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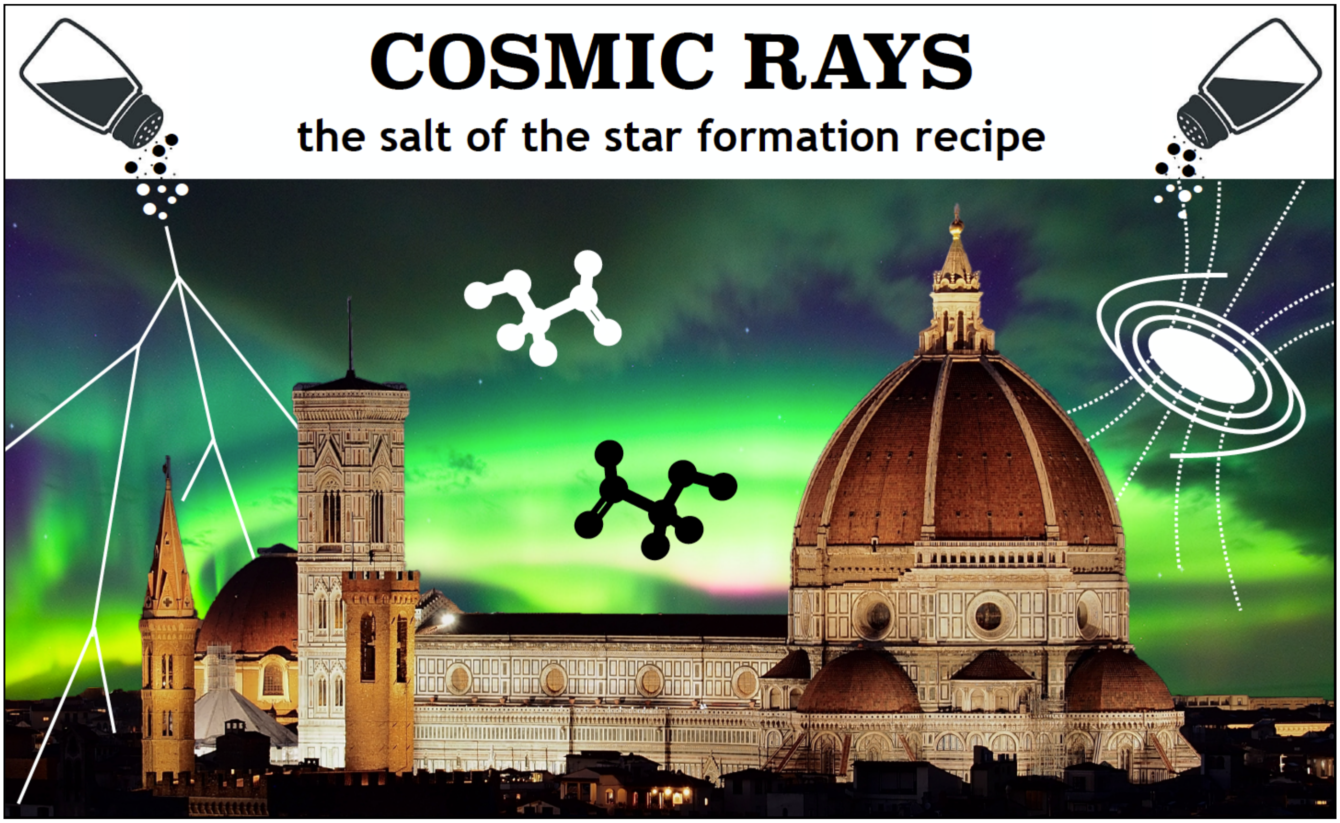

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Department of Physics and Astronomy

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Daniele Galli

INAF-Osservatorio Astrofisico di Arcetri, Italy

Cosmic-ray ionisation in clouds and disks

Low-energy cosmic rays are an important source of ionisation for the ISM, influencing its chemical, thermal and dynamical evolution. Available observational determinations of the cosmic-ray ionization rate in diffuse clouds and recent data from the Voyager I spacecraft support the existence of significant fluxes of low-energy cosmic-ray nuclei and electrons, but the penetration of this component inside dense clouds or circumstellar disks is hampered by strong losses and magnetic effects. In this talk I will review recent theoretical advances on this subject.

Tommaso Grassi

USM/LMU Munich, Germany

The effects of cosmic rays on microphysics

In many astrophysical environments cosmic rays control the rate of ionization events in the gas phase, and for this reason their effect on the chemical evolution and on the gas-magnetic field coupling is crucial. In this talk I will show how numerical simulations of increasing complexity (from toy models to realistic) are capable of determining the role played by cosmic rays when other parameters and processes come into play.

Alexei Ivlev

MPE, Garching, Germany

Cosmic-ray ionisation in circumstellar discs

Galactic cosmic rays are a ubiquitous source of ionisation of the interstellar gas, competing with UV and X-ray photons as well as natural radioactivity in determining the fractional abundance of electrons, ions and charged dust grains in molecular clouds and circumstellar discs. We model the propagation of different components of Galactic cosmic rays versus the effective column density of the gas, measured along the local magnetic field lines. Our study is focussed on the propagation at high densities, above a few g/cm^2, especially relevant for collapsing clouds and circumstellar discs. The propagation of primary and secondary CR particles (protons, electrons, and photons) is computed in the continuous slowing down approximation or in the diffusion approximation, depending on the nature of the dominant loss process. The CR ionisation rate is dominated by CR nuclei below about 130 g/cm^2, while for higher values of the effective surface densities it is due to electron/positron pairs created by photon decay. We find that a proper description of particle propagation is essential to compute the ionisation rate in the latter case. Our results show that the CR ionisation rate in high-density environments is larger than previously assumed. It does not decline exponentially with the density, but follows a more complex behaviour due to the interplay of diffusion and catastrophic processes governing the generation and propagation of secondary particles.

Stefano Gabici

APC, Paris, France

Cosmic ray penetration in diffuse clouds

I will review the theoretical models aimed at describing the penetration of cosmic rays into diffuse molecular clouds. Results from the models will be confronted with available data from low and high energy observations.

Dmitry Chernyshov

Lebedev's Insitute of Physics, Moscow, Russia

Role of self-excited turbulence in penetration of cosmic rays into molecular clouds

Cosmic ray anisotropy in molecular gas induced by energy losses may generate magnetic fluctuations associated with MHD waves. This effect should be especially intense in diffuse envelopes surrounding molecular clouds where damping rate of the MHD waves is low. We generalize models of cosmic rays exclusion from molecular clouds due to self-excited turbulence proposed earlier. We propose a model of CR penetration into molecular clouds through their diffuse envelopes, which describes CR transport on the way from a fully ionized interstellar medium to a dense interior of the cloud. We demonstrate that under influence of self-excited turbulence a simple universal spectrum of cosmic-rays is formed. This results may be important for studies of CR-induced ionization rate of molecular gas, X-Ray emission and in some case even for gamma-ray emission from the clouds.

Philipp Girichidis

AIP Potsdam, Germany

Dynamical and chemical impact of cosmic rays on the ISM

Cosmic rays are an important energy component in the interstellar medium with energy densities comparable to the thermal and magnetic one. Being relativistic particles they have different transport and cooling processes compared to the thermal gas. Cosmic rays diffuse relative to the gas and thus transport a significant fraction of the energy away from their production sites throughout the interstellar medium and into the halo. Their small cross section allows them to deeply penetrate into dense cores of molecular clouds. Using three-dimensional magneto-hydrodynamical simulations including cosmic rays as a relativistic interacting fluid, we investigate their dynamical and chemical impact on the interstellar medium and molecular clouds. We find that only 5-10 percent of the cosmic-ray energy injected by supernovae is lost via hadronic interactions. The remaining cosmic rays can thicken the galactic disk and delay the formation of molecular clouds. In addition they drive strong outflows with mass loading factors or order unity. On small scales and high densities we find that cosmic rays reduce the formation of molecular gas and shape the chemical signatures of molecular clouds via a spatially varying cosmic-ray ionisation rate.

Soonyoung Roh

Ulsan National Institute of Science and Technology, South Korea

Propagation of Cosmic Rays in Magnetized Protoplanetary Disks

The magnetorotational instability (MRI) is thought to be one of the driving mechanisms of mass accretion in protoplanetary disks (PPDs). For the development of the MRI, sufficient ionization degree for a good coupling between the gas and the magnetic fields in the disk is needed. Cosmic rays (CRs) are believed to be one of the main contributors of ionization sources in PPDs. In previous studies, ionization rates were estimated as a function of column density from the disk surface based on a work computing the attenuation of CRs in an unmagnetized cloud. In reality, however, CRs would undergo complex path due to the magnetic fields. In order to quantitatively analyze the propagation of CRs considering energy loss processes in magnetized PPDs, we have performed test particle calculations of CRs using a snapshot of a magnetohydrodynamic (MHD) simulation of the MRI-active protoplanetary disk as the background. We considered the local interstellar spectrum of CRs and calculated their trajectories in the disk. We will discuss the result in relation to the ionization rate within the disk.

Yuri Fujii

Nagoya University, Japan

MHD simulations of Protoplanetary Disks with Non-equilibrium Ionization Chemistry

Protoplanetary disks are weakly ionized by cosmic rays, X-rays and UV from the central star, gamma rays from radionuclides, etc. When the ionization fraction of the disk is high enough for the gas to be coupled with magnetic fields, magnetohydrodynamic (MHD) effects such as the magnetorotational instability (MRI) and/or the disk wind can play important roles on dynamical evolution of the disk. In order to find the relation between dynamical and chemical evolution of the disk, we performed three dimensional MHD simulations with non-equilibrium ionization chemistry. We find that the non-equilibrium ionization barely changes the dynamical evolution but the chemical evolution can be modified by the disk wind.

James Wurster

University of Exeter, UK

How cosmic rays shape a protostar

Magnetic fields are undeniably a critical factor in star formation. The initial strength of the magnetic field directly affects the mass of the protostar and the characteristics of its environment. Previous studies have shown that strong magnetic fields inhibit disc formation and promote strong, collimated outflows, while weak magnetic fields promote large discs and weak outflows. However, these results assume ideal magnetohydrodynamics (MHD), which is a poor approximation since the majority of the gas in a molecular cloud core is cold, neutral gas. When including non-ideal MHD processes, the formation and evolution of a protostar and its environment is considerably modified. Once formed, the protostar itself is highly ionised through thermal processes, but the surrounding gas is still only partially ionised, with the dominant ionisation source being cosmic rays. This weakly ionised medium directly and drastically influences the evolution of the protostar and environment, thus a proper understanding of the cosmic rays that ionise it is crucial. In this talk, I will discuss the effect that non-ideal MHD has on star formation, and show how changing the cosmic ray ionisation rate has a similar - if not greater - effect on the protostar than changing the initial magnetic field strength under the assumption of ideal MHD. I will focus on the properties of the protostar, discs and outflows, and how these properties vary when changing the cosmic ray ionisation rate.

Thomas Bisbas

University of Virginia, USA

Cosmic-ray induced destruction of CO in star-forming galaxies and implications for tracing H_2 gas

Molecular hydrogen plays the dominant role in the star-formation process of all galaxies. However, owing to its quantum mechanical properties, H_2 is not readily observable by radiotelescopes and because of this, the CO molecule is widely used as a tracer (CO-to-H2 conversion method). I will present a study on the effect of cosmic rays on the abundance distribution of CO in H_2-rich clouds under conditions typical for star forming galaxies and the Galactic Centre. By performing three-dimensional photodissociation and cosmic-ray dominated region simulations of a fractal cloud embedded in different cosmic-ray energy densities, we find that CO is very effectively destroyed in extreme ISM environments with cosmic-ray energy densities of the order of 50-1000 times the typical Milky Way value. This effect is strong enough to render Milky-Way-type Giant Molecular Clouds very CO-poor, and thus CO-untraceable. CO rotational line imaging will then show much clumpier structures than the actual ones. We also identify OH as the key species whose gas temperature sensitive abundance could mitigate the destruction of CO at high temperatures. I will also present recent ALMA observations of galaxies with high star forming rates supporting this model, indicating that atomic carbon is the most promising avenue for studying ISM in high-redshift Universe.

Paola Caselli

MPE, Garching, Germany

The importance of cosmic rays in star and planet formation

Cosmic rays are crucial for the dynamical and chemical evolution of molecular clouds and star/ planet forming regions. Here I shall focus on the role of cosmic rays on gas phase and surface processes and on their effects on nascent protoplanetary disks. Recent work on the penetration of cosmic rays in dense molecular clouds will also be mentioned.

David Neufeld

Johns Hopkins University, USA

The Galactic cosmic-ray ionization rate implied by observations of atomic and molecular ions

In the century following their discovery by Victor Hess in 1912, cosmic rays have been recognized as an important constituent of the Galaxy. With a total energy density somewhat larger that of starlight, cosmic rays are the dominant source of ionization for the cold neutral medium (CNM) within the Galactic ISM. In starless molecular cloud cores, they are also the dominant source of heating. Thus, cosmic-rays play a central role in astrochemistry by initiating a rich ion-neutral chemistry that operates within the CNM, and the cosmic-ray ionization rate (CRIR) is a key parameter in models for the chemistry of the ISM. In this talk, I will discuss recent estimates for the cosmic-ray ionization rate in the Galactic disk, obtained by using a detailed model for the physics and chemistry of diffuse interstellar gas clouds to interpret previously-published measurements of the abundance of four molecular ions: ArH^+, OH^+, H_2O^+ and H_3^+. The CRIR estimates thereby obtained show a remarkably small dispersion from one interstellar cloud to another. At the Galactocentric distance of the Sun, the primary CRIR per H nucleus is ~ 2×10^{-16} s^{-1} in both diffuse atomic clouds and diffuse molecular clouds. This value also agrees well with a rederivation of the CRIR implied by recent observations of carbon and hydrogen radio recombination lines along the sight-line to Cas A.

Takeshi Oka

University of Chicago, USA

H_3^+ , the ideal probe for in situ measurements of soft cosmic rays

Because of the simplicity of its chemistry the production through cosmic ray ionization of H_2 to H_2^+ followed by the fast reaction, $H_2^+ + H_2 \rightarrow H + H_3^+$, and the destruction by rapid dissociative recombination with electrons, $H_3^+ + e^- \rightarrow 3H$ and the possibility of measuring accurate abundance by its infrared spectrum, H_3^+, discovered in interstellar space in 1996 (Geballe & Oka), serves as a powerful probe to measure cosmic ray ionization rate ζ in regions with abundant H_2. For over 35 years since early theoretical estimate by Spitzer & Tomasko (1968), ζ had been thought to be on the order of 10^{-17} s^{-1} and independent of location because of the high penetration of the cosmic rays. However, the H_3^+ observation and analysis showed convincingly that the ionization rate in diffuse clouds is on the order of 10^{-16} s^{-1}, more than an order of magnitude higher than in dense clouds (McCall et al. 2004) and varies depending on the location (Indriolo & McCall 2012). It was found that the Galactic center (GC) has ζ on the order of 10^{-15} s^{-1} (Oka et al 2005) which met skepticism from many corners. Subsequently, however, more detailed analysis have shown that the correct value of ζ is even higher and on the order of 10^{-14} s^{-1}, 1000 times higher than in the solar vicinity (Le Petit et al. 2016; Oka et al. 2018). The new analysis of the data toward 30 stars covering the central 300 pc of the GC and its comparison with ζ values obtained from X-rays and γ-rays will be discussed.

Jesús Martín-Pintado

Centro de Astrobiologia - CAB - (CSIC, INTA), Madrid, Spain

On the effects of Cosmic rays on Galactic center molecular clouds

Cosmic rays (CRs) originate from energetic sources, usually traced by observations of synchrotron emission, X-rays and Gamma rays. CRs are expected to influence both the chemistry and the physical properties of the molecules clouds exposed to this type radiation. CRs interact with molecules and atoms both in gas phase and in ices producing: i) ionization of H_2 molecules and triggering gas phase chemistry ii) heating the molecular clouds by secondary electrons and iii) driving chemistry on icy dust grains. The Galactic center, mainly the Central Molecular Zone (a region of about 600 pc around the black hole) is an excellent laboratory to establish the effects of CRs on the properties of molecular clouds since it hosts a plethora of X-ray and high-energy sources that are expected to produce an enhanced CRs flux. In this talk, I will review the status of the investigation of the effects of the CRs on the properties of the molecular clouds in the Galactic center.

Shaoshan Zeng

Queen Mary University of London, UK

Chemical complexity in the Galactic Centre GMCs and the imprint of cosmic rays: The nitrogen-bearing family

Giant molecular clouds (GMCs) in the Galactic Centre (GC) are exposed to energetic phenomena such as widespread shock waves and enhanced cosmic-ray ionisation rates. For the latter, recent observations of molecular ions such as H_3^+ toward different lines of sight across the Central Molecular Zone of the GC (CMZ, the central 100 pc of the Galaxy) suggest the molecular gas in the CMZ is affected by enhanced cosmic-ray ionization rates $>10^{-15}$ s^{-1} (Goto et al. 2014). G+0.693 is a quiescent GMC located in the CMZ, which represents a prolific repository of large organic species in the ISM. Although this region has shown no signs of star formation, it presents similar level of chemical complexity as that found in the star-forming cluster Sgr B2(N). We performed a spectral line survey toward this cloud with IRAM-30m and GBT telescopes to explore the chemical complexity of this source and how it is affected by cosmic rays. Over 20 N-bearing species including cyanopolyynes (HC_3N through HC_7N) and molecules with peptide-like bonds such as formamide (NH_2CHO) and methyl isocyanate (CH_3NCO) have been identified. Comparing our derived abundances in G+0.693 with those from other astrophysical environments such as dark cloud cores, we find that the chemistry of these N-bearing species is possibly affected by an enhance cosmic-ray ionization rate. This further indicates that cosmic rays may play an important role in the chemistry of complex organics in the quiescent GMCs in the GC.

Farhad Yusef-Zadeh

Northwestern University, USA

Consequences of the High Rates of Cosmic-Ray Ionization toward the Galactic Center

Recent observations of the inner few hundred pc of the Galactic center indicate that the cosmic-ray ionization rate is higher than elsewhere in the Galaxy by one to two orders of magnitudes. These measurements are based on infrared H_3^+ molecular spectroscopy studies and the presence of fluorescent 6.4 keV FeI emission assuming that low energy cosmic-ray electrons interact with Galactic center molecular clouds. This interaction explains not only the ubiquitous warm molecular gas observed throughout the Galactic center but also the broken power law spectrum of GeV emission as observed with Fermi. Here we present the consequences of this interaction in the context of star formation in the Galactic center. In particular, we discuss, the higher Jeans mass, the longer ambipolar diffusion time scale and the unusual chemistry of molecular gas, as probed by the high abundance of methanol, SiO and other molecular species found toward the Galactic center.

Izaskun Jiménez-Serra

Queen Mary University of London, UK

The formation of COMs in the ISM: from Cold Cores to Galactic Center molecular clouds

In the past decade Complex Organic Molecules (or COMs, defined as carbon-based species with more than 6 atoms) have attracted much attention due to their link to prebiotic molecules or species involved in the processes leading to the origin of life. Thanks to the advent of higher-sensitivity instrumentation, we now know that these complex organics are ubiquitous in the interstellar medium (ISM), appearing not only in very cold environments such as cold pre-stellar cores but also in harsh environments such as the nuclei of galaxies. In this talk I will review the dominant formation/ destruction routes of COMs in the ISM and how they may be affected by different physical processes such as the impact of cosmic rays, shock waves or UV radiation. I will put special emphasis on the chemistry of molecules of prebiotic interest with peptide-like bonds such as formamide (NH_2CHO) and the recently discovered species methyl isocyanate (CH_3NCO).

Maria N. Drozdovskaya

Center for Space and Habitability (CSH), Universität Bern, Switzerland

The role of cosmic rays in setting the chemical content of protoplanetary disk midplanes

The chemical evolution of volatiles in protoplanetary disks begins in the earliest prestellar phase of star formation. Under the dark, cold conditions of cores the initial icy mantles of grains are built up. Already at this point, grain-surface chemistry starts to set the composition of these icy layers. Cosmic rays play a pivotal role here by setting the abundances of radicals available for the synthesis of more complex molecules and also for maintaining low abundances of gaseous molecules directly via spot heating and indirectly via reactive desorption. Protoplanetary disks are built up from the collapsing core materials, which are exposed to variable intensities of UV irradiation and heating. Cosmic rays continuously play a sub-dominant role in chemical processing during the collapse of the system and also in the outer, lower density regions of disks. Only in the innermost, high-density regions do they become attenuated. In this talk, the history of the protoplanetary disk composition will be unraveled with the help of sophisticated physicochemical models for a range of cosmic ray ionization rates (expansion of Drozdovskaya et al. 2014, 2016). The models will be used to access the degree of importance of cosmic rays in setting the abundance of volatiles in protoplanetary disk midplanes. Cometary data will be contrasted against the modeled volatile quantities, taking into account a range of possible cosmic ray ionization rates.

David Quénard

Queen Mary University of London, UK

Influence of the cosmic ray ionisation rate on complex organic molecules chemistry

Up to date, around 200 molecules have been detected in the interstellar medium. In this list, we define complex organic molecules (COMs) as molecules of six atoms or more that contain at least one carbon atom. Another sub-division can be defined between oxygen-bearing COMs (e.g. CH_3OH, CH_3CHO) and nitrogen-bearing COMs (e.g. CH_3CN, CH_3NCO). The search for COMs in space has considerably increased in the past decades, and they have been detected in various star-forming regions such as pre-stellar cores, hot cores and hot corinos, or shocked regions. Many works have been performed, both experimentally and theoretically, to try to understand the chemistry of COMs in space. One key parameter in chemical modellings is the ion irradiation induced by cosmic rays that may impact the gas-phase and grain-surface chemistry. Although all chemical codes are taking into account the cosmic ray ionisation rate, usually a fixed value is assumed, close to the "standard" value of 1.3×10^{-17} s^{-1}. However, there is increasing observational evidence that suggests that this value might be largely underestimated and that some environments may be affected by an enhanced cosmic ray ionisation rate. This is the case for instance of molecular outflows such as L1157 and the Galactic Centre, especially the Central Molecular Zone (CMZ), where COMs have also been detected. Moreover, recent laboratory experiments (e.g. Kanuchova et al. 2016) have shown that the formation of formamide, a nitrogen-bearing COM of prebiotic interest, is enhanced on ices after ion irradiation. This kind of process could explain the high abundance of certain COMs detected toward the CMZ (Zeng et al. resubmitted).

Will R. M. Rocha

University of St. Andrews, UK

Chemical evolution of PPDs employing optical constants of cosmic-ray processed ice into ProDiMo code

Protoplanetary disks (PPDs) may harbour astrophysical ices in very dense places, also known as midplane. These regions are shielded against stellar UV and X-rays radiation, because the extinction due to dust and gas between the ices and central protostar. Cosmic rays (CRs), on the other hand, might penetrate deeper into disk and trigger several chemical changes by converting parent species into Complex Organic Molecules (COMs). Such efficiency comes from inelastic interactions between CRs and targets, which produce a secondary internal radiation field driven by electrons and ionizing photons (gamma rays, X-rays, UV). In this work, we summarize several laboratory experiments by employing heavy ions to process astrophysical ices using the Grand Accélérateur National dIons Louds (GANIL) in Caen, France, as well as we show a new database of optical constants (or Complex Refractive Index) of bombarded ices (see Rocha et al. 2017, MNRAS, 464, 754). Furthermore, it is presented an application of such data in PPDs by using the thermochemical ProDiMo code. We conclude that such procedure is essential to reproduce many IR features in the spectrum of protostars between 5.0 and 8.0 microns such as the presence of astrobiological interested species, such as aliphatic ethers (e.g., R1-OCH2-R2), alcohols and acids.

Juris Kalvāns

Ventspils International Radio Astronomy Center of VUC, Latvia

Cosmic-ray induced diffusion, reactions and destruction of molecules in interstellar ices

Cosmic rays (CRs) affect icy mantles on interstellar grains in a variety of ways. We investigate how the composition of interstellar ices is affected by direct CR-induced molecule destruction and diffusion and reactions on grains warmed by CRs. Astrochemical model that considers surface and subsurface bulk-ice chemistry in a starless or star-forming (Kalvāns 2014, 2015) cloud core was employed. The CR-induced processes change the abundances of major icy species (water, carbon oxides) by no more than a few per cent. This is sufficient to significantly modify (by up to a factor of 100) the abundances of minor surface species, notably, carbon chains. For gas-phase species, molecular oxygen is affected most, with abundance reduced roughly by half. CR-induced ice molecule dissociation affect ice composition more than diffusion and reactions on warm grains. In order to correctly model the CR-induced processes, a sequence of rapid events needs to be considered: (CR impact in grain) molecule destruction local heating whole-grain heating grain cooling. Molecule dissociation and desorption, diffusion, and reactions (involving freshly created radicals) on warm grains have to be included.

References: Kalvāns, J. 2014, BaltA, 23, 137; Kālvans, J. 2015, A&A, 573, A38

Wasim Iqbal

Laboratoire d'Astrophysique de Bordeaux, France

Nautilus multi grain model: impact of cosmic-ray induced desorption in abundances of COMs in the ISM

Many chemical reactions occur at the surface of interstellar dust grains, producing a large diversity of molecules more or less complex. Most current astro-chemical models include only a single size of grains (0.1 micron representing most of the mass of silicate grains) to study the formation and destruction of molecules on the dust surface. We have studied the effect of considering a distribution of grain sizes (in the range of 0.005 micron to 0.25 micron) on the chemical evolution of various complex molecules in the cold dense clouds in the ISM. We used two grain size distributions, MRN (Mathis et al. 1977) and WD (Weingartner & Draine 2001). We divided the grain radius range of 0.005 micron to 0.25 micron into 10, 30 and 60 bins. Each bin has its own grain number density which comes from either MRN or WD distribution. Other important parameters such as grain surface temperature and cosmic ray induced desorption rates also vary with grain size. We present abundance of various molecules including some complex molecules in gas phase and also on the surface of dust grains at different time interval during the simulation. We also compare our results with observed abundances in TMC-1 and L134N clouds. We show that cosmic-ray induced desorption plays a very important role on smaller grains in determining the chemical path ways. We show how a multi grain model, by considering the different populations of grain sizes, can be a better tool in explaining observed abundances in ISM.

Mélisse Bonfand

MPIfR, Germany

The influence of cosmic rays on the chemistry in Sagittarius B2

The EMoCA survey (Exploring molecular complexity with ALMA) has unveiled the presence of at least five hot cores in Sagittarius B2-North (Sgr B2(N)), one of the main centers of activity of the Sgr B2 molecular cloud located close to the galactic center. The high sensitivity of the survey revealed spectra full of spectral lines allowing the identification of many chemical species, from simple diatomic molecules to more complex molecules such as iso-propyl cyanide (i-C_3H_7CN). In order to characterize the hot cores embedded in Sgr B2(N), we analyzed their spectra to derive their chemical composition and basic physical properties. The chemical kinetics code MAGICKAL (Model for Astrophysical Gas and Ice Chemical Kinetics And Layering, Garrod 2013) is used to simulate the evolution of the chemistry in the hot cores in order to compare the numerical predictions with the observations. Here we will show the influence of cosmic rays on the interstellar abundances of complex organic molecules predicted by the model. We wish to determine which level of cosmic-ray ionization better reproduces the chemical composition of Sgr B2(N)s hot cores in the extreme environmental conditions of the galactic center.

Guillermo Muñoz-Caro

Centro de Astrobiologia - CAB - (CSIC,INTA), Madrid, Spain

A comparison of UV, X-ray, and ion processing of icy dust analogs

The important role played by dust grains covered by ice mantles in space has gained increasing recognition among astrochemists. These particles shape the physics and chemistry in dense interstellar clouds and cold circumstellar regions. UV, X-rays, and cosmic rays (ions of variable energy) impinge on the dust and process energetically the ice and/or core in these particles. A comparison of the effects of the different types of radiation on ice and dust analogs will be presented. These include destruction and formation of species and physical processes such as non-thermal desorption.

Sergio Ioppolo

Queen Mary University of London, UK

Solid state chemistry driven by cosmic-ray induced secondary electrons

Interstellar ice grains are continuously exposed to cosmic rays throughout their lifetime. The complex solid state chemistry induced by secondary electrons produced during the interaction between cosmic rays and ice layers is still not fully understood. Here I will discuss our recent laboratory results on the formation of molecules after exposure of an initial ice layer to 1 keV electron bombardment. We applied VUV, UV-vis and mid-IR absorption spectroscopy to study interstellar and Solar System relevant ices before and after irradiation. VUV and UV-vis spectra were obtained at the synchrotron facility ASTRID2 ISA, University of Aarhus (Denmark), while mid-IR data were collected at the Molecular Astrophysics Lab at the Open University (UK). We found that upon exposure to electrons, new more complex species are easily formed. Moreover, relative intensities, peak position and shape of the absorption bands are modified and spectral reddening is observed in the UV spectral range. Therefore, experimental results will help understanding the molecular complexity induced by the interaction of electrons and ices and will support past (e.g., Hubble Space Telescope) and future (JUICE - JUpiter ICy moons Explorer; http://sci.esa.int/juice/) astronomical observations.

Gleb Fedoseev

INAF - Osservatorio Astrofisico di Catania, Italy

Laboratory simulations of cosmic-ray processing of N_2-containing ices at dark cloud conditions

Although N_2 may appear to be the most abundant nitrogen-bearing species in cold dark clouds and prestellar cores, so far it draws little attention in the solid-state astrochemistry. Solid N_2 is insensitive to mid-IR observations, thus, only indirect proves of its presence can be found. Moreover, N_2 demonstrates near complete inertness towards atom-addition reactions and is near-transparent to Ly-α radiation. This makes cosmic-ray processing to be the only potentially efficient trigger mechanism of N_2 solid state chemistry. Here we present the results of a laboratory research aimed to better understand cosmic-ray induced N_2 chemistry in cold dark clouds. It perceives two goals: to present the overall formation yields of few chosen CN-bearing species for the irradiation doses relevant to this star formation stage; and to investigate the possibility of utilizing these formation yields as an indirect probe of N_2-presence in the icy grain mantles. To achieve these goals, a detailed quantitative analysis of irradiation products obtained after ion processing of few chosen N_2-containing interstellar ice analogues with 200 keV H^+ and He^+ ions is performed. HNCO and OCN^- kinetic curves are obtained in each of the performed experiment. In turn, normalized formation yields are evaluated by interpolation of the obtained results to the low irradiation doses relevant to dark cloud stage. The obtained data can be used to interpret future observations towards cold dark clouds using JWST.

Maria Elisabetta Palumbo

INAF - Osservatorio Astrofisico di Catania, Italy

Experimental studies of the role of cosmic rays in the chemistry of interstellar icy grain mantles

Molecules in the solid phase have been detected in the line of sight of quiescent dense molecular clouds and star forming regions as icy mantles on dust grains. It is widely accepted that in these environments icy mantles are continuously processed by low-energy cosmic rays and UV photons. Most of our knowledge on the effects of energetic processing (i.e. UV photolysis and ion and electron bombardment) on ices is based on laboratory experiments. Experimental results clearly indicate that after energetic processing the chemical composition and the structure of the ice is modified. Both more volatile and less volatile (complex) species are formed and if C-bearing species are present in the original mantle a refractory residue is left over after warm-up to the sublimation temperature of volatile species. Due to the active role of dust grains in the formation of molecules, the chemical composition of icy mantles is significantly different from the composition of the gas and after the desorption of icy mantles the gas phase is enriched of (complex) molecules. Eventually these species could be incorporated in planets, satellites and comets formed with the star. Here we will present some recent laboratory experiments which show the formation of (complex) molecular species after ion bombardment (E=30-200 keV) of simple ices.

Gustavo A. Cruz-Díaz

NASA Ames research center, USA

Degradation of PAHs and radiation-induced products by cosmic ray analogs

Polycyclic aromatic hydrocarbons (PAHs) are one of the most abundant carbon-containing molecules in space. They are detected in different environments, from stellar nurseries to PDRs, and observed toward massive stars and the Galactic center. PAHs in the ISM are believed to be large, compact structures, enhancing their stability towards energetic degradation. The main goal of this present work was to monitor the effects of cosmic ray analogs bombardment on aromatic organic molecules regarding their destruction and possible product formation. In this presentation, we will discuss the degradation of two PAHs- Isoviolanthrene A (IVA), a large PAH with an elongated open structure and Coronene (Cor) which exhibits a compact close structure by different high energy sources. Samples were taken to Marshall Space Flight Center to be irradiated by protons, high energy electrons, and UV light both separately and simultaneously. Samples were also taken to Rio de Janeiro to be processed by hydrogen and helium ions using the particle accelerator at the Pontifical Catholic University. Samples were also exposed to VUV irradiation and low energy electrons at NASA Ames. Experiments were performed under HV conditions and room temperature. FTIR was used to monitor the PAH bands during the bombardment and irradiation. This presentation will detail the degradation rates and processes, as well as discuss radiation-induced products of these PAHs based the radiation type and energy level.

Christiane Helling

Centre for Exoplanet Science, University of St Andrews, UK

The effect of cosmic rays on the ionisation and chemistry of exoplanets and brown dwarfs

Exoplanets and brown dwarfs are exposed to a diversity of irradiating environments. (Exo)planets are irradiated by their host star, the received flux depending on their orbital distance. Brown dwarfs exist in high-radiation environments like star forming regions or as binary companion of a white dwarfs which may emit ultra-high energy cosmic rays. Single old brown dwarfs would be affected by only the interstellar radiation field. We have investigated the effect of cosmic rays as source of ionisation in the ultra-cool, cloud-forming atmospheres of exoplanets and brown dwarfs. This also allows us to evaluate the the chemical composition of the ionised gas under the influence of cosmic rays. Our results suggest that ion-neutral chemistry is significant for producing hydrocarbon chains, and may help to drive PAH production in oxygen-rich atmospheres, possibly giving the upper atmospheres of these planets a chemistry similar to that expected from those objects with an enhanced C/O ratio. Finally, chemo-ionization processes may also significantly enhance the electron fraction in the cloud layer.

John Robert Brucato

INAF-Osservatorio Astrofisico di Arcetri, Italy

Heterogeneous catalysis of organic molecules in harsh environments

In the astrobiology context, the study of the interaction between electromagnetic radiation, energetic particles and bio-molecules in heterogeneous environments is particularly relevant to investigate the physico-chemical mechanisms that lead to the synthesis of complex chemical compounds in space. Mineral matrices may play a fundamental role in processes that lead to the synthesis of complex molecules because their surfaces are dynamic, energetic environments able to selectively adsorb molecules, allowing their concentration, assisting prebiotic self-organization. Specifically, minerals can act as catalysts promoting selective synthesis of biomolecules on grain surface. In this context I will present laboratory results on biomolecule mineral surface interaction under space-simulated environments, providing a support for the interpretation of astronomical observations to detect organic compounds in space.

Alexei Struminsky

Space Research Institute, Russia

Radiation conditions near exoplanets of G-M-stars

Stellar and galactic cosmic rays (SCR and GCR) are main factors determining radiation conditions near exoplanets. A spectrum of GCR and its temporal variations are governed by modulation processes in the astrosphere - parameters of stellar wind and local characteristics of interstellar medium. Estimates of stellar wind velocities using the Parker model show that they differ from solar values by several times, but stellar magnetic field strength may differ by one-two orders. As a result GCR would be practically absent near exoplanets of stars with large stellar magnetic field. In this case radiation conditions would be determined by SCR - stellar activity, energy of stellar flares and orbital parameters of exoplanets. We plan to present estimates of GCR and SCR fluxes for some exoplanets accounting available data on magnetic field and activity of the hosting star.

Guillaume Gronoff

SSAI/NASA LaRC, USA

Chemical impact of Cosmic Rays: towards a new vision of planetary system evolution

Our understanding of the evolution of planets in the solar system is based upon the observation of its "building blocks", such as comets, as well as trying to understand the planets' past by inferring what created what is currently observed. This path, albeit successful in many ways, led to paradoxes such as the Faint Young Sun paradox therefore proving that one cannot simply extrapolate current conditions to the past. As an example, the Young Sun was faint, but way more active, and its increased activity lead to a dramatic increase of the "Solar" Cosmic Rays flux at Earth and planets. We computed that such as flux leads to the creation of N_2O, a potent greenhouse gas, and HCN, a very important prebiotic molecule, which may solve the Faint Young Sun paradox. Another example is the comets: they are subject to space weathering by cosmic rays, which deposit their energy deeper than the EUV-XUV flux. We show that cosmic rays leads to the creation of O_2 that could be observed in the comets that undergo their first passage close to the Sun, and slightly change their isotopic composition. These processes are particularly active around other stars, and it may be possible to observe their effect on exoplanets.

Vasily Kozhevnikov

Institute of High Current Electronics, Russia

The simulation of stratospheric discharges sustained by the secondary electrons from cosmic rays

Typical magnitudes of the electric fields existing in the stratosphere are an order weaker than static breakdown values needed to perform gas breakdown in normal conditions, the breakdown and the further discharge formation require special mechanism for the plasma onset. Such mechanism is called breakdown on runaway electrons, which are generated in the discharge plasma and enter to the continuous acceleration regime. Due to high energies, the flux of runaway electrons have significant ability to ionize the gas medium in the course of its motion. In the upper layers of the atmosphere, runaway electrons flows cause the appearance of large-scale luminous phenomena also known as "giant sprites", "blues jets" and blue starters. The necessary condition for the breakdown on runaway electrons is the intensive preionization of the gaseous medium carried out by cosmic rays. They produce intensive fluxes of secondary electrons with mean energies above 1 MeV. In order to describe stratospheric discharges we propose the purely kinetic model scaled to the small size of a discharge gap with artificial setup of pressure gradient and preionization similar to high-altitude atmospheric conditions. The mathematical model consist of Boltzmann-Maxwell system of equations for the one-dimensional spherically symmetrical model configuration describing the discharge of a capacitance to the gas-filled gap.

Elena Amato

INAF-Osservatorio Astrofisico di Arcetri, Italy

On the mechanisms of particle acceleration in astrophysical sources

The presence of high energy particles is ubiquitous in astrophysical environments and these particles are thought to play a fundamental role in many cosmic processes, such as star formation and the seeding of prebiotic conditions. In this talk I will review the main mechanisms that are invoked for the acceleration of particles in the different energy ranges and astrophysical settings. For each process I will also try to assess how theoretical expectations compare with observational evidence gathered both from multiwavelength emission of astrophysical sources and direct measurements of diffuse cosmic rays in the Galaxy.

Donna Rodgers-Lee

University of Hertfordshire, UK

The ionising effect of low energy cosmic rays from a Class II object on its protoplanetary disk

Young low-mass stars are typically more magnetically active than our Sun making it reasonable to assume that they accelerate particles to ~GeV energies, as the Sun itself is an effective MeV accelerator. These low energy cosmic rays may prove to be an important source of ionisation for the weakly ionised protoplanetary disks surrounding young stars. If angular momentum transport in these disks is mediated by magnetic fields then the ionisation rate is one of the most important quantities to consider. Since the Sun's heliosphere shields the solar system from galactic cosmic rays out to ~100 au, the protostellar analogue of the heliosphere could potentially suppress galactic cosmic rays out to ~1000 au thus eliminating an important source of ionisation from the protoplanetary disk. Based on the assumption that young low-mass stars accelerate protons to ~GeV, we estimate the ionising effect of these low energy stellar cosmic rays in protoplanetary disks. We solve their transport equation by treating the propagation of the cosmic rays as diffusive. We present our results investigating the influence of a number of parameters, such as the diffusion coefficient and energy of the cosmic rays, on the resulting ionisation rate. We find that, generally, the high column density in the inner region of the disk prevents the cosmic rays from significantly ionising the outer regions of the disk. We discuss further ways of investigating the ionising effect of low energy stellar cosmic rays.

Christian Rab

Kapteyn Astronomical Institute, Netherlands

Modelling of high-energy ionization processes in the circumstellar environment of young solar-like stars

High energy ionization sources such as X-rays, cosmic rays and stellar energetic particles (stellar cosmic rays, SP) can ionize molecular hydrogen, the most abundant chemical species in the environment of young stars. Therefore, they play a crucial role in the chemistry and evolution of the circumstellar environment. We use the radiation thermo-chemical disk code ProDiMo (PROtoplanetary DIsk MOdel) to model the impact of those high-energy ionization sources on the chemistry of protoplanetary disks. The model includes X-ray radiative transfer and makes use of particle transport models to calculate the individual molecular hydrogen ionization rates in the disk (Rab+ 2017). We study the impact on the chemistry via the ionization tracers HCO^+ and N_2H^+. We argue that spatially resolved observations of those molecules combined with detailed models allow for disentangling the contribution of the individual high-energy ionization sources and to put constraints on the SP flux in T Tauri stars. We further present a new extension to ProDiMo, which allows modelling of the disk plus envelope structure of embedded stars (i.e. Class I). With our new model, it is possible to study the impact of X-ray, cosmic-ray and SP ionization on the chemistry in the circumstellar structure. We present first results and discuss potential observational tracers that provide constraints on the disk/envelope ionization and the individual high-energy ionization sources.

Alexandre Marcowith

Laboratoire Univers et Particules de Montpellier, France

In-situ cosmic ray sources in young stellar objects

The role of cosmic rays in young stellar object dynamics is still elusive. Some recent observations tend to indicate that supplementary sources of energetic particles are required to explain ionization rate enhancements. In parallel, a few young stellar objects show evidence of non-thermal radio synchrotron emission. In this talk, I will discuss the potential scenarii that may lead to in-situ cosmic ray acceleration in young stellar objects. I will address the case of massive young stellar objects as potential sources of radio and gamma-ray radiation.

Francesco Fontani

INAF-Osservatorio Astrofisico di Arcetri, Italy

Carbon-chain growth induced by cosmic rays in the Solar-type protocluster OMC2-FIR4

Cyanopolyynes are carbon chains delimited at their two extremities by an atom of hydrogen and a cyano group, meaning that they could be excellent reservoirs of carbon. The simplest member, HC_3N, is ubiquitous in the galactic interstellar medium. Because of their potential to form (macro-)molecules of biogenic importance, understanding the growth of cyanopolyynes in regions forming stars similar to our Sun, and what affects them, is particularly relevant. In the framework of the IRAM/NOEMA Large Program SOLIS (Seeds Of Life In Space), we have obtained a map of two cyanopolyynes, HC_3N and HC_5N, in the protocluster OMC-2 FIR4. Because our Sun is thought to be born in a rich cluster, OMC-2 FIR4 is one of the closest and best known representatives of the environment in which the Sun may have been born. We find a HC_3N/HC_5N abundance ratio across the source in the range 1-30, with the smallest values ($\leq$10) in FIR5 and in the eastern region of FIR4. The low ratios ($\leq$10) can be reproduced by chemical models only if the cosmic-ray ionisation rate ζ is 4×10^{-14} s^{-1}. The large ζ is comparable to that measured in FIR4 by previous works, and is likely due to a flux of energetic ($\geq$10 MeV) particles from embedded sources. Other explanations, like a temperature gradient across FIR4, could also explain the observed change in the HC_3N/HC_5N line ratio. However, even in this case, a high constant cosmic-ray ionisation rate (of the order of 10^{-14} s^{-1}) is needed

Linda Podio

INAF-Osservatorio Astrofisico di Arcetri, Italy

Observational constraints on the CR ionisation rate in the protostellar shock L1157-B1

Cosmic rays have a crucial role in the physics and chemistry of the interstellar medium. Recent observational studies have shown that the CR ionisation rate can be constrained by measuring the abundance of key molecular ions such as HCO^+ and N_2H^+. An instructive case is represented by the protostellar shock L1157-B1. In the context of the ASAI & CHESS large programmes we performed an unbiased spectral survey of L1157-B1 and detected emission from several molecular ions, e.g. HCO^+, N_2H^+, and $HOCO^+$. The abundances of these ions strongly depends on the CR ionisation rate as the main formation path is through reactions of CO, N_2, and CO_2 with H_3^+ and H_3^+ is the direct product of the CR ionisation of H_2. We find that the best fit of the molecular ions abundance in L1157-B1 is obtained for a CR ionisation rate of $\sim 3 \times 10^{-16}$ s^{-1}, i.e. up to a factor of 10 larger than the typical ISM value. This finding provides strong evidence that protostellar shock can be a local source of energetic particles through the 1st-order Fermi acceleration mechanism.

Ignazio Pillitteri

INAF-Osservatorio Astronomico di Palermo, Italy

Hot and glowing: the high energy emission of the very young stellar object Elias 29

High energy emission is a key feature of very early star formation phases. Stars develop very early a powered-up version of the solar corona with temperatures up to 100 MK during energetic flares. Emission at energies in the range 10-100 keV has so far been elusive in detection. Its presence could be related to the interplay of a strong magnetic field and the plasma. We present the results of a long, simultaneous XMM and NuSTAR observation of the Class I object Elias 29 in the Rho Ophiuchi Dark Cloud. Variability in form of a flare and variable fluorescent emission of "cold" Fe at 6.4-6.6 keV is observed. The 250 ks long NuSTAR observation allows the first detection of high energy emission of likely non thermal origin in a very young stellar object.

Anabella Araudo

Astronomical Institute of the Czech Academy of Sciences, Czech Republic

Particle acceleration and magnetic field amplification in protostellar jets

Synchrotron radiation is commonly detected in relativistic jets such as those in radiogalaxies and microquasars. However, since the last two decades, synchrotron radio emission from a handful of non-relativistic jets powered by massive protostars has been reported. The detection of synchrotron radiation indicates the presence of relativistic electrons in the jets, likely accelerated by diffusing back and forth the internal and termination shocks. I will present an ongoing study of diffusive shock particle acceleration in protostellar jets with velocities between 100 and 1000 km/s. In the most powerful sources, non-resonant hybrid (Bell) instabilities can grow fast enough to dominate over Alfven waves and amplify the magnetic field. Rayleigh-Taylor instabilities in the contact discontinuity of the jet termination shocks can also contribute to magnetic field amplification. I will present the case study IRAS 18162-2048, the powering massive protostar of the famous Herbig-Haro objects HH 80 and HH 81.

Jan Forbrich

University of Hertfordshire, UK

New perspectives on high-energy processes from stellar radio astronomy

With significant new observing capabilities, centimeter-wavelength radio astronomy is currently in a renaissance leading up to the advent of the Square Kilometre Array (SKA). The sensitivity upgrades of both the NRAO Very Large Array (VLA) and the Very Long Baseline Array (VLBA) have begun to provide us with a much improved perspective on stellar centimeter radio emission, particularly concerning young stellar objects (YSOs) and ultracool dwarfs. For the first time we now have systematic access to the radio time domain. I will mainly present a deep VLA, VLBA, and ALMA radio survey of the Orion Nebula Cluster (ONC), where we have found hundreds of compact radio sources, a sevenfold increase over previous studies, and intricate detail on the radio emission of proplyds. We can now better disentangle thermal and nonthermal radio emission by assessing spectral indices, polarization, variability, and brightness temperatures (VLBA). With simultaneous radio-X-ray time domain information (Chandra), this project is providing first constraints on YSO radio flares and their relation with X-ray flares, as well as improved constraints on the overall high-energy irradiation of their surroundings, including protoplanetary disks. Additionally, I will comment on new insights on high-energy processes in ultracool dwarfs from radio observations.

Rachael Ainsworth

JBCA, University of Manchester, UK

Synchrotron emission in protostellar jet shocks revealed by metre wavelength observations

I will present a status update on a pathfinding project to study the metre wavelength properties of low mass young stellar objects (YSOs). I will present observations of a sample of well known YSOs made with the Giant Metrewave Radio Telescope (GMRT) at 50 and 90 cm - the first detections of these objects at such long wavelengths. The spectral energy distributions associated with jet emission arising close to each source show a continuation of the free-free spectra extrapolated from centimetre wavelengths to the metre-wave regime. In a few cases, emission with a synchrotron spectral index is detected and interpreted to arise from shocks in the outflows. This provides tentative evidence for the acceleration of particles to ~GeV energies at the shock fronts of these relatively low-power jets and suggests the possibility of low energy cosmic rays being generated by young Sun-like stars. Finally, I will present the first observations of a YSO with the Low Frequency Array (LOFAR), extending the study of young stars to 2 m and placing new constraints on important physical properties such as local electron density, ionized gas mass and emission measure.

Mayra Osorio

Instituto de Astrofisica de Andalucia (CSIC), Spain

Non-thermal radio emisision from the jet associated with an intermediate-mass protostar

Radio jets powered by young stellar objects are characterized by thermal free-free emission, but for a handful of sources non-thermal spectral indices have been found. This non-thermal emission is produced by particles that have been accelerated to relativistic velocities in strong shocks caused by the impact of the outflow on the ambient medium. This kind of energetic shock has been proposed as a mechanism to produce cosmic rays. Therefore, protostellar jets could provide a new laboratory to test theories of galactic cosmic ray production. We present multifrequency observations carried out with the Very Large Array (VLA) toward the protostar OMC-2 FIR 3 (HOPS 370) in the Orion region. From these observations, we conclude that the radio jet driven by this protostar is composed of a thermal free-free core (VLA 11) and several knots (VLA 12N, 12C, 12S) of non-thermal radio emission at distances of 7500-12,500 au from the protostar, in a region where a strong far-infrared source (OMC-2 FIR 4) and other shock tracers have been previously identified. These knots are moving away from the HOPS 370 protostar at velocities of about 100 km/s. The Class 0 protostar HOPS 108, which itself is detected as an independent, kinematically decoupled radio source, falls in the path of these non-thermal radio knots. These results favor the previously proposed scenario in which the formation of HOPS 108 is triggered by the impact of the FIR 3 outflow with a dense clump.

Posters

Marin Chabot

Institut de physique Nucléaire d'Orsay, Paris, France

PAH destruction by heavy cosmic rays and carbon chains production rates

The interstellar medium contains both cosmic rays (CRs) and PAH. The frontal impact of a single heavy CR with one PAH strips out many electrons. The highly charged species then relax by multifragmentation, potentially feeding the interstellar medium with hydrocarbon chains. I will present results of calculations for this process. The IAE model was used for collisional purposes while a new microcanonical model was used for fragmentation. Both models agree with experiments. The production rate of low hydrogenated hydrocarbon chains (N_c = 5–15) is found to be within 0.1 to 1 zeta depending on the size and morphology of the PAH, and on the adopted content of heavy particles in the impinging CR flux.

Laura Colzi

Università degli Studi di Firenze, Italy

Carbon isotope chemistry in intermediate- and high-mass star forming cores

Isotopic abundances in the interstellar medium (ISM) provide important information to understand stellar nucleosynthesis and its evolution in the Galaxy. The $^{12}C/^{13}C$ isotopic ratio is considered an important tracer that reflects the relative degree of primary and secondary processing in stars. It is also very important for constraining the $^{14}N/^{15}N$ isotopic ratio, which is usually deduced from observations of ^{13}C-isotopologues. Milam et al. (2005) derived, from observations of CN, CO and H_2CO in a sample of 18 molecular clouds, three Galactocentric gradients of $^{12}C/^{13}C$ finding a local ISM value of about 68.

The model of Roueff et al. (2015) considers the time-dependence of the $^{12}C/^{13}C$ ratio in different molecular species in low-mass cores, and shows that the $^{12}C/^{13}C$ ratio evolves with time in a different way for each molecule, reaching up to a factor two higher than the local ISM value.

We present here the first results of our new model for carbon isotopic chemistry in the ISM. We use the gas-grain chemical code of Sipilä et al. (2015a,b) with updated gas-phase and grain-surface chemical networks to simulate the $^{12}C/^{13}C$ ratio in high-mass star-forming cores, in order to provide constraints for comparison with observations. Cosmic rays play a pivotal role in the development of dense molecular clouds by providing heating and acting as the primary source of ionization. Here we discuss the effect of cosmic rays on the $^{12}C/^{13}C$ abundance ratio in dense high-mass star forming cores.

Alicja Domaracka

CIMAP-CNRS, Caen, France

Intra-cluster molecular growth processes induced by low-energy ion processing of carbonaceous system

To better understand the physical and chemical evolution of the atmospheres of planets/moons and the particle distribution in the interstellar medium it is essential to study energetic processing of carbon containing complex molecular system (e.g. hydrocarbons fullerenes and PAHs).

Recently, we have shown that keV ion collisions can lead to intra-cluster molecular growth processes in pyrene clusters (R. Delaunay et al. 2015 J. Phys. Chem. Lett. 6 1536). This growth is driven by the prompt fragmentation of molecules in loosely bound clusters when the impacting projectile ion deposits a large amount of energy and momentum to individual atoms through nuclear scattering (knock-out processes) leading to formation of reactive species. These molecular fragments may form covalent bonds with neighbouring molecules in the cluster on sub-picosecond time scales, well before the excited cluster dissociates.

This poster will be focused on molecular growth processes in clusters of 1,3 butadiene clusters by ion impact in the nuclear and in the electronic regime. The obtained results show similar product intensities and distributions, which means that also electronic excitation or pure ionization may lead to molecular growth. We have observed formation of "magic structures" of new species, which are more stable than similar sized products. This higher stability is explained by the formation of cyclic structures, the energies of which are found to be lower than those of the linear isomers.

Yasuo Fukui

Nagoya University, Japan

Cosmic-Ray Acceleration and Star Formation in the Gamma Ray SNR RXJ1713.7-3946

SNRs are the most probable site where cosmic-ray acceleration is verified in the Milky Way. RXJ1713.7-3946 is the brightest TeV gamma ray SNR observed by H.E.S.S. and attracted most intensive interest on the origin of cosmic rays (e.g., Aharonian et al. 2005; Fukui et al. 2003). RXJ1713.7-3946 is also a unique site of recent star formation as verified by the protostellar outflow and several protostellar infrared sources (Moriguchi et al. 2006; Sano et al. 2010). A recent comparative study between TeV gamma rays and the interstellar hydrogen (HI and H_2) has demonstrated good correspondence between them, supporting the hadronic origin of the gamma rays (Fukui et al. 2012; Inoue et al. 2012). The SNR RXJ1713.7-3946 is a top-priority object where cosmic-ray acceleration up to the highest energy close to the knee is taking place. Future goals in studying RXJ1713.7-3946 include the energy-dependent cosmic-ray penetration into the dense HI-H_2 gas and the detection of the lower energy cosmic-ray tail which contributes the ionization of the star forming clumps. In this contribution we will present the state-of-the-art understanding on the cosmic-ray acceleration in RXJ1713.7-3946 and a few similar young SNRs based on the extensive datasets of dense ISM obtained with ALMA, ASTE, NANTEN2 and Mopra (e.g., Sano et al. 2017; Maxted et al. 2017) and numerical simulations of gamma-ray production which utilized CTA simulators (Acero et al. 2017).

Siddharta Gupta

Indian Institute of Science and Raman Research Institute, Bangalore, India

Lack of thermal energy in superbubbles: hint of cosmic rays?

The study of gas expulsion in star forming regions is an excellent tool to test various stellar feedback models. The recent observations have suggested that the thermal energy from these regions is dramatically reduced due to radiative cooling. Non-thermal pressure support (e.g. cosmic rays) can play a crucial role in pushing the gas. To understand this, we use a two-fluid approach to simulate the interstellar bubble which serves as a standard model for the wind and ISM interaction. We use analytic methods and numerical simulations, and explore the dynamical effects of cosmic rays (CR) in various acceleration scenarios. We find that cosmic-ray acceleration mainly affects the structure if (1) the reverse shock gas Mach number exceeds 12 and (2) the CR acceleration time scale $\tau_{acc} \approx \kappa_{cr}/v^2$ is shorter than the dynamical time, where κ_{cr} is the CR diffusion coefficient and v the upstream speed. We analyze the X-ray and gamma-ray properties to quantify the dominating feedback process.

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Michał Hanasz

Centre for Astronomy, Nicolaus Copernicus University, Poland

Synchrotron emission from cosmic ray driven galactic winds in star forming galaxies

Cosmic rays accelerated in supernova remnants are energetic enough to drive high mass-loaded galactic winds reaching velocities of the order of 1000 km/s in star forming galaxies. Those winds are capable of evacuating significant fraction of gas, that would otherwise be available for star formation, and therefore provide an efficient feedback mechanism. The mass-loading and the terminal wind speed depend primarily on an on an unknown value of diffusion coefficient of cosmic rays in the interstellar medium. We perform a series o numerical simulations of galactic wind model with PIERNIK code. The code has been recently equipped with a new module for modeling energy-dependent transport of CR electrons with synchrotron and adiabatic cooling losses taken into account. We construct synchrotron radio-maps of galaxies at different radio-frequencies. We compare the synthetic radio-maps with the maps of real galaxies and discuss observational constraints for the CR diffusion coefficients.

Juris Kalvāns

Ventspils International Radio Astronomy Center of VUC, Latvia

Temperature spectra for interstellar grains heated by cosmic rays

Recent data on cosmic-ray (CR) intensity and spectra allows more precise estimates for the frequency of CR impacts on interstellar grains that raise grain temperature to a particular extent. This frequency is an important parameter in astrochemistry that defines the rate of CR-induced surface molecule desorption and other heating-induced processes on the grains. We present detailed calculations of frequencies that indicate how often a grain reaches a certain temperature because of CR hits (i.e., temperature spectrum of CR-heated grains). We considered bare and ice-covered grains in interstellar molecular clouds suffering impacts by 30 CR species, whose spectra is attenuated by hydrogen column densities characteristic for starless and prestellar cores, were considered by the cloud (see Kalvāns 2016). The more precise CR-induced grain heating frequencies are high and have to be tweaked to account for shielding by cloud gas and magnetic fields. We also present an initial estimate how the new frequencies affect the composition of interstellar clouds. The new data indicate an efficient CR-induced desorption that shapes the composition of interstellar ices in dense cores and keeps a fraction of volatile species in the gas phase in more diffuse regions.

Mateusz Ogrodnik

Torun Centre for Astronomy, Nicolaus Copernicus University, Poland

Piernik MHD code: modelling energy dependent transport of cosmic ray electrons with energy spectrum

Cosmic ray electrons are one of the main ingredients of the total cosmic ray population, being the main source of galactic synchrotron emission. A new extension to MHD code PIERNIK allows us to model energy dependent propagation of cosmic-ray electron population in the magnetized interstellar medium, taking into account evolution of spectrum. Our algorithm, "Cosmic Ray Energy SPectrum" (CRESP) was developed to seek numerical solutions of Focker-Planck equation. Cosmic ray spectrum is approximated with power-law in the momentum space. Algorithm includes alteration of cosmic ray spectrum by a number of physical processes (i.e. synchrotron energy losses) and allows injection / acceleration of particles in the interstellar medium. New extension of PIERNIK code opens up an opportunity to model a set of astrophysical phenomena, among which are ISM heating, cosmic ray propagation, synchrotron and gamma ray emission, formation of galactic magnetic field.

Bilal Ramzan

National Central University, Taiwan

Structure of interstellar clouds with cosmic rays and waves

Cosmic rays are coupled to thermal plasma through magnetic fluctuations embedded in the plasma. These fluctuations can be described by hydromagnetic waves. To investigate the dynamic effect of cosmic rays on an interstellar cloud, we adopt a four-fluid model consists of plasma, cosmic rays, and two oppositely propagating Alfvén waves. We study the influence of cosmic rays and waves on the structure of the cloud, which bears importance on the star formation processes inside the cloud.

Víctor M. Rivilla

INAF-Osservatorio Astrofisico di Arcetri, Italy

The role of cosmic rays and other energetic phenomena in the chemistry of P-bearing molecules in the Galactic Center

Phosphorus (P) is one of the essential elements for life due to its central role in biochemical processes. Recent searches have shown that P-bearing molecules (in particular PN and PO) are present in star-forming regions, although their formation routes remain poorly understood. In this poster we show observations of PN and PO towards seven molecular clouds located in the Galactic Center, which are exposed to different physical processes and energetic phenomena such as cosmic rays, protostellar heating, shock waves, and intense UV/X-ray radiation. PN is detected in five out of seven sources, whose chemistry is thought to be shock-dominated. The two sources with PN non-detections correspond to clouds exposed to intense UV/X-rays/cosmic-ray radiation. PO is detected only towards the cloud G+0.693-0.03, with a PO/PN abundance ratio of ~1.5. We have compared our observational results with a new developed chemical model that mimics the conditions of the Galactic Center. We conclude that P-bearing molecules likely form in shocked gas as a result of dust grain sputtering, while are destroyed by intense UV/X-ray/cosmic-ray radiation.

Hermann Rothard

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Radiolysis and sputtering of carbon dioxide ice by swift (MeV-GeV) ions

The chemical and physical changes induced by heavy irradiation of pure solid CO_2 at low temperature (T=15–25 K) are analyzed. The experiments were performed with Ti (570 MeV) and Xe (630 MeV) ions at the M-branch of GSI/Darmstadt and with Ni ions (46 and 52 MeV) at IRRSUD GANIL/Caen in order to simulate the effects of cosmic rays. The evolution of the thin CO_2 ice films (deposited on a CsI window) was monitored by mid-infrared absorption spectroscopy (FTIR) [1]. The dissociation rate of CO_2, determined from the fluence dependence of the IR absorption peak intensity, is found to be proportional to the electronic stopping power S_e. We also confirm that the sputtering yield shows a quadric increase with electronic stopping power [1,2,3]. Furthermore, the production rates of daughter molecules such as CO, CO_3, C_3 and O_3 were analyzed and found to be proportional to S_e [3].

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A star-forming dense cloud core embedded within the brightest gamma-ray SNR RX J1713.7-3946

RX J1713.7-3946 (hereafter RXJ1713) is the brightest gamma-ray supernova remnant (SNR) in the Galactic plane (H.E.S.S. Collaboration et al. 2017). Gamma-rays of RXJ1713 are believed to be produced by ultrarelativistic cosmic-rays via proton-proton interactions (e.g., Fukui et al. 2012). The young age ~1600 yr means a high level of cosmic-rays will still be trapped inside the SNR shell. RXJ1713 is also interacting with molecular and atomic gases located at ~1 kpc. Sano et al. (2010) revealed that a dense molecular core ìpeak Cî shows strong signs of low-mass star formation including bipolar outflow and a far-infrared protostellar object, and has a steep gradient with a r^(-2.2 ± 0.4) variation in the average density within radius r. Synchrotron X-rays are enhanced around peak C, indicating that the dense cloud core is embedded within the SNR shell, and survived shock erosion owing to the shock propagation speed is stalled in the dense core. According to numerical calculations, the shock-cloud interaction excites turbulence and magnetic field amplification around the dense core that may facilitate cosmic-ray electrons in the lower-density inter-clump space leading to enhanced synchrotron X-rays around dense cores (e.g., Inoue et al. 2009, 2012). In this contribution, we will present the low-mass star formation in a unique environment with the high level of cosmic-rays and shock-erosion.

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Cosmic Ray-Driven Radiation Chemistry in Astrochemical Models

Cosmic rays are widely known to have significant physiochemical impact on interstellar sources. In addition, laboratory astrophysics experiments have indicated that cosmic ray interactions with dust-grain ice mantles could lead to astrochemically relevant species, including complex organic and prebiotic molecules [1].

In spite of the growing body of experimental work on interstellar radiation chemistry, incorporating cosmic ray-driven reactions and processes into astochemical models has proven challenging, in part because of a lack of relevant data for many species now included in chemical networks. Recently [2], we have developed a general method of estimating radiochemical yields (G-values), rate coefficients, and decomposition pathways for species that have not been studied in detail in the laboratory in this context. Here, we will describe the derivation and application of our method, as well as point to much needed areas for future development in astrochemical radiation chemistry modeling.

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Synchrotron signatures from the cosmic-ray driven dynamo

Cosmic-ray-driven dynamos produce magnetic arms in galactic disks and large-scale helical magnetic fields in galactic halos. Relying on numerical models of hybrid N-body and CR-MHD simulations we show formation of those structures. We discuss the relation of the 3D magnetic field structures with their counterparts in radio maps of synchrotron radio-emission. We suggest that X-shaped structures on polarisation radio-maps of edge-on galaxies result from the projection of large-scale magnetic helices onto the plane of sky.

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Cosmic ray acceleration and star formation in the superbubble 30 Doradus C

Superbubbles are formed by the effect of shock-wave of supernova explosions interacting with the surrounding interstellar medium (ISM) and accelerated cosmic ray. The superbubble 30 Doradus C in the Large Magellanic Cloud has a diameter of ~ 100 pc, and north-western part of the shell is bright in synchrotron X-ray. TeV gamma ray was also detected by H.E.S.S, suggesting cosmic ray accelerations up to the energy of 100 TeV. 30 Doradus C harbors OB association LH 90, three young stellar objects (YSOs), and ~40 massive stars. Here we present CO and HI observations toward 30 Doradus C. We obtained CO data with ALMA in the J=1-0 and 3-2, and with ASTE in J=3-2 lines, as well as HI data with ATCA, whose resolutions are ~3", ~4", 22", and 12', respectively. The HI clouds are located at the inner rim of the X-ray shell, indicating an expanding gas motion of ~15 km/s, where clumpy CO clouds are embedded within the HI clouds. The synchrotron X-ray emission has four peaks near the CO clumps within a distance of 2 pc, suggesting that shock-cloud interaction enhances the X-ray emission due to the propagation of shock-wave in the inhomogeneous ISM. We also found that the three YSOs are associated with the dense molecular clumps whose diameters and virial masses are typically ~ 3 pc and ~ 1000 Msun. These indicate ongoing star formation on the shell of 30 Doradus C under the influence of shock-cloud interaction and the accelerated cosmic rays.