Molecules and planets in the outer Galaxy: is there a boundary of the Galactic Habitable Zone?

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Fuligno Cenacle

Book of Abstracts

Contents

Session-1: Star-forming regions at sub-Solar metallicity: observations / 23

Registration and Welcome

Corresponding Author: francesco.fontani@inaf.it

Session-1: Star-forming regions at sub-Solar metallicity: observations / 24

Organic and inorganic molecules in protostellar cores: Exploring the outer Galaxy and the Magellanic Clouds

Nearby low-metallicity laboratories, such as the outer part of the Galaxy, as well as the Large and Small Magellanic Clouds (x0.1-0.5 solar metallicity), are excellent targets to study the star-forming "core"-scale chemical phenomena, such as the formation of complex organic molecules, in different environments. In the last decade, there has been a great progress in astrochemical studies of interstellar molecules in these sub-solar metallicity regions. We here present the results of the ALMA survey of protostellar cores in the outer Galaxy and the LMC/SMC. Chemical analyses of low-metallicity protostellar cores (especially hot cores) suggest that molecular abundances do not always simply scale with the metallicity of their parent environments. Complex organic molecules such as CH3OH show a large abundance variation within low-metallicity sources. In some LMC hot cores, CH3OH is significantly depleted beyond the level of the metallicity difference. For the outer Galaxy sources, although the sample statistics is still poor, complex organic molecules are commonly detected with the abundances that roughly scale with their metallicity. In contrast to organic molecules, inorganic molecules such as SO and SO2 are ubiquitously detected in lowmetallicity
hot cores. The reason of such chemical diversity of organic molecules in low-metallicity protostellar cores remains unexplained. This presentation will summarize the recent observational progress in understanding of the chemical diversity of protostellar cores located in sub-solar metallicity
environments. Preliminary results of ALMA follow-up observations with the higher spatial resolution or the wider spectral coverage toward selected sources will also be presented.

Session-1: Star-forming regions at sub-Solar metallicity: observations / 25

Isotopic abundance ratios: What's up in the outer edge of the Milky Way?

Isotopic ratios (e.g. 12C/13C and 14N/15N ratios) measured within interstellar molecular clouds depend on the chemical evolution of the galaxy due to stellar nucleosynthesis, and thus they can provide unique constraints to the history of star formation in galaxies. Moreover, isotopic ratios also depend on local chemical fractionation effects, which are closely connected to the physical conditions of molecular clouds and cores (e.g. density and temperature, or UV radiation field). In this talk, I will review the main observed galactocentric trends of isotopic ratios, and I will introduce the CHEMOUT (CHEMical complexity in star-forming regions of the OUTer Galaxy) project.
The latter include observations of a sample of 35 high-mass star-forming cores at Galactocentric distances up to about 23 kpc obtained with the IRAM 30m telescope. The study of isotopic ratios with these recent observations towards star-forming regions located in the outer Galaxy allow us for the first time to extend the prediction of Galactic Chemical Evolution models to these distances

Session-1: Star-forming regions at sub-Solar metallicity: observations / 26

Observations of star-forming regions in the Magellanic Clouds

Session-1: Star-forming regions at sub-Solar metallicity: observations / 27

Disks at low metallicities

Over the past decade, technological advancements have enabled spatially resolved studies of disks around young stars at larger and larger distances, opening up studies of these objects in environments that differ from those of the Solar neighborhood, and culminating in the recent discovery of a Keplerian disk around the driving star of HH 1177, a massive young stellar object (MYSO) in the low-metallicity environment of the Large Magellanic Cloud. Starting from the HH 1177 system as a benchmark for extragalactic low-metallicity studies, I will discuss what observational and computational work is being carried out to capitalize on this discovery with the aim of better understanding how disks around low-metallicity MYSOs evolve on the one side, and what the impact of exposure to low-metallicity stars is on disks around lower mass YSOs.

Session-2: Planets and planet formation at sub-Solar metallicity: observations / 28

The metallicity content of planet-host stars: the Ariel reference sample

Most of our current understanding of planet formation mechanism is based on the correlations of metallicity of planet-host stars with planet frequency and therefore, precise and accurate metallicity determinations are fundamental. In this talk, I will present the results of the characterization of the Ariel reference sample for a diverse sample of stars in terms of stellar mass (up to 1.8 $M_{\odot}$) in collaboration with the "Ariel stellar characterization"working group. The standard methodology to derive high-precision stellar parameters from high-resolution spectra is based on the iron ionisation and equilibrium conditions and spectral synthesis techniques. Our analysis indicates a
close relationship between stellar mass and giant planet radius, with more inflated planets at lower metallicities. We find that giant planets are more frequent around more metal-rich stars that belong to the thin disc, while lower-mass planets are found also in more metal-poor environments, and are more frequent than giant planets in the thick disc.
The Galactic environment, although often overlooked, plays a significant role in shaping the planetary system. We provided observational data to investigate the impact of the chemical evolution of the Milky Way on the current planet populations

Session-2: Planets and planet formation at sub-Solar metallicity: observations / 29

Chemical abundances of stars hosting planets

The characterization of solar-type stars is fundamental for various fields in astrophysics, including exoplanet detection and the chemical evolution of our Galaxy. In particular, the determination of chemical abundances for stars at different metallicities and ages provides us with a key insight on how and when the various chemical elements were formed within the Galaxy. The chemical trends observed in different parts of the Galaxy (thin disk, thick disk, bulge and halo) also serve to understand how those different populations were formed. On the other hand, knowing the particular characteristics of a given star is essential to be able to detect its hosted planets as well as to characterise their mass, radius, structure and bulk internal composition. The probability of finding planets is clearly related to the chemical makeup of the stars and these planets in turn can have an influence on the stellar composition. In this talk I will review some of the important advances on studying the chemical peculiarities of stars hosting planets

Session-2: Planets and planet formation at sub-Solar metallicity: observations / 30

From primordial composition of stars to the present-day composition of their rocky exoplanets

Stellar atmospheres offer the only observational window into the remnants of planet-forming disk composition, given that disks, with lifetimes typically lasting only a few million years, have long dissipated around most discovered planet-hosting stars. When modeling the interiors of rocky planets an one-to-one relation between the composition of the planet and the host stars is typically assumed. However, Adibekyan et al (2021) showed that while there is a relation between the composition of rocky planets and their host stars, the relation is not one-to-one. The study by Adibekyan et al. (2021) has two potential limitations: i) The interiors of the planets were modeled assuming they are made only of core and mantle, i.e., no volatiles, and ii) the present-day stellar abundances were used as a proxy for the primordial protoplanetary disk composition. Some astrophysical processes, such as atomic diffusion, can influence the stellar composition as the star evolves. Thus, the present-day stellar abundances can be measurably different from their primordial composition.
Over the last two years, we worked on the EXO-Terra project, which aimed at a comprehensive analysis of the star-planet compositional link by overcoming the two aforementioned limitations. Additionally, we increased the sample by about 50%. I propose an oral contribution to present the final results of the EXO-Terra project.

Session-2: Planets and planet formation at sub-Solar metallicity: observations / 31

(Small) Planet frequency around metal-poor stars

The determination of planet occurrence rates around stars in the iron-poor regime is a relatively underexplored area of investigation in the exoplanet field. Yet, measuring observationally the critical metallicity below which planet cannot form constitutes a crucial input to planet formation theories, and it is key for gauging the galactic epoch at which the formation of any planets started. I will briefly outline the theoretical expectations for planet formation in low-metallicity environments. I will then discuss the outcome of occurrence rate calculations aimed at probing the metallicity limit beyond which planet formation is predicted to be suppressed, with a particular focus on the small planet population.

Session-2: Planets and planet formation at sub-Solar metallicity: observations / 32

Discussion

Session-4: Planets and planet formation at sub-Solar metallicity: theory / 33

From Stars to Planets: How Planet-Formation Environments Shape Planetary Compositions

With the advent of the JWST era and the upcoming generation of space- and ground-based facilities, understanding the connection between planetary compositions and the properties of their native environments has become a central challenge in exoplanet research. This connection is shaped by the process of planet formation and is profoundly influenced by the thermophysical and chemical properties of the gas and solids that planets accrete from their circumstellar discs. While early models often used the Solar Nebula as a template with simple ice-line chemistry, it is now clear that planet formation occurs around a variety of stars and at different stages of disc evolution. In this talk, I will discuss how planetary compositions are shaped by both the initial chemical and thermophysical conditions in discs and their subsequent evolution over time. I will
also illustrate key metrics that have emerged from recent exploration of this parameter space, highlighting how knowledge of stellar properties in a broader Galactic context provides important constraints on the variety of planets that can form around different stars.

Session-4: Planets and planet formation at sub-Solar metallicity: theory / 34

The genetic link between planet formation and the host star

environments, which in turn are connected to those of the host stars. The majority of our understanding of this genetic link, however, is still implicitly built on the sole case study of the Solar System and the reconstructed characteristics of the Solar Nebula. Is this a reliable foundation? Both the mass and accretion rate of protoplanetary disks are known to be proportional to the stellar mass. The stellar metallicity determines the maximum dust-to-gas ratio of disks. The balance between the disk accretional heating and the stellar luminosity sets the disk thermal structure and, together with the stellar composition and refractory-to-volatile ratio, controls the local abundance of planet building material. The growth rate of planets is limited by the local availability of dust and gas, which is governed by the disk mass transport processes and by planetary migration, in
turn set by the disk mass. Planets formed around different stars will therefore be born in different disk environments and, due to these star-disk connections, can be the product of diverging growth and migration histories even when they share the same final physical properties. In this talk I will review recent advances in our growing understanding of this multifaceted problem.

Session-4: Planets and planet formation at sub-Solar metallicity: theory / 35

STILES: the Impact of stellar XUV radiation on exoplanetary atmosphere evolution

Exoplanets form and evolve in environments dominated by the presence of their host stars. In particular, the stellar high-energy radiation strongly affects the evolution of a planetary atmosphere in several ways. It can control the chemical composition of the atmosphere through photochemical processes, but it can also cause atmospheric heating. In the latter case, if enough energy is deposited, the atmosphere heats up and begins to expand, leading to a phase of hydrodynamic instability, and may also provide mass-loss to photo-evaporation. These events may shape the evolutionary history of planets and modify on a global scale the distribution of planetary populations.
Photoevaporation is regulated by metallicity that, when sufficiently high allows planets to
retain atmospheres for longer, even in close-in orbits.

Session-3: Star-forming regions at sub-Solar metallicity: theory / 36

Star-forming regions at sub-Solar metallicity: astrochemical modelling

The chemistry of star forming regions heavily depend on the physical conditions of their gas. While there are many studies that have investigated such dependencies, the influence of the metallicity, as well as the initial elemental abundances, is less studied and, moreover, has only recently being investigated in the context of star forming regions in the outer galaxy. In this talk I shall review the astrochemical work that has been done so far.

Session-3: Star-forming regions at sub-Solar metallicity: theory / 37

Astrochemistry in extreme galactic conditions

Photodissociation Regions (PDRs) characterize the interface between the ionized and molecular gas phases. They are dominated by the presence of far-UV photons and play an important role in understanding the chemistry and the thermal balance of the interstellar medium (ISM), since it is in these regions that the atomic-to-molecular (HI-to-H2) transition occurs. I will review recent developments on understanding PDRs in the ISM of Milky Way and beyond. I will particularly focus on how the HI-to-H2 transition and the transition of carbon phases (C+/C/CO) are affected by varying the intensity of the FUV radiation field, the cosmic-ray ionization rate, and the metallicity.

Session-3: Star-forming regions at sub-Solar metallicity: theory / 38

Cosmic rays: shaping dynamics and chemistry in star-forming regions

Low-energy (<1 TeV) cosmic rays (CRs) are a key element in several physical and chemical processes of the interstellar medium, from the large scales of molecular clouds to the small scales of protostellar systems. During the last decade, significant progress has been made in understanding their transport regimes at different depths of a cloud and their interaction with magnetic fields. I will focus on the role of cosmic rays in the origin of interstellar chemistry showing how observations of molecular species can yield insights into the interstellar and local cosmic-ray spectrum

Session-3: Star-forming regions at sub-Solar metallicity: theory / 39

Chemical models with non-Solar metallicity

Low-energy (<1 TeV) cosmic rays (CRs) are a key element in several physical and chemical processes of the interstellar medium, from the large scales of molecular clouds to the small scales of protostellar systems. During the last decade, significant progress has been made in understanding their transport regimes at different depths of a cloud and their interaction with magnetic fields. I will focus on the role of cosmic rays in the origin of interstellar chemistry showing how observations of molecular species can yield insights into the interstellar and local cosmic-ray spectrum.

Session-3: Star-forming regions at sub-Solar metallicity: theory / 40

Chemical modeling of Magellanic Clouds and low-metallicity clouds/hot cores

I will review the status and results of astrochemical modeling of low-metallicity clouds, including the Magellanic Clouds. A particular emphasis will be placed on the results of grain-surface/ice chemical modeling. I will also present preliminary results from our most recent hot-core chemical models, using metallicities and gas-to-dust ratios appropriate to the outer galaxy. The influence on complex organic molecule abundances in particular will be considered

Session-3: Star-forming regions at sub-Solar metallicity: theory / 41

The physics of the metallicity dependent IMF

Understanding what sets the stellar initial mass function (IMF) in diverse environments remains a critical but unanswered question in astrophysics. The mass of stars that form is closely linked to the thermodynamics of interstellar gas, which controls how gas fragments as it collapses under gravity. As the Universe has grown in metal abundance over cosmic time, this thermodynamic behaviour has evolved from a primordial regime dominated by molecular hydrogen cooling to a modern regime where the dominant process in dense gas is protostellar radiation feedback, transmitted to the gas via dust grains. In this talk, I will present results from a suite of semi-analytical models and high resolution radiation-magnetohydrodynamics simulations that self-consistently include non-equilibrium chemistry, radiation feedback, and magnetic fields to construct the IMF at different
metallicities from first principles. I will show that the transition in the IMF from the primordial regime to the modern regime begins at metallicity Z ~ 0.0001Z, passes through an intermediate stage where metal line cooling is dominant, and then transitions to the modern dust- and feedback dominated regime at Z ~ 0.05Z. This transition is accompanied by a dramatic change in the peak IMF mass, from ~50 Msun at Z ~ 10^(−6) Z to ~ 0.3 Msun once radiation feedback begins to dominate, which marks the appearance of the bottom-heavy Solar neighborhood IMF. I will close by providing some predictions for the IMF and its sensitivity to chemistry in low metallicity ISMs that will be tested by ongoing JWST observing programs.

Session-5: Galactic Chemical Evolution: link with the Galactic Habitable Zone / 42

Galactic Chemical and Dust Gradients: Predictions and Insights from Chemical Evolution Models

Galactic chemical evolution models are crucial ingredients to place first, broad constraints on the limits and the evolution of the Galactic Habitable Zone (GHZ), as well as for the conditions for life formation within our Galaxy. In fact, by comparing model predictions of element abundances with observations from different stellar populations and the interstellar medium (ISM), we can place stringent constraints on Galactic evolution, thereby refining our understanding of Galactic habitability. In this talk, I will present recent findings on the chemical abundance gradients within the Galaxy, with a particular emphasis on the outer regions beyond the solar annulus, where new data have significantly altered our "chemical"perspective on such regions. Additionally, I will
provide a comprehensive overview of dust evolution in galaxies. Dust, with its scaling relations, is indeed a critical factor in the understanding of galactic evolution and in particular can serve as a more direct proxy than metallicity in studies related to planetary systems. Therefore, I will also discuss recent advancements in dust modelling for local disk galaxies, highlighting both the progress made and the challenges that remain in this field.

Session-5: Galactic Chemical Evolution: link with the Galactic Habitable Zone / 43

Modelling GHZs in cosmological-scale galaxy evolution simulations

Theoretical studies of galactic habitable zones (GHZs) have predominantly focused on the Local Neighbourhood, Milky Way, or the Local Group. However, with the establishment of the latest wave of cutting-edge observational instrumentation, GHZ indicators can now be observed in large numbers of other galaxies out to much further distances that ever before. This highlights the need for simulations that extend beyond our Local Group, to model galaxy chemical evolution (GCE) and the formation of GHZs across a full range of galaxy types and epochs. Such simulations have become all the more important following recent indications from JWST and ALMA that the metallicity in high-redshift galaxies (z~8) is comparable to that seen at intermediate redshift (z~2), and that in-situ dust formation should proceed rapidly in the interstellar medium. These developments open-up the possibility of life in the very early Universe and in the outskirts of local galaxies. In this talk, I will present the latest progress in the study of GHZs using cosmological-scale galaxy evolution simulations, and will signpost exciting future developments in this field.
First, I will outline the three main types of cosmological-scale simulations used, namely analytic, semi-analytic, and hydrodynamical. I will discuss each of their advantages and disadvantages for GHZ studies.
Second, I will provide an overview of the work already done on studying habitability in cosmologicalscale simulations over the last ~10 years, including the typical assumptions made about chemical enrichment and planet formation.
Finally, I will discuss future developments in this field, with a particular focus on the L-GALAXIES semi-analytic simulation. L-GALAXIES includes a sophisticated GCE model which tracks the formation and evolution of stellar populations, their nucleosynthesis of all the heavy chemical elements, and the subsequent ejection of these elements into the surrounding gas. L-GALAXIES now also includes models for binary stellar evolution and dust production & destruction, which are crucial intermediate stages in the formation of habitable planets. The next step is to implement models for (a) complex molecule formation and (b) sterilisation from rare sources such as AGN and GRBs. This will allow us to probe GHZs within galaxies across all space and time in greater detail than ever before.

Session-5: Galactic Chemical Evolution: link with the Galactic Habitable Zone / 44

Galactic habitable zones with chemical evolution models

The Galactic habitable zone is defined as the region with a metallicity that is high enough to form planetary systems in which Earth-like planets could be born and might be capable of sustaining life. Life in this zone needs to survive the destructive effects of nearby supernova explosion events. Our aim is to find the Galactic habitable zone using chemical evolution models for the Milky Way disk, adopting the most recent prescriptions for the evolution of dust and for the probability of finding planetary systems around M and FGK stars. Moreover, for the first time, we express these probabilities in terms of the dust-to-gas ratio of the interstellar medium in the solar neighborhood as computed by detailed chemical evolution models. At a fixed Galactic time and Galactocentric distance, we determined the number of M and FGK stars that host earths (but no gas giant planets) that survived supernova explosions. The probabilities of finding terrestrial planets but not gas giant planets around M stars deviate substantially from the probabilities around FGK stars for supersolar values of [Fe/H]. For both FGK and M stars, the maximum number of stars hosting habitable planets is at 8 kpc from the Galactic Center when destructive effects by supernova explosions are taken into account. Currently, M stars with habitable planets are roughly10 times more frequent than FGK stars. Moreover, we provide a fit for the relation found with chemical evolution models in the solar neighborhood between the [Fe/H] abundances and the dust-to-gas ratio.

Session-5: Galactic Chemical Evolution: link with the Galactic Habitable Zone / 45

Galactic Chemical Evolution: impact of stellar yields and link with the Galactic Habitable Zone

The chemical evolution of the elements in the Milky Way is a key diagnostic to understand the enrichment history and the abundance distribution of metals necessary to form Earth-like planets in the Sun and in other stars in the solar neighborhood. The production of specific elemental ratios (and isotopes) can be used to constrain different uncertainties affecting galactic chemical evolution simulations. Theoretical stellar yields are one of the major uncertainties, as it is consistently reported by several works in the literature. In this talk I will focus on the chemical evolution of key elements that underpin the formation of planets like C, N, O, Mg and Si, and I will put into context their main uncertainties, among others the stellar yields. I will discuss possible strategies to solve the puzzles that still affect the production of these elements in stars.

Session-6: Galactic Habitable Zone in space and time / 46

Galactic habitable zone from the perspective of phosphorous enrichment

Phosphorus (P) is one of the vital elements for life. So, it is important to know how P abundance changes with place and time in the Galaxy for the discussion of habitability. So far, it was considered that core-collapse supernovae are the major production site of P.
However, the observed P abundances of Galactic stars have challenged this hypothesis. Recently, a new model for the chemical evolution of P is proposed and shows a good agreement with the observations. This new theory claims novae originated from massive white dwarfs, i.e., ONe novae, as the major P site, and predicts a high production of P in low-metallicity environments. Accordingly, the outer disk must possess the high fraction of P among metals, as implied from the recent observation of gaseous abundances, which might raise the potentiality of habitability there

Session-6: Galactic Habitable Zone in space and time / 47

The best place and time to live in the Milky Way: the impact of Gamma Ray Bursts and Supernovae on planetary habitability

Several factors contribute to the emergence and development of life on planets. In addition to local factors (e.g., intrinsic planetary properties and host star characteristics), planetary habitability can be influenced by the larger-scale radiation environment of the galaxy. Powerful astrophysical transient sources of high-energy radiation, such as Gamma Ray Bursts (GRBs) and Supernovae (SNe), can pose life-threatening risks and potentially cause mass extinctions. Their radiation can directly harm biota or induce extinction by depleting most of the protective atmospheric ozone layer on terrestrial planets. For this reason, nearby high-energy transient astrophysical events have been proposed as possible triggers of mass extinctions on Earth. In this talk, I will present a model that
connects the rate of these high-energy events to star formation and metallicity evolution within the galaxy and accounts for the probability of terrestrial planets forming around FGK and M stars. Using this model, we assessed the habitability of the Milky Way throughout its cosmic history, considering potentially disruptive astrophysical transients, with the aim of identifying the safest places and epochs to live within our galaxy. This model also allows for the evaluation of whether a GRB or an SN may have influenced one of the mass extinction events that have occurred on Earth in the last 500 million years

Session-6: Galactic Habitable Zone in space and time / 48

Habitability across cosmological timescales

Even if only a minor fraction of the terrestrial planets in the habitable zone around red dwarfs turn out to have conditions required for the emergence of intelligent life, the large numbers of such stars, coupled to their extremely long main-sequence lifetimes, suggest that most intelligent observers should find themselves on planets around red dwarfs in the distant future, and not around solar-type stars in the current era of the Universe. This would make us outliers in the cosmic distribution of observers, but how much of a concern is this? Here, we take a closer look at this problem and some its many potential solutions, including mechanisms that could adversely affect the habitability of planets in the far future.