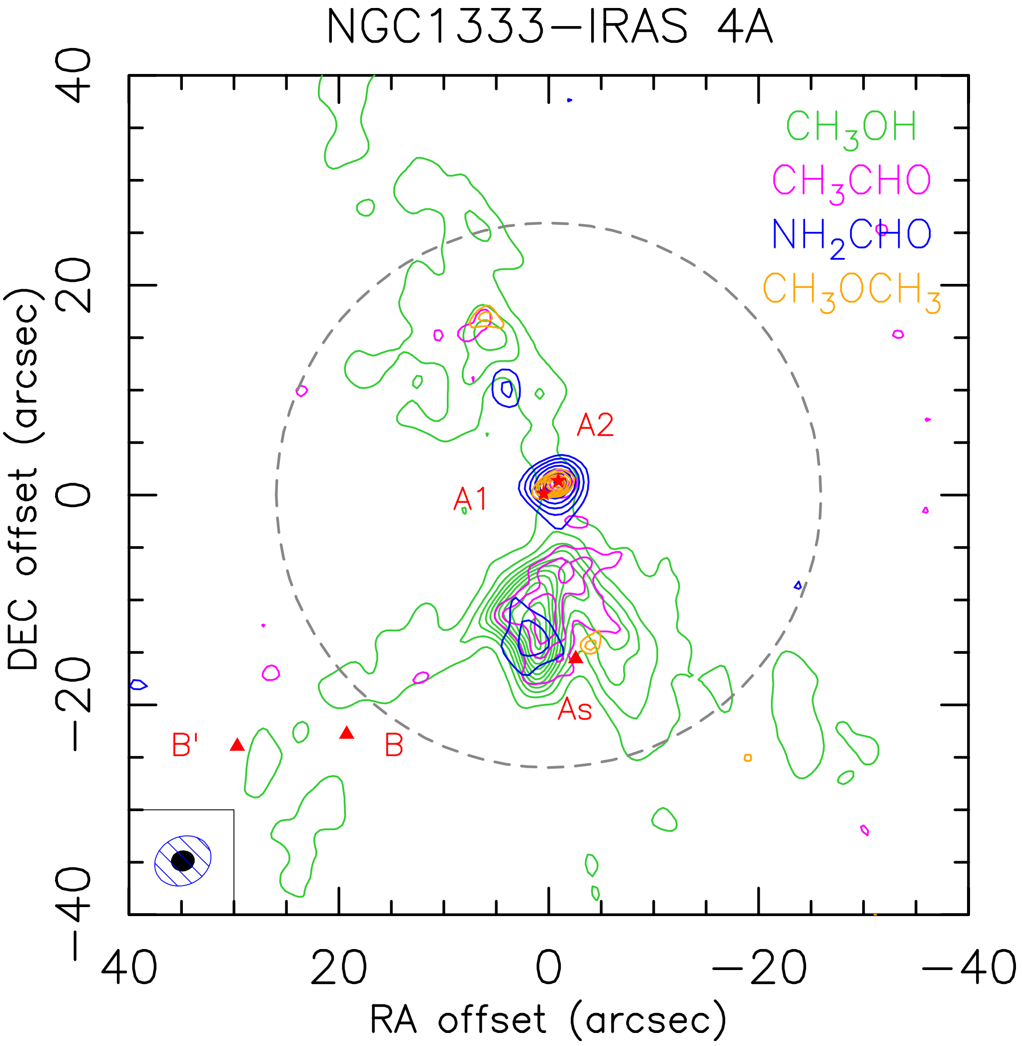


Figure 1: NOEMA/SOLIS observations towards NGC1333 IRAS 4A.
Countour map of the iCOMs emission at 3..:

1. methanol (CH_3OH, in green), tracing large scale (~1’) emission that covers almost both outflows
2. acetaldehyde (CH_3CHO, in magenta), tracing intermediate scale (~15’’) that partially covers only the southern outflow
3. dimethyl ether (CH_3OCH_3, in orange), tracing a compact (~2”) and weak component in the northern outflow and the southern shocked region (As, [1]);
4. formamide (NH_2CHO, in blue) tracing a compact (~6”) component in the south-east outflow.

In the lower-left corner the synthetized beams for the formamide lines (blue, ~4”) and for the other species (black, ~2”), respectively, are indicated. The primary beam (~ 52”) is shown with a dashed grey line.

Supplementary material for discussion

IRAM hunt for hot corinos and WCCC objects in the OMC-2/3 filament

M. Bouvier[1], A. López-Sepulcre[2,1], C. Ceccarelli[1,3], E. Bianchi[1], M. De Simone[1], A. Dehghanfar[1], J. Enrique-Romero[1], A. Jaber Al-Edhari[1], C. Kahane[1,3], B. Lefloch[1,3], J. Ospina-Zamudio[1], F. Vazart[1], N. Balucani[4,1], C. Codella[5,1], R. Neri[2], C. Vastel[6]

[1]*Univ. Grenoble Alpes, IPAG, F-38000 Grenoble, France*

[2]*Institut de radioastronomie Millimétrique (IRAM), 300 rue de la Piscine, 38406 Saint-Martin-D'Hères, France*

[3]*CNRS, IPAG, F-38000 Grenoble, France*

[4]*Dipartimento di Chimica, Biologia e Biotecnologie, Università degli Studi di Perugia, 06123, Perugia, Italy*

[5]*INAF- Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125, Florence, Italy*

[6]*IRAP, Université de Toulouse, CNRS, UPS, CNES, Toulouse, France*

Hot corinos and WCCC (Warm Carbon Chain Chemistry) objects are two chemically distinct types of low-mass protostars. On the one hand, hot corinos are dense ($\geq 10^7$ cm^{-3}), hot ($\geq$100 K), and compact ($\leq$ 100 au) regions, enriched in iCOMs (interstellar Complex Organic Molecules; e.g. CH_3OH, CH_3CHO)[1]. On the other hand, WCCC objects have an inner region deficient in iCOMs but a larger zone (a few thousands of au) enriched in hydrocarbons (e.g. CCH, c-C_3H_2)[2]. The obvious question is whether the proto-Solar System experienced a hot corino phase, a WCCC phase or neither.

In this context, we have been searching for hot corinos and WCCC candidates in the OMC-2/3 filament, the nearest high-mass star formation region and, thus, the best known analogue of our Sun birth environment [3],[4]. We use the abundance ratio [CCH]/[CH_3OH] to determine the chemical nature of the protostars as done in recent studies [5],[6].

We present here 1.3 mm observations of nine solar-type protostars located in the OMC-2/3 filament (Fig.1). Thanks to the superb spectral capabilities of the IRAM 30m telescope, we detected several transitions of CCH and CH_3OH allowing us to evaluate the abundance ratio for each protostar. Our preliminary conclusion is that single-dish observations are insuffcent to disentangle the emission of CCH and CH_3OH from the protostars envelope with respect to the parental molecular cloud. High spectral resolution (e.g. NOEMA) will thus be crucial.

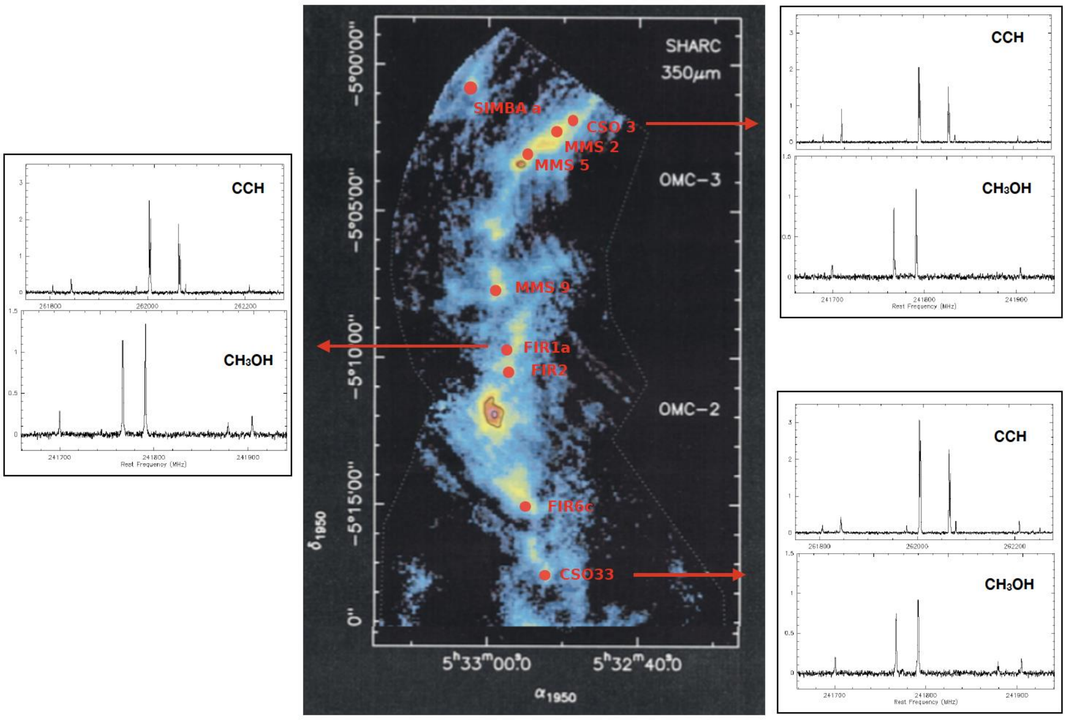


Fig. 1: The OMC-2/3 filament with the nine young protostars studied in the presented work. The spectra on the sides show examples of obtained spectra. Please note that the intensity scale is the same, for each molecule (CCH or CH_3OH), in the showed spectra. These spectra show little variation of the lines intensity, a fact that suggests that single-dish observations are dominated by the cloud emission.

References

[1] Ceccarelli et al., prpl.conf 47C (2007)
[2] Sakai & Yamamoto, IAUS 280, 43 (2011)
[3] Adams, ARA&A, 48, 47 (2010)
[4] Pfaltzner et al., PhyS, 90f8001P (2015)
[5] Higuchi et al., arXiv180408245H (2018)
[6] Öberg et al., ApJ 788, 680 (2014)

Hot corino in the intermediate-mass protostar CepE-mm

J. Ospina-Zamudio[1], B. Lefloch[1,2], E. Bianchi[1], M. Bouvier[1], C. Ceccarelli[1,2], A. Dehghanfar[1], M. De Simone[1], J. Enrique-Romero[1], A. Jaber Al-Edhari[1], C. Kahane[1,2], A. Lòpez Sepulcre[5,1], F. Vazart[1], N. Balucani[3,1], C. Codella[4,1], C. Favre[4], R. Neri[5]

[1] *Université Grenoble Alpes, IPAG, F-38000 Grenoble, France*

[2] *CNRS, IPAG, F-38000 Grenoble, France*

[3] *Dipartimento di Chimica, Biologia e Biotecnologie, Università degli Studi di Perugia, 06123, Perugia, Italy*

[4] *INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125, Florence, Italy*

[5] *Institut de Radioastronomie Millimétrique, 300 Rue de la Piscine, F-38406, Saint Martin d'Hères, France*

Interstellar Complex Organic Molecules (iCOMs) have been detected towards the protostellar stages of solar-like hot corinos and high-mass (HM) hot cores. Intermediate-mass (IM) protostars can provide the link between the solar-like and HM chemical complexity, but is still to be constrained.

We report here an unbiased spectral line survey of the isolated IM Class 0 protostar, CepE-mm ($L=100L_\odot$; [1]) with the IRAM 30m antenna (Figure 1) and complemented with NOEMA observations at 0.4" – 1.4" angular resolution (Figure 2 and 3) as part of the SOLIS (Seeds Of Life in Space) Large Program [2].

A chemical richness comparable to that of nearby solar-type stars [3] is detected, indicating the presence of a hot corino surrounded by a carbon-chain rich envelope. We find that the different components of the system (envelope, outflow and hot corino) contribute to the iCOM emission. The composition of the hot corino is comparable to that of solar-type objects.

At large scale, CepE-mm displays the chemical signatures of both hot corinos and WCCC sources. NOEMA resolves the protostellar core into a binary system (Figure 2). Both sources are separated by 1000 AU, embedded in a C-rich cocoon, and drive powerful outflows. A strong chemical differentiation is observed between the two protostars, which remains to be understood.

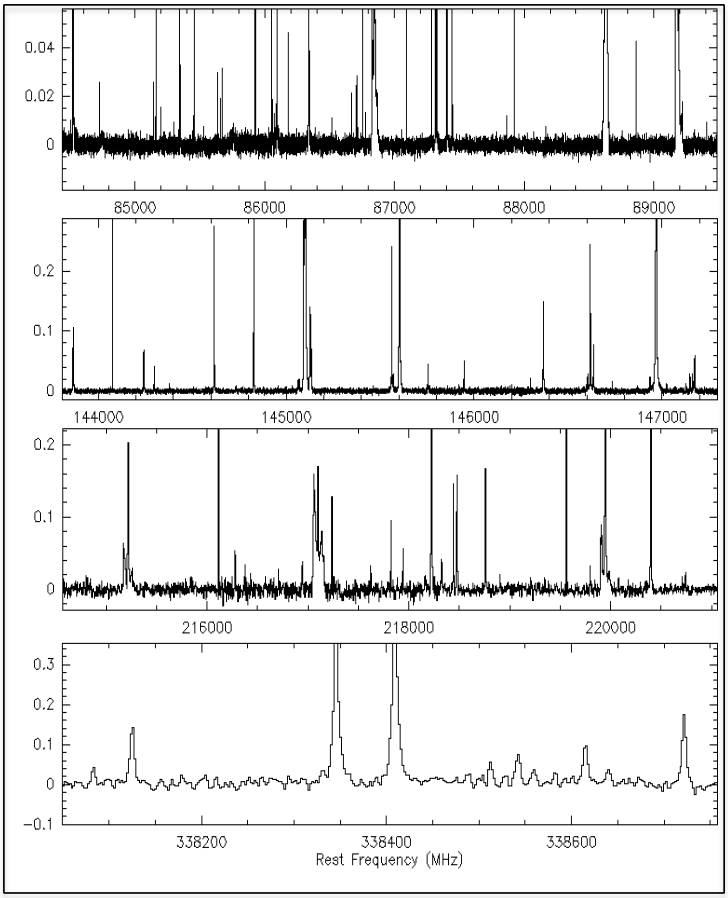


Figure 1: Selected windows from the 30m spectral survey [1].

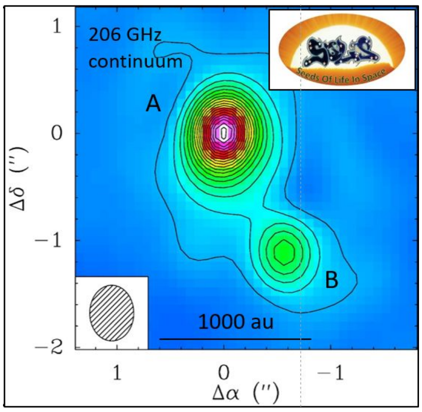


Figure 2: CepE-mm 206 GHz continuum map as seen with NOEMA.

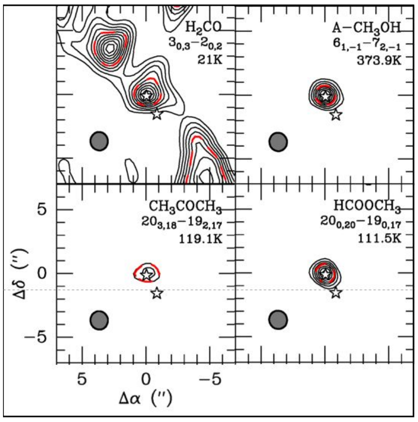


Figure 3: Selected molecular emission maps as seen with NOEMA [1].

References

[1] Ospina-Zamudio, J. et al., 2018, A&A 618, A145

[2] Ceccarelli, C. et al., 2017, ApJ, 850:176

[3] Lefloch, B., et al., 2018, MNRAS, 477:4792–4809

Unveiling the accretion-ejection connection in protostars ALMA/NOEMA/JWST synergy

B. Tabone[1], S. Cabrit[2], G. Pineau des Forêts[2], L. Podio[3], C. Codella[3]

[1] Leiden Observatory, Leiden University, 2300 RA Leiden, The Netherlands

[2] LERMA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Université, UPMC Univ. Paris 06, 75014 Paris, France

[3] INAF, Osservatorio Astrofisico di Arceti, Largo E. Fermi 5, 50125 Firenze, Italy

The mechanism of angular momentum extraction from protoplanetary disks (hereafter PPDs) is fundamental to understand the accretion process in young stars and the formation conditions of planets. Magnetic outflows launched from the disk surface (so-called "MHD disk-winds") are recently invoked to extract the angular momentum required to drive disk accretion onto the forming star [1,2], and to prevent inward planet migration [3].

The combination of high spatial and spectral resolution of ALMA is now allowing to detect a growing number of rotating flows suggestive of molecular winds launched from protoplanetary disks; the most convincing example so far being the protostellar HH212 jet (see Fig. a and [4,5,6]). *However, considering the observing pressure on ALMA, these high-resolution observations are restricted to a limited number of molecular lines and sources.*

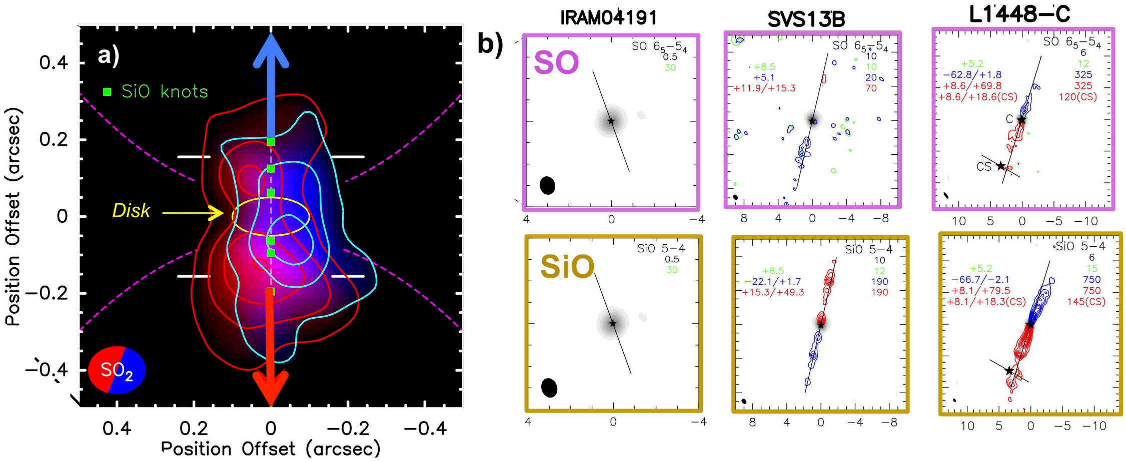
NOEMA is now providing a competitive sensitivity together with a broad frequency coverage that would allow us probe the physical and chemical conditions of disk winds previously identified by ALMA at high angular resolution. Indeed, the access to many lines and several frequency bands opens the possibility to:

- probe the density and the temperature of these winds (e.g. using H_2CO lines as a probe of the temperature), which are required to obtain accurate estimates of mass-loss rates and total angular momentum-loss rates,
- study the chemistry of winds which can give a unique insight on the poorly known Class 0 disk chemistry and the dust content of these winds.

In this perspective, the pioneer "CALYPSO" IRAM-PdBI large program has unveiled the chemical and physical evolution of protostellar jets/outflows on a sample of 16 nearby protostars [7] (see Fig. b). *New NOEMA legacy programs exploiting the broad instantaneous bandwidth could be conducted in synergy with future JWST observations at similar angular resolution (~ 0.5") to give a comprehensive statistical view of the warm and hot molecular content of young protostellar jets.* Such programs would greatly benefit from dual-band frequency capabilities allowing to by map several transitions of the same tracer (e.g. CO, CS, HCN, OCS…) simultaneously, to constrain the wind density, temperature, and chemical abundances.

Références

[1] Ferreira et al. 2006, A&A, 453, 785
[2] Bai 2016, ApJ, 218, 152
[3] Ogihara et al. 2018, A&A 615, A63
[4] Tabone et al. 2017, A&A, 607, L6
[5] Lee et al. 2017b, ApJ, 843, 27
[6] Tabone et al. submitted
[7] Podio et al. in prep



a) ALMA discovery of a rotating SO_2 outflow (red and blue) at 0.13'' ~ 50 au resolution in HH212 consistent with a MHD disk-wind launched out to 40 au [3]. b) The CALYPSO IRAM-PdBI view on SO and SiO content of protostellar jets. The bolometric luminosity of the source is increasing from the left to the right [7].

Session # 5
Solar System

Long-term monitoring and chemical inventory in Jupiter and Saturn's atmospheres

T. Cavalié[1,2], R. Moreno[2], T. Fouchet[2], E. Lellouch[2], V. Hue[3], S. Guerlet[4], M. Dobrijevic[1]

[1]*Laboratoire d'Astrophysique de Bordeaux, Univ. Bordeaux, CNRS, B18N, allée Geoffroy Saint-Hilaire, Pessac 33615, France*
[2]*LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Univ. Paris Diderot, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France*
[3]*Southwest Research Institute, San Antonio, TX 78228, United States*
[4]*Universités, UPMC Paris 06, UMR 8539, LMD, F-75005 Paris, France*

In this flash talk, we aim at presenting how NOEMA can contribute in the next decade to a multi-wavelength and multi-instrument campaign aiming at : (i) the long-term monitoring of species deposited in Jupiter's stratosphere by comet Shoemaker-Levy 9 in 1994, and species being delivered to Saturn by ring rain [1] and the Enceladus geysers [2] and (ii) determining the chemical inventory in Jupiter's and Saturn's auroral regions where ion-neutral chemistry is taking place [3] owing to the observatory large instantaneous bandwidth.

Références

[1] Waite et al. (2018). Science 362, 51.
[2] Cassidy and Johnson (2010). Icarus 209, 696-703.
[3] Guerlet et al. (2015). Astronomy & Astrophysics 580, A89.

Probing the subsurface of Iapetus' two faces

L.E. Bonnefoy[1, 2], E. Lellouch[2], A. Le Gall[1], C. Leyrat[2], J.-F. Lestrade[3], N. Ponthieu[4]

[1]*Laboratoire Atmosphères, Milieux, Observations Spatiales (LATMOS), UVSQ /CNRS/Paris VI, UMR 8190, 78280 Guyancourt, France*

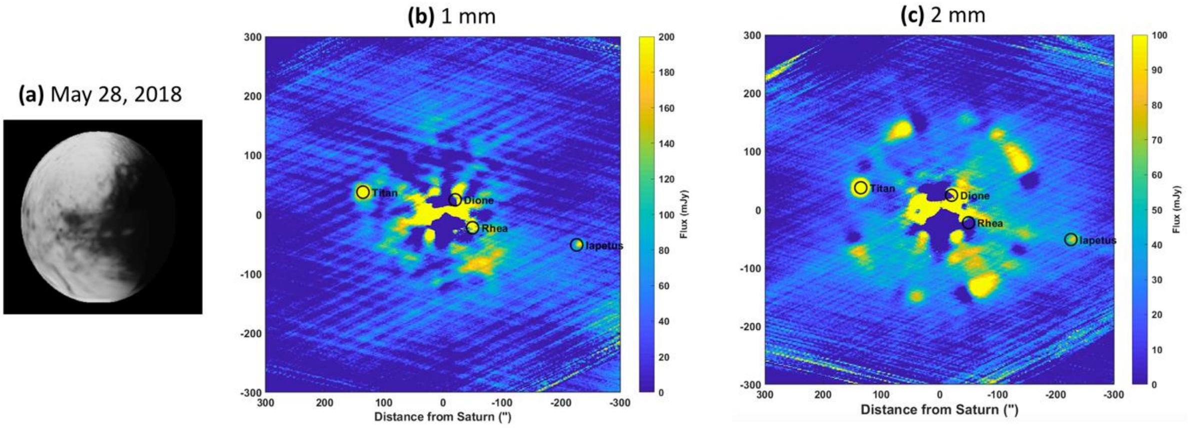
[2]*LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Univ. Paris Diderot, Sorbonne Paris Cité, 5 place Jules Janssen, 92195 Meudon, France*

[3]*Observatoire de Paris, CNRS, 61 Av. de l'Observatoire, F-75014, Paris, France*

[4]*Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France*

The Cassini mission has observed the near-surface thermal emission from Iapetus in the far-infrared (with Cassini's Composite Infrared Spectrometer CIRS) [1] and at 2.2 cm wavelength (with the Cassini Radar/Radiometer) [2,3]. These observations show a strong dichotomy between the leading and trailing hemispheres of the moon; this dichotomy should also be visible at millimeter wavelengths i.e. at IRAM NIKA2 operating wavelengths.

We are currently conducting an observing campaign to bridge the gap between CIRS and radar datasets by observing different longitudes of Iapetus at mm and cm wavelengths with, respectively, IRAM NIKA2 and the JVLA (Jansky Very Large Array, New Mexico, USA). In May 2018, we acquired 1- and 2-mm observations of Iapetus' anti-Saturn side from IRAM NIKA2 (Fig. 1), and in February-March 2019 we will collect new observations on Iapetus's leading and trailing sides. These observations, combined with those from CIRS, the Cassini Radar/radiometer and JVLA, will provide insights into the thermal, physical, and compositional properties of Iapetus's near-surface as well as into their variations with both depth and longitude.


(a) May 28, 2018

(b) 1 mm

(c) 2 mm

Fig. 1: (a) Iapetus appearance on May 28, 2018 (b) Calibrated map of the 1.15 mm thermal flux around Saturn as measured by NIKA on May 28, 2018. Saturn's emission has been subtracted as well as possible, but residuals due to imperfect PSF fitting are still present, leaving only Titan and Iapetus detected (c) Same as (b); but at 2 mm.

References:

[1] Howett et al., 2010, Icarus 206, 573–593.

[2] Ostro et al., 2006, Icarus 183 (2), 479–490.

[3] Le Gall et al., 2014, Icarus 241, 221–238.