30 Years of PhotoDissociation Regions
A symposium to honor David Hollenbach’s lifetime in science
June 28 - July 3 2015  Asilomar - USA

Abstract Book

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Models of PDRs
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PDRs and star formation
PDRs and the ISM of galaxies
PDRs in starburst, (U)LIRG, and high-z environments

http://pdr30.strw.leidenuniv.nl
Spurred by the discovery by the Kuiper Airborne Observatory of widespread, very extended [CII] 157 $\mu$m and [OI] 63 $\mu$m emission associated with regions of massive star formation, the first models for photodissociation regions (PDRs) appeared thirty years ago. These models described the interaction of far-ultraviolet photons with dense neutral atomic gas separating the highly ionized hydrogen plasma from the surrounding molecular cloud in which these stars are born. Since then we have come to appreciate that PDRs are merely a denser and more energetic example of a widespread phenomena and that essentially the entire neutral interstellar medium of galaxies is a PDR governed by the same physics and chemistry. Indeed, PDR studies cover now surfaces of protoplanetary disks, photo-evaporation of globules and pillars, planetary nebula, characteristics of diffuse interstellar clouds, and the nuclei of galaxies, including starburst and Ultra-Luminous InfraRed Galaxies (ULIRGS) and range from the here and now all the way back through the era of ubiquitous star formation when galaxies were assembled. Clearly, over these 30 years, PDRs have evolved from a curiosity to a mainstay of astronomical research and dense PDRs have become a laboratory for the study of physical and chemical processes relevant for the evolution of the interstellar medium of galaxies. With the results of Herschel Space Observatory and the Atacama Large Millimeter Array now becoming widely available, it is timely to organize a symposium on the many facets of PDRs and their role in studies of the Universe and at the same time honor one of the pioneers of these studies, David Hollenbach.

The goal of this meeting is to overview the state of the art in theoretical PDR studies, to review the processes that control the physical and chemical conditions in PDRs and their emission characteristics, to compare and contrast these models with recent observations of PDRs obtained with the Spitzer Space Telescope, the Herschel Space Observatory, the Stratospheric Observatory For Infrared Astronomy, and the Atacama Large Millimeter Array, to connect studies of dense PDRs in regions of star formation to the studies of the evolution of the interstellar medium of galaxies over the history of the Universe, and to link and compare and contrast studies of PDRs to those of regions dominated by X-rays, by turbulence, by shocks, and by cosmic rays. This symposium aims to bring together astronomers involved in observations of PDRs associated with regions of massive star formation and of the neutral interstellar medium of galaxies, with astronomers versed in the modeling of PDRs and of the infrared spectral characteristics of the interstellar medium, and with atomic and physicists and chemists with a deep understanding of the physical and chemical processes affecting neutral interstellar gas.
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Opening Lecture by David Hollenbach
PDRs: Their Prehistory and Possible Future Directions

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Many observations and much theoretical modeling preceded the photodissociation region (PDR) paper of Tielens & Hollenbach (1985). The Orbiting Astronomical Observatory 3 (or "Copernicus Satellite") made ultraviolet absorption measurements of columns of various gas phase species in diffuse and translucent clouds in the early 1970's. These observations in particular spurred a number of theoretical modeling efforts of such clouds, illuminated by the interstellar ultraviolet radiation field. In these early years chemical reaction rates were quite uncertain, and chemical networks small. A number of heating mechanisms were invoked, but in general the models set temperatures without treating thermal balance. The rapid development of infrared astronomy in the period 1975-1985, especially the observations made by the NASA Learjet, the Kuiper Astronomical Observatory (KAO), and the Infrared Astronomical Satellite (IRAS) of the [CII] (158 \( \mu \)m), [OI](63 \( \mu \)m) and infrared continuum emission from molecular clouds illuminated by the ultraviolet radiation from nearby, young, massive stars were the main catalysts in developing the more general theories of photodissociation regions, which included not only diffuse and translucent clouds, but also the illuminated surfaces of opaque molecular clouds. By 1985 the chemical rates and heating mechanisms were much better understood, which allowed self-consistent models that incorporated chemical and thermal steady state, treated the structure of a cloud as a function of depth into the cloud, and allowed predictions of infrared, submillimeter and millimeter radiation from the clouds.

Since 1985 many more observations and models have been made, the subject of this conference. I conclude this contribution with personal speculations on some future directions that PDR research will take. Further work on the PDRs on the surfaces of protoplanetary disks should help reveal the chemical and thermal structure, the surface density distribution, and the dynamics of these evolving disks, aiding our understanding of planet formation. Some possibilities for individual Galactic clouds include further investigations of the cosmic ray ionization rates in clouds as a function of depth into the cloud, the mass contained in the dark or “hidden” \( \text{H}_2 \) layer, and the carbon chemistry and inventory in clouds. Balloon surveys of [CII], [OI], and [NII] emission in the plane of the Milky Way and in the Magellanic Clouds may allow us to discover how Giant Molecular Clouds are formed and destroyed and provide a template for studies of
more distant galaxies. PDR studies may continue to help us predict the neutral phases of the interstellar media in galaxies, and the factors that control star formation rates in these galaxies. Finally, at high redshift, C$^+$ seen in (redshifted) ultraviolet absorption or infrared emission (along with redshifted [OI] 63 $\mu$m) will provide measures of the star formation rates, and physical conditions in the interstellar media of these distant galaxies and damped Ly$\alpha$ absorbers.

REFERENCES

The Physics and Chemistry of PDRs
In this review I present the basic structure of a Photodissociation Region (PDR) and discuss the dominant heating and cooling processes. A PDR is gas in which far-ultraviolet (FUV) radiation plays a role in the heating and/or chemistry (Tielens & Hollenbach 1985). PDRs can be found where radiation escaping an HII region illuminates a nearby molecular cloud or in molecular cloud surfaces illuminated by the interstellar radiation field. The same physical processes and chemistry at work in the molecular cloud PDRs are also at work in diffuse interstellar clouds but with generally lower FUV fields and column densities.

In the outer regions of the cloud, the gas consists mainly of atomic H, He, O, and single ionization states of metals (e.g., C+, Si+, S+). At deeper layers, molecular H2 forms on grains and C+ recombines to atomic C. After C+ recombination, CO forms through a series of ion-neutral and neutral-neutral chemical reactions. Atomic and molecular freeze-out onto grains and grain surface reactions can additionally modify abundances and gas cooling in the cloud interior (Hollenbach et al. 2009) and may also be important for H2O production in the diffuse ISM (Sonnentrucker et al. 2015).

Typically, grain photoelectric heating dominates in the outer layers while collisions with warm grains or cosmic-ray heating is of increasing importance in the deeper layers. However, for some conditions, more exotic processes such as vibrationally excited H2 (Sternberg & Dalgarno 1989) or H2 formation heating (Le Bourlot et al. 2012; Röllig et al. 2013) may become important. The main parameter which governs the heating rate and PDR structure is the ratio of incident FUV field strength, $G_0$, to gas density, $n$ (Bakes & Tielens 1994; Weingartner & Draine 2001). For example, for high $G_0/n$, grain charging leads to a reduced heating efficiency and a drop in the line strengths of the PDR cooling lines (Malhotra et al. 2001). For low $G_0/n$, H2 and CO self-shielding draws the molecular gas to the cloud surface and reduces the atomic gas column density and line intensities (Wolfire et al. 1989, Burton et al. 1990). I will demonstrate how the PDR heating and structure changes with varying $G_0/n$.

The fine-structure lines of [OI] and [CII] dominate the cooling in the outer layers with CO dominating in the deeper layers although a host of cooling lines and emission diagnostics probe different depths and physical conditions (e.g., Le Petit et al. 2006; Kaufman et al. 2006, Röllig...
et al. 2006). In addition to gas emission lines, PDRs also emit dust continuum emission and PAH features (Peeters et al. 2011). The production of these gas emission lines and dust features will also be discussed.

REFERENCES

Peeters, E. 2011, EAS, Publication Series, 46, 13
Dust Temperature Fluctuations and Surface Processes: Impact on \( \text{H}_2 \) Emission Lines in PDRs.

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\( \text{H}_2 \) emission lines are a powerful tool to study PDRs, as they give informations about the conditions near the H/\( \text{H}_2 \) transition. However, the modeling of \( \text{H}_2 \) excitation state and the H/\( \text{H}_2 \) transition – which then controls the apparition of other species, e.g. the CO transition – requires a careful understanding of several physico-chemical processes. Two remain problematic in models: the \( \text{H}_2 \) formation process, which controls the position of the H/\( \text{H}_2 \) transition and can induce formation pumping, and the slow ortho-para conversion processes, with a competition between reactive collisions in the gas (with \( \text{H}^+ \) and H) and thermalization on dust surfaces.

ISO and Spitzer observations of \( \text{H}_2 \) emission lines provide constraints for the models, and show very efficient \( \text{H}_2 \) formation in PDRs (Habart et al., 2011). The introduction of detailed \( \text{H}_2 \) formation mechanisms in the Meudon PDR Code has led to an improved formation efficiency at the edge, in better agreement with the observations (Le Bourlot et al., 2012), but discrepancies remain in low-UV-flux PDRs, related to the ortho-para conversion processes.

Dust grains are the support of both the formation mechanism and an efficient ortho-para conversion process. Small grains are the largest contributors as they account for most of the total dust surface. But small grains undergo temperature fluctuations caused by the absorption of individual UV photons. As the surface processes are very sensitive to the dust temperature, these fluctuations need to be taken into account, but are problematic for both stationary and time-dependent PDR models (due to the short timescales involved).

I have thus developed a statistical formalism based on master equations to compute the average efficiency of surface processes perturbed by fluctuations of the grain temperature. I present here the application of this method to \( \text{H}_2 \) formation (Bron et al., 2014) and ortho-para conversion, and show the strong impact of fluctuations in PDRs. The integration of this method with the Meudon PDR Code then allows us to directly compare to \( \text{H}_2 \) observations in PDR.

REFERENCES

H$_2$ enhanced radiative grain alignment in IC63/IC59

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The alignment of interstellar dust grains with the magnetic field gives rise to polarization of both the light from background stars and the thermal dust emission. Over the last decade a comprehensive theory for interstellar grain alignment has been developed and observationally tested. With the advent of this quantitative theory, the polarization can be used to probe the magnetic field and the dust, gas and radiation field characteristics of the region. This ”Radiative Alignment Torque” (RAT) theory predicts that molecular hydrogen formation on the surfaces of dust grains should enhance the grain alignment by providing additional torques on the grains. We have observed this effect in the reflection nebulae/Photo-dissociation regions (PDR) IC 63 (Andersson et al. 2013) and performed detailed ab initio modeling of the region (Hoang et al. 2015). Here we will review the results from both the IC 63 and IC 59 PDRs and discuss the uses of the combination of polarimetry, H$_2$ fluorescence, multi-band polarimetry and far-infrared photometry to provide unique probes of the physics of PDRs.

REFERENCES

The chemistry of PDRs

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The chemistry of PDRs is driven by the penetration of FUV photons. Depending on the FUV radiation strength and gas density, different physical processes and chemical reactions control the molecular composition as a function of cloud depth. Traditionally considered as harsh environments to host a rich chemistry, modern-day observations using multi-wavelength techniques and broad-band spectrometers do show a distinctive “PDR molecular content”.

Specific “PDR molecules” are the CF$^+$, CO$^+$, HOC$^+$, CH$^+$, SH$^+$, OH$^+$ or H$_2$Cl$^+$ ions. Their formation represents the first steps of the PDR chemistry. The list of molecules detected in prototypical PDRs such as the Horsehead or the Orion Bar steadily increases. It ranges from well-known radicals (e.g. C$_2$H, CN, OH, HCO), heavy ions such as l-C$_3$H$^+$ involved in the formation of small hydrocarbons (e.g., C$_3$H$_2$ and C$_2$H), isotopologues and isotopomers (e.g., $^{13}$CCH, C$^{13}$CH, DCN and HNC), to PAHs and even complex organic molecules (COMs such as CH$_3$CN, CH$_3$NC, HCOOH, CH$_2$CO, etc.). Explaining the presence of COMs in PDRs is particularly challenging, and opens new avenues for grain surface and ice-mantle photodesorption studies.

The emission from all the above species not only reflects subtle chemical and excitation processes (photoreactions, reactions with vibrationally excited H$_2$, state-to-state formation, fractionation reactions, photo-erosion of grains, etc.), also they trace the steep gradients in the PDR gas properties (physical conditions, molecular fraction, ionization fraction, etc.) as a function of cloud depth. Their emission not only dominates the spectra of galactic PDRs and star-forming regions near massive stars. They are also becoming powerful diagnostic tools to understand the emission from sources as different as the nuclei of distant galaxies, planetary nebulae, protostellar shocks irradiated by FUV fields, or the illuminated surfaces of protoplanetary disks.

In this contribution I will review the on-going observational and modeling efforts made to characterize the chemistry of PDRs. I will also show the first ALMA images of the Orion Bar.
REFERENCES

The rate of photodissociation of astronomical molecules varies by species and the nature of the incident ultraviolet radiation, e.g., [1]. Many observable species are known to be the products of photodissociation. I will discuss the photodissociation of relevant molecules and the calculation of photolytic rates for astrochemical models, considering the important ultraviolet irradiated environments (including cosmic-ray induced fields) and the detailed wavelength dependence of their absorption cross sections. This is part of an update to the Leiden database of molecular photodissociation rates and shielding functions [2].

Isotopic abundance anomalies in molecules probe their formation history and can preserve information about the physical conditions of a previous epoch, for example in the nebula from which the Solar system formed [3]. There are two important mechanisms with which to explain the isotopic anomalies of the elements H, N, C, and O as observed in planetary bodies, meteorites, and extrasolar objects. Low temperature isotope-exchange reactions are known to be an important driver of the case H$_3^+$/H$_2$D$^+$, formed inside photodissociating regions. The influence of isotopic-selective photodissociation is also important for the heavier molecules. I will describe the above isotope fractionation phenomena and, in particular, the important cases of CO and N$_2$ photofractionation [4,5].

REFERENCES

Models of PDRs
Models of PDRs: State of the art

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PDR modelling has a long history (Tielens and Hollenbach 1985). State-of-the-art PDR codes simulate the physical and chemical processes in neutral interstellar gas computing as consistently as possible and in a coupled way the radiative transfer, the thermal processes and the chemistry (Le Petit et al. 2006). If at first, these codes have been developed to study the H/H\textsubscript{2} transition, they are now able to model the formation of complex molecules in the gas phase and on grains surfaces (Hollenbach et al. 2009), and to compute in detail energy transfers between the various energy reservoirs (thermal, internal, radiative energy, ...). Today, state-of-the-art PDR codes are among the most powerful tools we have to study in detail the many processes that take place in interstellar gas.

In this review, I will overview the state-of-the-art in PDR models. I will try to highlight where they succeed and where they fail. Often, failures of PDR codes come from a poor knowledge of atomic and molecular data. I will try to point out where experimental and theoretical data are urgently needed. With the increase of the sensitivity and of the resolution of new instruments as ALMA, we see that a new generation of PDR codes is required. One can wonder if the efforts have to be done towards a better modelling of the micro-physical processes or on taking into account clumpiness and the geometry of objects with 3D PDR codes (Bisbas et al. 2012). One the other hand, most of PDR codes are stationary and a key question is how to deal with stochastic processes, dynamics, and time dependent effects. I will try to answer to theses questions with several examples as the modelling of H\textsubscript{2} formation and of complex molecules on grains as well as the question of high-J CO as observed by Herschel.

REFERENCES

PDR model benchmark

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The last three decades saw an increasing number of sophisticated numerical models computing the physical and chemical structure of photon dominated regions (PDRs), regions in the ISM where the intense far-UV radiation of nearby, massive stars is dominating the local conditions. The continuous confrontation of model results with observations lead to a growing understanding of the dominating physical processes and chemical reactions in PDRs and lead to an ever increasing complexity of the numerical model codes. The strong non-linearities of the involved problems as well as the complex numerical algorithms at work made it necessary to establish a reference standard (model benchmark) to allow easier debugging and more importantly to better understand the model codes.

To this end, we performed an international PDR-model comparison study from 2004 to 2007 aiming to include all established PDR model codes (Röllig et al. 2007). By means of a series of very reduced test problems we were able to compare and evaluate numerous processes and solution approaches. As a result we established the first reference database of PDR benchmark models and made it publicly available to all interested modelers.

\[ \text{Figure 1: CH and OH density profile BEFORE the benchmark.} \]

\[ \text{Figure 2: CH and OH density profile AFTER the benchmark.} \]
In Fig. 1 and 2 we see the progress made during the benchmark in the example of the density profiles of OH and CH in a test cloud. The large spread in the profiles predicted by the participating models could be reduced significantly. These Figures demonstrate not only a better understanding of the internal routines in each individual model but also an improvement in the understanding of how to bring model computations of very different models in agreement with each other.

Ten PDR model codes participated in the benchmark and since then a number of new codes emerged, each with a particular application in mind. Many of the already established codes were developed further to improve their accuracy and to extend their applicability. During my talk I will discuss the status of benchmarking of PDR codes and discuss their validity. What are the advantages and disadvantages of different models and toolboxes available? How can they be improved, how can they be made available to the community? Is a large diversity among the available models beneficial?

REFERENCES

Testing the KOSMA-$\tau$ 3D PDR code: the Orion Bar PDR

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The components of the interstellar medium (ISM) are continuously heated due to energy input from different sources, one source being the radiation of young and massive stars. Photon-dominated regions (PDRs) describe the conditions where the interstellar far-ultraviolet (FUV; 6-13.6 eV) radiation field determines the energy balance and the chemistry of the ISM. The KOSMA-$\tau$ PDR model simulates the chemical and the physical structure and the line emission of spherical clouds (“clumps”) in the ISM. Furthermore, it has been shown that a superposition of spherical clumps, having a specific mass-spectrum and a specific mass-size relation, can be used to mimic the fractal structure of the ISM. Here, we introduce an extension of the KOSMA-$\tau$ code, denoted KOSMA-$\tau$ 3D that can be used to model star forming regions with arbitrary 3D geometry. Therefore, a 3D compound made of voxels (“3D pixels”), containing clumps with a discrete mass distributions, is assembled. The characteristics defining the individual clumps can vary between different voxels, supporting the analysis of the spatial structure of the region.

A probabilistic approach is used to calculate the averaged FUV extinction caused by the clumps within each voxel. To analyse each individual clump the new code is combined with the KOSMA-$\tau$ PDR model. Line emissivities and optical depths of individual clumps are used to calculate the distribution of voxel-averaged emissivities and optical depths, and the radiative transfer through the compound yields full spectral cubes. Hereby, the new code accounts for the intrinsic line widths of single clumps and additionally for a velocity dispersion between individual clumps.

The Orion Bar PDR, a well-known and luminous star forming region with an interesting edge-on geometry, is used as a test-case for the new 3D code. New HIFI/Herschel data from the HEXOS guaranteed-time key program and complementary data from the Caltech Submillimeter Observatory (CSO) are fitted. Simulation results, based on the clumpy edge-on cavity wall suggested by Hogerheijde et al. (1995), or on a cylindrical filament are presented. Simulations and observations are compared in terms of the layered positions of the emission peaks, the “chemical stratification” and on the line integrated intensities at the peak positions. Most PDR models fail to reproduce this combination. Our best fitting model reproduces the line integrated intensities of many simulated cooling lines within a factor four and the stratification pattern within 0.02 pc (or better).

REFERENCES

Astronomers at the University of Maryland and scientists at Lawrence Livermore National Laboratory are testing cometary models for the formation of the Pillars of the Eagle Nebula using scaled laboratory astrophysics experiments at the National Ignition Facility (NIF). Because these experiments require the evolution of deeply nonlinear hydrodynamics, the NIF shots features a new long-duration source mimicking illumination from a cluster of stars. Multiple radiation cavities (hohlraums) are driven with UV laser light in series to create a 30-60 ns 250 kJ x-ray pulse. The pulse illuminates scaled millimeter-size science packages with directional radiation to create shock-driven and ablative hydrodynamic flows behind a clump that represents a gravitational condensation in a molecular cloud. Through an ongoing series of developmental shots at the University of Rochester Laboratory for Laser Energetics Omega EP laser, and now shots at NIF, we are refining an experimental platform and assessing diagnostics.

A preceding companion talk by Marc Pound will review theories and observations of molecular pillars, and a related poster by David Martinez will detail the experimental platform.

In this talk I will present results from the developmental shots at Omega EP, and preliminary results from first NIF shots.

†Prepared by LLNL under Contract DE-AC52-07NA27344.

REFERENCES

PDRs vs XDRs vs CRDRs vs TDRs

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I will discuss how we can distinguish between P(hoto-)DRs, X(-ray-)DRs (e.g., Meijerink & Spaans, 2005), C(osmic-)R(ay-)DRs (e.g., Meijerink et al. 2011), and T(urbulence-)DRs (e.g., Kazandjian et al. 2012). What are the similarities and differences in the structure and characteristics of these different regions and their observational characteristics? Which are the key tracers for diagnosing and interpreting these different physical mechanisms? Specifically, I will show how the CO ladder of luminous infrared galaxies observed with the Herschel Space Observatory (Rosenberg et al. 2015) can serve as a tracer of XDRs vs PDRs (or shocks) in combination with other tracers such as HCN and HCO\(^+\) or the [OI] 63 \(\mu\)m and [CII] 158 \(\mu\)m fine-structure lines. I will discuss how these models allow us to characterize the physical properties of the interstellar medium in galactic nuclei (e.g., Rosenberg et al. 2014).

REFERENCES

Kazandjian, M.V., Meijerink, R., Pelupessy, I., et al. (2012), 542, 65
Rosenberg, M.J.F., Meijerink, R., Israel, F.P. et al. (2014)
We present numerical hydrodynamic simulations of molecular clouds with self-consistent CO gas-phase and isotope chemistry (Szücs et al., 2014). We probe a range in metallicity, interstellar radiation field strength, cloud mass and virial parameter. The simulations are post-processed with line radiative transfer modelling to obtain $^{12}\text{CO}$ and $^{13}\text{CO}$ emission data in the $J = 1 \rightarrow 0$ rotational transition. The emission maps are analysed with frequently used observational methods, i.e. the column density measurement of the optically thinner $^{13}\text{CO}$ isotope (e.g. Pineda et al. 2008), the mass estimation based on the cloud size and line of sight velocity dispersion measurement (i.e. virial mass, e.g. Hughes et al. 2010) and the direct conversion of the CO intensity into $\text{H}_2$ mass by a fixed conversion factor ($X_{\text{CO}}$ factor, Bolatto et al. 2013). The inferred cloud masses and column density distributions are compared to the true values. We find that the methods trace the true molecular cloud mass within a factor of 2 uncertainty, unless the metallicity is below 0.6 solar. The exception is the $^{12}\text{CO}$ column density measurement, which systematically underestimates the true mass, in some cases by more than an order of a magnitude. The virial mass estimate works the best in the considered parameter ranges, even when the cloud is out of virial equilibrium. The galactic $X_{\text{CO}}$ conversion factor appears to be a robust choice over a relatively wide range of cloud conditions, while methods which try to take the metallicity dependence of the conversion factor into account tend to overestimate the true cloud masses. We discuss the chemical and radiative transfer reasons for the success or the failure of each of the methods and put the results into a broader context.

REFERENCES

Gas-ice chemical interplay in interstellar clouds

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When diffuse clouds evolve into molecular clouds, gas-phase molecules freeze out on surfaces of dust particles to form ices. On these surfaces, water is the main constituent of the icy mantle in which a complex chemistry is taking place. Our goal is to follow the evolution of a gravitationally bound diffuse cloud into a molecular cloud in various environments. We fully considered the gas-dust interplay by including the details of freeze-out, chemical and thermal desorption, and the most important photo-processes on grain surfaces. For this purpose, we used time-dependent rate equations to calculate the molecular abundances in the gas phase and on solid surfaces and perform 3-d hydrodynamical simulations with the adaptive mesh code \texttt{FLASH}. In non-PDR, Milky Way like conditions, our findings show that while the dust grains are still bare, water formation is enhanced by grain surface chemistry that is subsequently released into the gas phase, enriching the molecular medium (Hocuk & Cazaux 2015). The CO molecules tend to gradually freeze out on bare grains. This causes CO to be well mixed and strongly present within the first ice layer. Once one monolayer of water ice has formed a strong depletion of gas-phase water and CO molecules occurs. While hydrogenation converts solid CO into formaldehyde (\texttt{H}_2\texttt{CO}) and methanol (\texttt{CH}_3\texttt{OH}), water ice becomes the main constituent of the icy grains. For PDR like conditions, our initial findings show that the results are different in several ways. The differences will be presented during this conference.

REFERENCES

The role of PAHs in PDRs

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Observe any PDR in the mid-infrared, and you will see beautiful emission bands peaking at ~ 3.3, 6.2, 7.7, 11.2 and 12.7 $\mu$m. They are called the “Aromatic Infrared Bands” (AIBs) and are attributed to the emission of large carbonaceous molecules: Polycyclic Aromatic Hydrocarbons (PAHs), and very small carbonaceous grains (VSGs), heated by the UV photons pervading the PDR.

The intensity and shape of the AIBs is tightly connected to the chemical evolution of PAHs and VSGs which depends on the local physical conditions: mainly the intensity of the radiation field, the electron density, and, to a lesser extent, to the gas temperature. The AIBs therefore offer a unique way to probe physical conditions in PDRs, including at high angular resolution (e.g. in protoplanetary disks or distant galaxies). But PAHs and VSGs are more than tracers, they are key actors in the physics of PDR. The most energetic far-IR photons can ionize them, therefore liberating electrons which carry a fair amount of kinetic energy (a couple eV or so), and heat the gas through collisions. This mechanism, called the UV-photoelectric heating, is in fact the most efficient source of gas heating and it therefore determines the thermal balance of PDRs. Finally, PAHs and VSGs are suspected to be a favored site for the formation of H$_2$ which is another key process in the chemical and thermal balance of PDRs.

In this presentation, I will describe the recent progress that has been achieved in understanding the photo-chemical evolution of PAHs in PDRs, how this relates to the observed spectra, and how, in turn, mid-infrared spectroscopy can be used to trace the physical conditions in PDRs. I will discuss our current understanding of the photoelectric heating by PAHs and VSGs in PDRs, from the theoretical and observational point of view, and I will briefly discuss the role of PAHs and VSGs in the formation of H$_2$. 
PAH emission in NGC2023: how subtle variations reveal sub-populations with different molecular structure and charge.

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The mid-IR spectra of photodissociation regions (PDRs) are dominated by the well-known emission features at 3.3, 6.2, 7.7, 8.6, 11.3, and 12.7 micron, generally attributed to polycyclic aromatic hydrocarbon molecules (PAHs). PAHs drive much of the physics and the chemistry in these PDRs, e.g. by heating the gas and as a catalyst in the formation of molecular hydrogen on their surfaces. Thus, PAHs and PDRs are intimately connected, and a complete knowledge of PDRs requires a good understanding of the properties of the PAH population.

One of the best ways to investigate the detailed characteristics of the PAH population is by analyzing IR spectral maps. Here, we present the results of such an analysis of spectral maps obtained with Spitzer/IRS in the 5-20 micron range toward the reflection nebula NGC 2023. These maps show subtle, but significant spatial variations in individual PAH emission bands. The overall dominant charge state of the PAH population is certainly a key factor in driving these variations. However, with our maps, we can also probe changes within the so-called ionic PAH emission bands that all originate from PAHs with the same charge state. We find that even within these bands, spatial variations occur that indicate contributions from at least 2 spatially distinct components, and thus PAH sub-populations, to the 7–9 micron PAH emission. We attribute these changes to molecular structure variations in the PAH sub-populations.

REFERENCES
Observational evidence of the evaporation of aromatic / aliphatic very small grains in the NGC 7023 PDR

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Carbon is an important building block of both interstellar gas and dust in Photo-Dissociation Regions (PDRs). A significant fraction of this element (up to 20\%) is tied up in the carriers of the Aromatic Infrared Bands (AIBs), which consist in Polycyclic Aromatic Hydrocarbons (PAHs) and evaporating very small grains (eVSGs, Rapacioli et al., A&A 429, 2005; Pilleri et al., A&A, 542, 2012). The nature of PAHs and eVSGs and their link with smaller hydrocarbons are still under debate, in particular the aliphatic/aromatic composition of PAHs (Joblin et al., ApJ 458, 1996) and whether the photo-destruction of PAHs can inject fresh hydrocarbons into the gas phase, which could explain why the abundances of small hydrocarbons (e.g., CCH and c-C\textsubscript{3}H\textsubscript{2}, C\textsubscript{4}H) in cool PDRs are one or two order of magnitudes higher than those predicted by current gas-phase chemical models (Pety et al., A&A 435, 2005, Guzman et al., ApJL 800, 2015).

In this contribution, we will present our recent results on the aromatic-aliphatic nature of PAHs/eVSGs and their link with gas phase chemistry in the prototypical PDR NGC 7023. We obtained spatially resolved spectro-imagery observations in the near-IR using the AKARI space telescope to study the spatial variation of the 3.3 and 3.4\,\mu m emission features, that are associated with aromatic and aliphatic C–H bonds in PAHs, respectively. The comparison with mid-IR Spitzer observations shows that PAHs containing aliphatic side-groups are released from the photo-evaporation of eVSGs, which strongly suggests that eVSGs have mixed aromatic/aliphatic composition (Pilleri et al., A&A in press). We performed a spectral survey in the 3, 2 and 1mm range using the IRAM-30m telescope to determine the hydrocarbons census in this PDR. This survey was completed with high resolution maps of key hydrocarbon species (CCH and c-C\textsubscript{3}H\textsubscript{2}) obtained with the Plateau de Bure Interferometer to investigate the chemical link between PAHs/eVSGs and gas-phase hydrocarbons. Our results show that the photo-evaporation of eVSGs not only releases PAHs but also small hydrocarbons in the gas-phase.
Observations of PDRs in the Galactic Environment
Spitzer and Herschel observations of Galactic PDRs

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Photon dominated regions or photodissociation regions (PDRs) are regions where the FUV radiation dominates the energetic balance and chemistry. The regions close to the O and B stars: HII regions, reflection nebulae, the planetary nebulae formed at the end of the life of low mass stars, the outer layers of molecular clouds, diffuse clouds, the nuclei of starburst galaxies and the inner regions and surface of protoplanetary disks are PDRs. The emission of PDRs dominate the sky in the far-infrared (far-IR) range and it is in PDRs where the interchange of energy between massive stars and the interstellar medium occurs. Consequently, the comprehension of the physical and chemical processes occuring in PDRs are necessary to understand the evolution of molecular clouds, and eventually of the galaxies. Spitzer and Herschel space telescopes provided, for the first time, observations in the near to the far-IR range at high spatial resolution and sensitivity with no blockage by any atmospheric feature. Their unprecedented spectral coverage combined with the high spectral and angular resolution have allowed a detailed study of the physics and chemistry of the dust and gas in these regions. In this talk, we give a review of the main Spitzer and Herschel results on PDRs and their implication in our knowledge of the evolution of the interstellar medium.
Spectral mapping of galactic PDRs: cooling and molecular diagnostics

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As part of the Herschel Key programme (SAG 4), we have produced one of the most detailed spectroscopic maps of the local PDRs ever performed in the FIR. This programme comprises a representative sample of PDRs covering a wide range of excitation conditions with varying incident radiation fields ($10 < G_0 < 10000$ in Habing units) and densities ($10^3$ cm$^{-3} < n < 10^6$ cm$^{-3}$). We study the fine structure lines of [C II] (158 $\mu$m), [O I] (63 and 145 $\mu$m) and compare their emission to molecular tracers including rotational and rovibrational H$_2$, and high-rotational lines of CO, OH and CH$^+$ when available.

Each lines show a specific morphology and by spatially resolving the lines we establish their origin, excitation mechanisms and contribution to the cooling as a function of the density structure and the energetics associated with the illuminating stars. Our main results concern:

1) the origin of the [CII]158 $\mu$m line (neutral vs. ionized) and its increasing contribution to the total cooling in low excited PDRs (reaches up to 50% in PDRs with $G_0 < 50$); 2) an important overestimation by PDR models of the [OI] 63 $\mu$m line self-absorbed; 3) an unexpected large amount of H$_2$ rotational emission in the lower excited PDRs; 4) the direct evidence of high-J CO excitation by UV photons only in the high excited PDRs; 5) the impact of the chemical reaction with FUV-pumped vibrationally excited H$_2$ on the abundance and excitation of molecules such as CH$^+$ and OH in high excited PDRs.

Enhanced emission of the far-IR lines trace the presence of condensations at high thermal pressure inside PDRs, where strong dust emission in the far-IR and submm are also detected. We study the bulk of cool/warm dust and gas together in order to derive the dust density profile and investigate how these populations spatially coincide and how evolve the small dense structures found in PDRs (photo-evaporation vs star formation).

REFERENCES

PDR observations: from Herschel to SOFIA

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The past decade has brought substantial progress in observationally constraining our understanding of PDRs. This is largely due to the rapid progress in instrumentation technology that became available with Herschel and recently with SOFIA. Of major importance is the fact, that these observatories, for the first time, allow velocity resolved observations of the bright PDR-characteristic line emission in the FIR-fine structure lines [CII] 158 $\mu$m and [OI] 63 $\mu$m, as well as several other, previously not observationally accessible, molecular lines. In addition, the possibility of extended line mapping in the FIR that these observatories provide, has given new insight by allowing details comparison of the line ratios and their spatial variation.

This talk will summarize the key progress in several areas, that was thus achieved, which has provided us with much better constraints on the physical processes relevant in PDRs. It will also address some of the unexpected results, that challenge our understanding of PDRs.

REFERENCES
Near-infrared spectroscopy of Galactic PDRs with AKARI

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The near-infrared region (2–5 μm) contains a number of interesting features from gas and solid species in PDRs. The Infrared Camera (IRC) onboard the infrared satellite AKARI provides a unique capability to study this spectral region with high sensitivity even in the warm mission phase with the grism (R ≈ 100) and the prism (R ≈ 20–40) (Onaka et al. 2012). The IRC made observations of a number of PDR-HII region complexes on the Galactic plane. Most spectra show the aromatic and aliphatic emission features at 3.3–3.5 μm together with hydrogen recombination lines. Spectra taken with the prism cover up to 5.5 μm and detect the 5.25 μm band clearly in a number of PDRs for the first time, which shows a good correlation with the 3.3 μm band (Mori et al. 2014). A large fraction of the spectra also show absorption bands of H₂O ice at 3.0 μm and CO₂ ice at 4.27 μm. The absorption of H₂O ice affects the continuum in the 3 μm region, which could produce a jump-like structure across the 3.3 μm band emission.

In this report, we present recent analysis of IRC near-infrared spectra of about 100 Galactic PDR-HII regions. The intensities of the emission bands at 3.3–3.5 μm are estimated by taking account of the H₂O ice absorption. Part of the results are reported in Mori et al. (2014), which shows a weak trend that the ratio of the aliphatic 3.4–3.5 μm to the aromatic 3.3 μm bands decreases with the continuum at 3.7 μm to the 3.3 μm band intensity. The latter ratio is thought to indicate the ionization fraction of the band carriers, suggesting the destruction of aliphatic structures near the boundary between the PDR and ionized region. Here we also report the results of the ice features. The CO₂ and the H₂O ice column densities show a linear correlation as seen in massive YSOs, supporting that a major part of the structure seen across the 3.3 μm band is due to the H₂O ice absorption. Our results also suggest that the formation of ice may start at the region of Aᵥ ≈ 5 in general PDRs.

REFERENCES

Herschel PACS and SPIRE spectroscopy of the Photodissociation Regions associated with S 106 and IRAS 23133+6050

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We present recent Herschel PACS and SPIRE observations of the Galactic PDRs associated with the star forming regions S 106 and IRAS 23133+6050. While both sources have very different morphologies – IRAS23133+6050 is an ultracompact H ii region, and S 106 is a classical H ii region more reminiscent of the Orion nebula – they share similar PDR parameters, potentially due to similar spectral type exciting stars. For each object we analyze a full PACS/SPIRE spectrum from 55–210 µm, including all of the major ionic cooling lines of [O i], [C i] and [C ii], along with the full CO spectrum in that range (J_U = 4 – 23). From these lines, as well as the total far-IR continuum flux, we use classical PDR diagnostics (e.g., cooling line ratios) to determine the average PDR parameters (density, n; UV radiation field, G_0) which we then use as inputs to constant thermal pressure numerical PDR models (as described by Wolfire et al. 2010 and Hollenbach et al. 2012). In addition, the full CO ladder spectrum for these objects is investigated, firstly by employing RADEX (van der Tak et al. 2007) fits to the CO line fluxes and subsequently using rotation diagrams. The diagnostic diagrams and CO lines indicate that at least two distinct combinations of UV field and density (referred to as clump: n \sim 10^6 \text{ cm}^{-3}, G_0 \sim 10^6; \text{ and interclump: } n \sim 10^4 \text{ cm}^{-3}, G_0 \sim 10^4) exist within both PDRs. For S 106 an extra excitation component is observed in the high-J CO lines which could be representative of a shock, or an additional extremely dense PDR component. Following this we discuss the derived parameters in the context of other galactic PDRs and H ii region expansion.

REFERENCES

Excitation coefficients for ions

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In order to retrieve actual molecular abundances from astrophysical observations of molecular spectral lines, knowledge of the rotational levels excitation schemes is essential. Actual excitation results of a trade-off between photon excitation and collisional excitation by the main constituents of the interstellar gas, electrons, molecular hydrogen, and, to a lesser extent, atomic hydrogen and helium. These rates are almost always obtained from theoretical investigations, by computing classical or quantum dynamics of the interaction of molecules with these colliders. However, recently, a series of experimental attempts are planned or are being tempted, to overcome this shortcoming.

Many types of molecules are observed and consequently, many collisions have been studied recently, like hydrides (Lanza et al. 2014), water and its isotopomers (Faure et al. 2012), organic molecules (Wiesenfeld and Faure 2013), atomic and molecular ions.

While for ISM cold or warm cloud, the main projectiles H$_2$, the collisional effects in PDR are both due to electronic collisions (and molecular collisions (Wiesenfeld and Goldsmith 2014; Wiesenfeld and Masso 2014). Computation of electronic collisional rates is performed mainly with the R-matrix theory (Tennyson 2010)

Scheme for computing inelastic rates goes into four steps:

1. Compute the interaction potential between the observed species and the projectile. The energy interaction is computed mainly by using \textit{ab initio} quantum chemistry methods. The two molecules in interaction are taken as rigid. Usually a large number $N$ of points are computed, each point being characterized by a set of intermolecular coordinates (one distance $R$, several angles $\Omega$).

2. Fit the $N$ points onto one single functional form $F(R, \Omega)$, suitable for the subsequent dynamics.

3. Perform the quantum dynamics for a series of collision energies $E_k$, resulting of inelastic cross sections $\sigma_{f\rightarrow i}(E_k)$.

4. Average the section $\sigma_{f\rightarrow i}(E_k)$ over the Maxwellian probability of kinetic energy at a given temperature $T$, to get the rate $k_{f\rightarrow i}(T)$.
This program has been applied with quite some success for several decades, and results are constantly updated with the improvement of computer performance (see review papers like Roueff and Lique 2013; Dubernet et al. 2013).

The case of molecular ions bears special difficulties, because of both the long distance anisotropy of the interaction potential, and because of the large binding energy of the van der Waals complex between the molecular ion and H2. The same is true, but to a lesser extent for the interaction of atomic ions with molecular H2.

We shall present some very recent results concerning both the atomic species CII and the molecular species HCO+, both in collision with molecular hydrogen H2. It will be shown that remarkably, the actual excitation rates depend in a much weaker way on the details of the potential energy surface than their neutral counterparts. Collisional deexcitation rates are very large, because of the large, anisotropic charge-quadrupole and charge-induced dipole interactions, that decay slowly at large distances. An example of newly computed rates compared to the ones in the literature (LAMDA database, http://home.strw.leidenuniv.nl/moldata/) appears in figure 1.

REFERENCES

Tennyson, J. (2010) Physics Reports, 491, 29
H$_2$ excitation and mapping in the Orion Bar with IGRINS  

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The Orion Bar, with its known illumination and edge-on geometry, is a perfect nearby laboratory for the study of high-density photodissociation regions illuminated by powerful ultraviolet fields. In such regions, the ro-vibrational lines of molecular hydrogen have significant diagnostic power about conditions at the H/ H$_2$ transition. To exploit this power, we must examine a large range in level energies by observing many H$_2$ lines. Since PDRs were first described 30 years ago by Tielens & Hollenbach (1985), technology for infrared spectroscopy has improved tremendously. The Immersion Grating INfrared Spectrograph (IGRINS) has high spectral resolution ($\sim 7.5$ km s$^{-1}$) and instantaneous coverage of the entire H & K bands (1.4 – 2.5$\mu$m, Park et al. 2014). We used IGRINS to make a deep integration and velocity-resolved, spatially registered, 6" by 15" maps of the Orion Bar in many H$_2$ transitions. The results include detections of $\sim 90$ lines, including first detections of many high V lines (up to $V_u = 8$) in both the H & K bands. The detections range up to $E_u/k \sim 45000$ K. With the broad range of upper state energies, the data reveal the effects of radiative and collisional excitation and collisional de-excitation in the level populations. The large number of detections includes 12 pairs and 1 triple from a common upper state, in some cases bridging from the H to K band, that allow us to determine the extinction from the emitting region. We compare our results with PDR models to test the underlying assumptions of the models, to determine the physical conditions in the emitting regions, and to study variations in physical conditions from the ionization front into the cloud and between clump and inter-clump gas on arc-second scales.

REFERENCES

Conversion of hydrogen gas from atomic (H\text{I}) to molecular (H\text{2}) form is of critical importance for the evolution of the interstellar medium (ISM) and for star-formation in galaxies.

Recently, Lee et al. (2012) used the H\text{I} data provided by the Galactic Arecibo L-band Feed Array H\text{I} Survey, together with far-infrared data from the IRAS Survey and the V-band extinction image provided by the COMPLETE Survey, to derive H\text{I} and H\text{2} surface densities for several hundred sight-lines towards five dark and (low-mass) star-forming regions within the Perseus molecular cloud. These are B1, B1E, B5, IC348, and NGC1333. We use the Sternberg et al. (2014, hereafter S14) theory for interstellar atomic to molecular conversion to analyze and fit the H\text{I}-to-H\text{2} transitions in Perseus.

Our basic results (Bialy et al. 2015 in prep.) are shown in Figure 1 below. The points are the Lee et al. data, and the red curves are our model fits. The observations indicate complete H\text{I}-to-H\text{2} transitions. The measured H\text{I} mass surface densities of 5.8 to 8.2 M\odot pc\textsuperscript{-2} in combination with S14 theory imply that the transitions are dominated by “H\text{I}-dust” shielding in outer atomic envelopes.

The implied ratios $I_{\text{UV}}/n$ of the FUV intensity to hydrogen volume density range from 0.13 to 0.08 cm\textsuperscript{3} in the Perseus clouds. For an FUV radiation field strength $I_{\text{UV}} \approx 0.8$ in Perseus, the effective gas densities in the atomic envelopes range from 6.2 to 10.5 cm\textsuperscript{-3}. The inferred densities are a bit lower than expected for pure CNM. For dust-photoelectric heating by the ambient radiation (Wolfire et al. 2003) the H\text{I} gas densities are consistent with a multiphase WNM/CNM mixture in which the WNM contributes significantly to the shielding of the H\text{2} cores.

Our analysis has important implications for the interpretation of global H\text{I}-to-H\text{2} in galaxies and star-formation thresholds in the Kennicutt-Schmidt relation.

REFERENCES

Figure 1: The molecular to atomic mass surface density ratio $\Sigma_{\text{H}_2}/\Sigma_{\text{HI}}$, as a function of the total mass surface density $\Sigma_{\text{tot}} \equiv \Sigma_{\text{HI}} + \Sigma_{\text{H}_2}$, for B1, B1E, B5, IC348 and NGC1333. The points are the Lee et al. data, and the red curves are our “best-fits” to the data. The best-fitting values of $\Sigma_{\text{HI}}$ are also indicated.
The carbon inventory in a cold, quiescent, filamentary molecular cloud

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We present spectral line images of [CI] 809 GHz, CO J=1–0 115 GHz and HI 1.4 GHz line emission, and calculate the corresponding C, CO and H column densities, for a sinuous, quiescent Giant Molecular Cloud about 5 kpc distant along the $l = 328^\circ$ sightline (hereafter G328) in our Galaxy. The [CI] data comes from the High Elevation Antarctic Terahertz (HEAT) telescope, a new facility on the summit of the Antarctic plateau where the precipitable water vapor falls to the lowest values found on the surface of the Earth. The CO dataset comes from the Mopra southern galactic plane CO survey (Burton et al. 2013, Braiding et al. 2015; see also www.phys.unsw.edu.au/mopraco) and the HI from the corresponding Parkes/ATCA survey (the SGPS). Together, they provide wide-field ($1^\circ$ scale) panoramic imaging at good spatial and spectral resolution ($\sim 2'$ and 1 km/s) of the atomic and molecular gas of the interstellar medium. We identify a filamentary molecular cloud, $\sim 75 \times 5$ pc long with mass $\sim 4 \times 10^4 M_\odot$ and a narrow FWHM velocity range of just 2 km/s. The morphology and kinematics of this filament are similar in CO, [CI] and HI, though in the latter appears as self-absorption. We calculate line fluxes and column densities for the three emitting species, which are broadly consistent with a PDR model for a GMC exposed to the average interstellar radiation field. The [C/CO] abundance ratio averaged through the filament is found to be approximately unity. The G328 filament is constrained to be cold ($T_{\text{Dust}} < 20$ K) by the lack of far–IR emission, to show no clear signs of star formation, and to only be mildly turbulent from the narrow line width. We suggest that it may represent a GMC shortly after formation, or perhaps still be in the process of formation. This presentation reports and extends results from Burton et al. (2014).

REFERENCES

Burton, M. et al. (2013), PASA, 30, e044
Complex organics in the Horsehead PDR


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The Horsehead nebula is a prototypical photodissociation region. Its closeness (∼400 pc) and favorable almost edge-on geometry make it an excellent source to serve as a template to chemical models. Due to the low-UV flux ($G_0 \sim 100$) and high density ($n_H \sim 10^5$ cm$^{-3}$), dust grains close to the cloud edge are expected to be covered by ice mantles, which can be photodesorbed into the gas, producing a peculiar chemistry and molecular content. I will summarize our results from an unbiased spectral line survey at 3, 2 and 1mm with the IRAM-30m telescope towards the warm PDR and its associated cold dense core (WHISPER; PI: J. Pety). We detected a new species in the ISM, the hydrocarbon C$_3$H$^+$, which confirm the top-down scenario in the formation of small carbon chains, like C$_2$H and C$_3$H$_2$, in the presence of FUV radiation (Pety et al. 2012; Guzmán et al. 2015). We also detect the complex organic molecules H$_2$CO, CH$_3$OH, HCOOH, CH$_2$CO, CH$_2$CHO and CH$_3$CCH, with similar abundances in the PDR and dense core, and show the importance of the interplay between the solid and gas phase chemistry in the formation of (complex) organic species, and confirm that photodesorption by FUV photons is an efficient mechanism to release frozen species in the gas phase (Guzmán et al. 2011, Guzmán et al. 2013, Guzmán et al. 2014). Finally, we detect CH$_3$CN and its isomer CH$_3$NC in the PDR (Gratier et al. 2013). Surprisingly, and in contrast to the other complex molecules, CH$_3$CN is 30 times more abundant in the PDR than in the core, suggesting a specific formation mechanism.

REFERENCES

Guzmán, V. V., Pety, J., Gratier, P., et al. (2014), Faraday Discussions, 168, 103
Current models of photodissociation regions, such as Hollenbach et al. 2009, predict that gas-phase water will exist mainly between $A_V$’s of about 3 and 8 mag. into dense molecular clouds, with the depth of the peak water abundance dependent upon the intensity of the FUV field and the gas density. At depths into the cloud greater than $A_V \sim 10$, these models predict that water will be predominantly locked in ice on grain mantles. This picture holds great appeal since it is consistent with, and would seem to explain, the low $O_2$ column densities and high water-ice column densities observed toward dense molecular clouds. However, these models are based on a competition between the rates of a number of physical processes, including photodissociation, photodesorption, grain-surface and gas-phase chemistry, and freeze out. At least two questions arise: (1) Are the assumed rates correct?; and, (2) Are there other unaccounted for processes?

To help answer these questions, we mapped a $25'\times40'$ region toward the Orion Molecular Ridge, a face-on PDR and the largest velocity-resolved map made by the Herschel Space Observatory. Unlike our earlier study using data obtained with SWAS, and which contained 77 spatial positions (Melnick et al. 2011), the current study includes 2,220 o-H$_2$O 557 GHz and o-NH$_3$ 572 GHz spectra acquired with Herschel along with fully-sampled maps of the same region in transitions of $^{12}$CO, $^{13}$CO, C$^{18}$O, HCN, CN, C$_2$H, and N$_2$H$^+$ obtained with FCRAO. Some of these species are predicted to have their peak abundance at $A_V$’s $< 10$, such as HCN, CN, and C$_2$H, while others, such as $^{12}$CO, $^{13}$CO, C$^{18}$O, N$_2$H$^+$, and NH$_3$, absent freeze out, are expected to reach and retain their peak abundance at $A_V$’s $> 5$ – i.e., throughout the well-shielded cloud. In this talk we show that the integrated intensity correlations among these species can be used to determine the distribution of gas-phase water within dense molecular clouds and their surface PDRs. In addition, we present the results of a complementary study – i.e., a strip scan made in o-H$_2$O, o-NH$_3$, and $^{13}$CO across the edge-on PDR toward Cepheus B.

REFERENCES
PDRs in Circumstellar Media

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Planetary Nebulae (PNe) constitute one of the latest stages of evolution of low and intermediate mass stars (1-8 M☉). By the ejection of the outer layers, PNe seed back enriched gas, as well as molecules and dust to the interstellar medium. In the short-lived planetary nebula phase, the ionized gas is the result of the interaction of the previously ejected envelope with the far ultraviolet (FUV) photons emitted by the hot (30,000-100,000 K) central star (Bernard-Salas & Tielens 2005). The study of circumstellar PDRs is of great importance for a proper understanding of the evolution of the ejected material, especially the excitation conditions under the influence of UV photons from the hot central nucleus. The ultraviolet photons will process the dust and photo-dissociate the molecules previously ejected, and as the stellar temperatures become higher some ionization will occur. This ionization gives rise to warm gas (10⁴ K) which cools through the emission of copious amounts of FUV and visible line emission, which give these nebulae their optical prominence. Shocks may also photo-dissociate molecules, heat the gas and cause copious amounts of [CII] and [OI] emission, and are the result of the interaction of the fast stellar wind, which dominates the late-AGB phase (Sahai & Trauger 1998), with the slow AGB wind. This interaction is very important since it sculpts the nebula in its beautiful shapes. In this talk I will discuss how PDRs can be used to trace the evolution of the AGB ejecta during the PN phase, their morphology, and how PNe present an ideal setting for PDR studies including the effects of variations in dust properties, elemental abundances, and shocks.

REFERENCES

The photochemistry of stellar outflows

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In this talk, an overview will be given on the role of (UV) photons in the chemistry of stellar ejecta. On the one hand, I will focus on AGB ejecta where penetrating photons from the interstellar radiation field are key to its chemistry. Furthermore, I will present recent results on photochemistry of ejecta from massive stars such as Wolf Rayet and ring nebula. I will discuss how such environments can be used as laboratories for studying PDRs including the effects of variations in dust properties (carbon dust versus silicates), elemental abundances, X-rays, shocks.

REFERENCES
The Herschel Planetary Nebula Survey (HerPlaNS): Molecules in the Far-Infrared Spectra of Planetary Nebulae

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The Herschel Planetary Nebula Survey (HerPlaNS) is an imaging and spectroscopy survey of 11 planetary nebulae (PNe) in the far-IR using the PACS and SPIRE instruments aboard the Herschel Space Observatory. A line survey in these PNe over the entire spectral range between 51 and 672\(\mu\)m revealed the first detections of \(\text{OH}^+\) emission in PNe (Aleman et al. 2014; Etxaluze et al. 2014). The rotational emission lines of \(\text{OH}^+\) at 152.99, 290.20, 308.48, and 329.77\(\mu\)m were detected in the PACS and SPIRE spectra of three PNe: NGC 6445, NGC6720, and NGC 6781. Rotational lines of \(\text{OH}, \text{CO}, \text{and} \text{CH}^+\) have also been detected only in these three objects from our sample. From the observations, we derived excitation temperatures and column densities for \(\text{OH}^+\) in the range of 27-47 K and \(2 \times 10^{10} - 4 \times 10^{11}\) cm\(^2\), respectively. In these objects, the \(\text{OH}^+\) rotational line emission is mostly likely produced in the photodissociation region (PDR). The emission of \(\text{OH}^+\) is observed only in PNe with hot central stars (\(T_{\text{eff}}>100000\) K), with ring-like or torus-like structure. The fact that we do not detect \(\text{OH}^+\) in objects with \(T_{\text{eff}}<100000\) K suggests that the hardness of the ionizing central star spectra (i.e. the production of soft X-rays, \(\sim 100-300\) eV) could be an important factor in the production of \(\text{OH}^+\) emission in PNe, as seems to be the case in recent \(\text{OH}^+\) detections in ultraluminous galaxies and supernovae remnants.

REFERENCES

The [CII] emission puzzle: shocks or PDRs?

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Recent observations of the [C\textsc{ii}] 158 \textmu m line with Herschel and SOFIA in Galactic star-forming regions (S106, Simon et al. 2012; Cep B, Mookerjea et al. 2012; M17, Perez-Beaupuits et al. 2012; W43, Carlhoff 2014, Schneider et al., in prep.) revealed a surprisingly complex spatial and kinematic emission distribution. We propose that a part of the observed [C\textsc{ii}] emission can be attributed to shocks.

**PDRs vs high-velocity shocks**

SOFIA [C\textsc{ii}] observations of the bipolar nebula S106 revealed extraordinary dynamics (several velocity components, large line widths, and wing emission). Such an emission profile is not seen in any other atomic or molecular tracer and not associated with the bulk emission of the cloud. However, stellar outflows, winds, and high-velocity accretion shocks can produce highly excited gas that can cool via the classical PDR tracer lines. I will present these observations in S106 and our approach to disentangle the [C\textsc{ii}] emission arising from the PDR and ionized components and from the shocked gas.

**PDRs vs low-velocity shocks by colliding flows**

In addition to high-velocity shocks (\(v\sim 20 \text{ km s}^{-1}\)), that are associated to local star-formation activity within a cloud, low-velocity (\(v\sim 10 \text{ km s}^{-1}\)) shocks can be related to large-scale colliding flows that form the densest cloud structures where OB-clusters in molecular clouds form. In W43, we observed (Nguyen-Luong et al. 2013) extended, low-velocity SiO emission associated with such low-velocity shocks. In contrast to recognizing [C\textsc{ii}] in the framework of a static PDR, I will show that it is a good tracer of the transitional phase between atomic and molecular gas. UV-heating and photodissociation takes place as well, but would serve mainly to increase the [C\textsc{ii}] abundance. I will discuss the spatial distribution of [C\textsc{ii}] emission seen with Herschel/HIFI and compare to recent 3D MHD simulations (Glover, Clark) that find a scattered spatial [C\textsc{ii}] distribution, adding a turbulent component in the colliding flow scenario of cloud formation.

**REFERENCES**

PDR Diagnostic Diagrams: Guides to the Underlying Physics of FUV Illuminated Gas in Galaxies

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The fundamental physical processes controlling Photodissociation Regions were identified 30 years ago (Tielens & Hollenbach 1985), and soon thereafter the first precomputed grids of PDR models appeared (Wolfire, Tielens & Hollenbach 1990), focusing on the FIR line and continuum tracers of PDR surfaces (e.g. OI, CII, FIR continuum). These diagnostic diagrams could be used (a) to understand the regimes of UV field and density in which different physical processes were important, and (b) to infer the physical conditions in galaxies from observations. Subsequent work (Kaufman et al. 1999) extended the modeling to include FIR and sub-millimeter tracers of the atomic-to-molecular transition and fully-molecular regions of PDRs (e.g. lines of CI and CO). More recently, grids of models have been produced for diffuse clouds (Le Petit et al. 2006), ensembles of cloud sizes (Röllig et al. 2006), galactic nuclei subject to intense X-ray radiation (Meijerink, Spaans & Israel 2007), gas with non-solar metallicities (Kaufman et al. 2006), and the chemistry of molecular ions (Hollenbach et al. 2012).

When used appropriately, diagnostic diagrams allow observers to determine PDR properties including gas density, FUV field strength, number of cloud surfaces in the beam, volume filling factors, masses of atomic and molecular gas, abundances of trace species, and the cosmic ray ionization rate. I will review the basic use of PDR diagnostic diagrams for determining these properties, while also pointing out some limitations and potential pitfalls of using pre-computed results. Galactic and extragalactic examples will be discussed.

REFERENCES

A photodissociation region in H\textsubscript{II} region N55 of the LMC

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We present observations of molecular line emission, morphology and physical characteristics of a spatially resolved and edge-on PDR in H\textsubscript{II} region N55 in the LMC. The H\textsubscript{II} region N55 is ionized by at least six O type stars. The PDR at the northern edge of lower lobe in the H\textsubscript{II} region is illuminated by an O6 star and two O9 stars located within 3pc southward of the PDR within the H\textsubscript{II} region. This PDR has a slabbed clumpy structure in H\textsubscript{2} 28\textsubscript{\mu}m, PAH and dust emission which give us an edge-on view. We will present the FUV radiation field hardness G0 powered by the luminosities of these stars, excitation temperature and column density of warm molecular hydrogen gas and its distribution relative to PAH, dust and CO observations. We have high angular resolution observation of H\textsubscript{2} 28\textsubscript{\mu}m and Si\textsubscript{II} 34\textsubscript{\mu}m using Spitzer IRS. Moreover, SAGE-LMC photometric data using Spitzer IRAC (4.5, 5.5, 8.0\textsubscript{\mu}m), MIPS (24, 70 and 160\textsubscript{\mu}m), and Herschel PACS (100, 160\textsubscript{\mu}m), SPIRE (250, 350 and 500\textsubscript{\mu}m) from HERITAGE. In addition, we have high angular resolution interferometric observation of 13CO(1-0) emission of this PDR using ALMA, and 12CO(3-2) observation using ASTE. In 13CO(1-0) emission, which is optically thin and traces the cold gas, this PDR is a thin clumpy structured. The CO(3-2) emission is more extended. We plan to present a preliminary model of this PDR.
The impact of optically thick HI on the envelopes of molecular clouds and its implication for the HI-to-H$_2$ transition

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Recent observations of nearby galaxies have shown that the HI surface density sharply saturates at $\sim 10$ M$_\odot$ pc$^{-2}$ on kpc scales. This holds even on sub-pc scales, as shown by Lee et al. (2012) for the Perseus molecular cloud. The three-dimensional H$_2$ formation model by Krumholz et al. (2009) explains this saturation as the minimum HI surface density required for shielding H$_2$ against photodissociation. While the predicted HI surface density of $\sim 10$ M$_\odot$ pc$^{-2}$ for solar metallicity is consistent with the observations, however, the HI saturation could alternatively result from a large amount of the optically thick HI.

We investigate the impact of high optical depth on the observed HI saturation in Perseus by using Arecibo HI emission and absorption measurements obtained toward 26 radio continuum sources (Stanimirović et al. 2014; Lee et al. 2015). We calculate the spin temperatures and optical depths of individual HI components along each line of sight and derive the correction factor for high optical depth HI. The pixel-by-pixel correction to the optically thin HI column density image results in only a $\sim 10\%$ increase in the total HI mass and the HI surface density is still uniform with $\sim 7$–9 M$_\odot$ pc$^{-2}$, suggesting that H$_2$ formation is mainly responsible for the HI saturation in Perseus. We also compare the optically thick HI with the observed “CO-dark” gas and find that the optically thick HI only accounts for $\sim 20\%$ of the “CO-dark” gas in Perseus.

REFERENCES

Photodissociation regions (PDRs) are found in massive star forming sites at the interface between the H\textsc{ii} region and the molecular cloud from which the stars formed. Magnetic fields could play an important role in the evolution of PDRs (e.g., Abel et al. 2004, Pellegrini et al. 2007), however this possibility has been the subject of very few studies due to the paucity of relevant data. The recent survey of dust polarized emission by Planck can, for the first time, reveal the magnetic field structure in the PDRs closest to the Sun (e.g., in Ophiucus). I will show and discuss some examples, where the magnetic field is observed to have different orientations relative to the ionization front. In addition, I will present an analytical model that describes the magnetic field structure in a PDR formed around an expanding H\textsc{ii} region and its application to the Rosette Nebula (Planck Collaboration Int. XXXIV. 2015). We find that, due to the compression of the field lines by the expansion of the ionized gas, there is a local increase of magnetic pressure in the PDR. This could contribute to the confinement of gas at high thermal pressure in PDRs, whose presence is also evidenced by highly excited molecular lines with Herschel (Goicoechea et al. 2011, Joblin et al. in prep.).

REFERENCES

PDRs and Star Formation
PDRs and star formation

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Photodissociation regions (PDRs) are regions where far ultraviolet photons dominate the energy balance or chemistry of the gas. Substantial fractions of both the volume and the mass of typical molecular clouds are located in these regions (Hollenbach & Tielens, 1997), and so it is no surprise that PDRs play an important role in regulating star formation in molecular gas. In this talk, I will discuss why PDRs play such an important role in the star formation process and how we can use observations of them to better understand the physics of molecular clouds.

REFERENCES

Protoplanetary disks evolve in very harsh, intensely irradiated environments. Young stars are very luminous at ultraviolet and X-ray wavelengths due to their high chromospheric activity and due to rapid accretion that results in high-temperature shocks at the stellar surface. PDRs and XDRs form on the irradiated disk surface heating the gas to temperatures that far exceed local dust temperatures. This heating drives thermal flows or photoevaporative winds from the disk surface and in combination with viscous accretion, the disk rapidly loses mass and disperses (e.g., Hollenbach et al. 2000, Dullemond et al. 2007, Alexander et al. 2014). Indeed, observations indicate that primordial gas and dust in disks are short-lived, with lifetimes of the order $\sim$ few Myr (e.g., Zuckerman et al. 1995, Haisch et al. 2001, Pascucci et al. 2006), comparable to planet formation timescales.

I will describe thermochemical models of disks and review our current understanding of the structure of protoplanetary disks. I will discuss disk dispersal in various contexts and the implications of photoevaporation for planet formation.

REFERENCES

Extreme PDRs and XDRs: A multi-wavelength view into protoplanetary disks

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Protoplanetary disks offer a unique laboratory to study PDRs and XDRs over an extreme range of physical and irradiation conditions. The FP7 DIANA project (Disc Analysis, PI P. Woitke) has compiled to date the most extensive multi-wavelength database of protoplanetary disks to model them with state-of-the-art radiation thermo-chemical disk models. New features in the codes include 2D X-ray radiation transport, surface chemistry, PAH charge exchange and adsorption, and extensive mid-IR to far-IR cooling (H\(_2\)O, CO, CO\(_2\), CH\(_4\), etc., overall more than 40000 lines).

I will discuss in this talk the interplay between cosmic rays, X-rays and UV in disks and how this changes the disk chemistry and emerging line fluxes. Example of this are (1) the interplay between adsorption processes and element abundance for the abundance of molecular ions (Rab et al. 2015, Kamp et al. 2015) (2) Water in T Tauri versus Herbig disks (Antonellini et al. 2015), (3) disks in low mass versus high mass star forming regions (Vicente et al. 2013, 2015), and (4) surface chemistry versus gas phase chemistry.

By combining the radiation thermo-chemical disks models with our multi-wavelength datasets we will constrain the overall disk structure and composition. By building a large sample analysed in an homogeneous way (Woitke et al. 2015), we can search e.g. for differences between T Tauri and Herbig disks in terms of their gas content or dust composition and what the consequences are for the planetary systems forming around them.

REFERENCES

The Evaporation of Circumstellar Disks, PDR Models, and Radiation Fields in Young Star Forming Clusters

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Most stars – and hence most planetary systems – form within stellar clusters, and these background environments can provide a variety of disruptive influences on disks and planets (Adams 2010). This contribution focuses on the role played by cluster radiation fields at various wavelengths, including the FUV (Adams et al. 2006), EUV (Fatuzzo & Adams 2008), and X-ray components (Adams et al. 2012). For each of these wavelengths, we describe the distributions of radiative fluxes produced by the clusters and delivered to their constituent star/disk systems. The FUV radiation field provides the dominant effect and can lead to significant evaporation of the circumstellar disks. The corresponding photoevaporation process due to external FUV radiation involves PDR regions (Adams et al. 2004). The second half of this talk develops photoevaporation models and explores their implications for setting upper limits on disk lifetimes.

REFERENCES

Shocks and PDRs from Young Stellar Objects with Herschel

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David Hollenbach’s pioneering models of shocks and PDR’s and their emergent infrared spectra set the groundwork for the interpretation of the spectacular molecular and atomic spectra of young stellar objects obtained with Herschel. In particular, a series of diagnostics were proposed in Hollenbach & McKee (1989) to distinguish between \( J \)-type shocks, \( C \)-type shocks, and PDRs, which can now be tested against observations from the Photoconductor Array Camera and Spectrometer (PACS) instrument.

The major Herschel / PACS surprise was the large abundances of warm and hot gas (\( T > 300 \) K) in low-mass protostars, indicating that these are feeding back on their parental material in unexpected ways (Karska et al. 2013, 2014b, in prep.). I will summarize the observations and present an overview of where we currently stand in our understanding of energetic processes in low-mass protostars. The interpretation of the data will be based on a simple radiative-transfer analysis and comparisons to available shock and PDR models, with a brief discussion of the results from the more sophisticated and detailed physicochemical models. One of the key results, in terms of feedback processes, is that we need to combine the chemistry of PDRs with the physics of shocks to fully understand and interpret the PACS data, thereby combining two of David Hollenbach’s primary scientific interests.

REFERENCES

Star Formation Near Sgr A*  
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We present several different lines of evidence in favor of on-going star formation within a couple of pcs of Sgr A*. First, we report the detection of 44 partially resolved compact sources with size scales ranging between 400 and 1600 AUs. The bow-shock appearance of these sources face the direction of Sgr A*. We interpret these sources as a candidate population of photoevaporative protoplanetary disks (proplyds) that are associated with newly formed low mass stars. The disks are externally illuminated by strong Lyman continuum radiation from the 100 OB and WR massive stars distributed within 10" of Sgr A* (Yusef-Zadeh et al. 2015). Second, we report the detection of water masers with multiple and single velocity components. Third, we investigate SED modeling of 64 infrared excess sources in the inner pc of Sgr A* indicating the presence of YSO candidates. Lastly, we identify a bipolar outflow candidate in one of the clumps of SiO emission in the molecular ring.

REFERENCES

PDRs and the ISM of Galaxies
Photodissociation regions (PDRs) are important structures for regulating star formation and controlling the transition from atomic to molecular interstellar gas. I will discuss PDR structural dependence on metallicity, gas density, and the intensity of the ionizing ultraviolet background (UVB) in the Milky Way and external galaxies. The intensity of the metagalactic UVB is critical to understanding both the interstellar medium (ISM) and intergalactic medium (IGM) and depends on both QSOs and star-forming galaxies. An increase in the UVB by factors of 2–5 may be required (Kollmeier et al. 2014; Shull et al. 2015) to explain the observed distribution of H I column densities in the Ly$\alpha$ forest (Danforth et al. 2014) compared to cosmological simulations of baryon structure formation. The LyC production rates from OB associations depend on stellar metallicity and rotation and the initial mass function. Topping & Shull (2015) coupled non-LTE model atmospheres to recent evolutionary tracks (Ekström et al. 2012; Georgy et al. 2013). They found a median LyC production efficiency $Q_{\text{LyC}} = (6\pm2) \times 10^{60}$ LyC photons per $M_\odot$ of star formation, equivalent to a rate calibration of $10^{53.3\pm0.2}$ photons s$^{-1}$ per $M_\odot$ yr$^{-1}$, a 50% increase over previous estimates. Despite the importance of massive stars for cosmological reionization at $z \approx 7$, their LyC rates remain uncertain, as are reliable estimates for the escape fraction ($f_{\text{esc}}$) of Lyman continuum (LyC) radiation from star forming regions. The spatial structure of PDRs, the evolution of their gas dynamics, and their H I opacity may be key parameters in controlling LyC leakage from the ISM surrounding OB associations.

REFERENCES

The origin of the [CII] line in the Milky Way

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I will review our current understanding of [C II] emission from the interstellar medium (ISM) in the Milky Way. The [C II] line traces different phases of the ISM, including the diffuse ionized medium, warm and cold atomic clouds, clouds in transition from atomic to molecular, and dense and warm photon dominated regions (PDRs). I will discuss how understanding the relative importance of the different phases of the interstellar medium to the [C II] emission locally is an important tool for interpreting unresolved observations of [C II] emission in distant galaxies. I will also summarize future prospects to observe [C II] in the Milky Way that will advance our understanding of the [C II] emission from different phases of the interstellar medium.
STRUCTURE OF DARK MOLECULAR GAS IN THE GALAXY I - A Pilot Survey for 18-cm OH near $l \approx 105^\circ, b \approx +1^\circ$

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A high-sensitivity, blind survey for OH emission in a small patch of sky near the Galactic Plane will be described (Allen, Hogg, & Engelke 2015). Spectra were recorded with 2 hr integrations on a sparse grid of 3 X 9 pointings with a step size of 0.5° using the GBT (FWHM $\approx 7.6'$). 21 of the 27 spectra show detectable 1667 MHz features, confirming the ubiquity of this molecular emission line in the general diffuse ISM. With few exceptions, the main OH lines at 1665 and 1667 MHz appear in the ratio of 5:9 characteristic of LTE at our sensitivity levels. No OH absorption features are recorded, consistent with the low levels of continuum background in this direction. At each pointing the OH emission profiles show several components coinciding with well-known features of Galactic structure such as the Local Arm and the Perseus Arm. In contrast, little CO emission is seen in the survey area; less than half of the $\geq 50$ identified OH spectral features show detectable CO(1-0) counterparts at the sensitivity levels of the CfA CO(1-0) survey (Dame, Hartmann, & Thaddeus 2001), and these are generally relatively faint. There are no CO features without corresponding OH emission in our survey.

Some of the main conclusions of this work so far are as follows: 1. Main-line OH emission is ubiquitous in the Galactic ISM; it appears to come from a larger area of low-volume-density molecular gas. 2. The morphology and extent of main-line OH emission resembles that of the “dark molecular gas” in the Galaxy discovered earlier in far-IR and gamma-ray emission, but with the added advantage that radial velocity information is also provided. 3. The additional mass of molecular gas present in the ISM implied by these observations is substantial; although the volume density is low, its spatial extent is large, approaching that of the HI. Further work is needed to establish the quantitative details of this connection. Although UV absorption observations and modeling suggest that the relation between OH and H$_2$ column densities is less complicated than for CO and H$_2$, the question of what excitation temperature to use in order to convert the observed OH line strength into a column density remains somewhat uncertain.

Recent extensions and future directions for this work will be described.

REFERENCES

[N \text{II}] Fine Structure Line Emission from the Milky Way
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We discuss preliminary results from a survey of [N II] emission from the Milky Way carried out with the \textit{Herschel} Space Observatory using the PACS and HIFI instruments. With PACS, we have observed the 122 $\mu$m and 205 $\mu$m fine structure lines towards approximately 150 pointing directions distributed in the plane of the Milky Way, following the in–plane directions observed by the GOT-C\textsuperscript{+} project (Langer et al. 2010). For each pointing direction we have 25 observations of each line and from the relative intensities of the different lines of sight, find that the [N II] is spatially extended. [N II] emission is detected in a majority of pointing directions, and in almost every direction observed in the inner Milky Way. The ratio of the intensities of the two [N II] lines can be used to determine the electron density in the region, where the [N II] is present (see e.g., Oberst et al. 2006). We find $n(e)$ between 10 and 100 cm\textsuperscript{-3}, and [N II] column densities between $10^{13}$ and $10^{14}$ cm\textsuperscript{-2}. These densities are much greater than expected for the Warm Ionized Medium (WIM), and suggest that the [N II] is produced in much denser ionized regions. We also obtained HIFI spectra of the 205 $\mu$m [N II] line, and can make detailed comparisons with the GOT-C\textsuperscript{+} [CII] spectra. It appears that a good fraction of the [C II] components match very well with those of [N II] suggesting that these are interface regions. There are [C II] components without [N II] which may be “CO Dark H\textsubscript{2}”, while we do not find any [N II] components without [C II].

REFERENCES
Far-infrared and gamma-ray surveys indicate there are significantly more nucleons in the diffuse interstellar medium than are traced by H I and CO emission. Using the Planck far-infrared Arecibo GALFA 21-cm line surveys, we identified a set of isolated interstellar clouds and assessed their dust-to-gas ratios—taking into account only the atomic gas traced by the 21-cm line. Significant deviations from the standard dust-to-gas ratio are found both from cloud to cloud and within regions of individual clouds. The outskirts of the clouds are most similar to the truly diffuse ISM and the standard dust-to-gas ratio. Within the clouds, the dust per unit gas increases over 300% in many clouds.

We are engaged in a follow-up observing program to determine the reason for the enhanced apparent dust-to-gas ratio. The first (already widely accepted) hypothesis is that the extra dust is associated with molecular gas. Based on the dust-to-(atomic)gas enhancement, we predict detectable amounts of molecular gas. Results of a search for OH absorption toward radio sources in one cloud were, to our surprise negative, indicating relatively little molecular gas.

The second hypothesis is that the 21-cm line is underestimating the amount of atomic gas, so the apparent dust-to-gas ratio was overestimated. Cold gas would be optically thick in the 21-cm. We measured 21-cm absorption profiles toward one cloud, and have proposed to survey the others. Results to date indicate that the gas is in fact remarkably cold; however, the column density of cold atomic gas does not appear sufficient to explain the enhanced dust-to-gas ratio. There could also be warm or ionized gas; we have begin observations with SOFIA to measure the [C II] 157 μm line brightness to search for extra gas traced by ionized Carbon.

The third hypothesis is that the dust properties evolve inside of the clouds, so that the apparently enhanced dust-to-gas ratio is actually measuring different dust properties. There is already some indication of this from the Planck data alone, which indicate the emissivity index changes at the same time as the dust temperature decreases in the cloud cores. The emission at frequency $\nu$ is $\nu^\beta B_\nu(T)$ where $\beta$ is the emissivity index and $B_\nu(T)$ is the blackbody function at temperature $T$. It is qualitatively expected that the grains will be colder in regions where starlight is more excluded, but the emissivity index is a property of the grains. If this hypothesis is the only one active, then there may be no ‘dark gas’ at all, but there is a critical new physical process that changes grain properties with the resultant effect on their ability to heat interstellar gas and coagulate into planets around forming stars.
Diffuse clouds as low density PDRs

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The diffuse interstellar medium holds a significant fraction of the total mass of neutral gas in the Milky Way, and as such plays an important role in the interstellar matter life cycle. Due to their relatively low densities, the properties of diffuse clouds are better probed by absorption spectroscopy rather than by emission lines. The advent of the Herschel and Planck missions, and the SOFIA airplane has led to tremendous progresses in the exploration of the diffuse ISM with detections of new species (e.g. Gerin et al. 2012, Neufeld 2015), a systematic exploration of interstellar hydrides (see also Neufeld - 2015), the characterisation of the mean pressure (Gerin et al. 2015), and full sky maps of the dust and CO emission ( ). Parallel spectacular advances have been obtained in the modeling of these systems using both both three-dimensional MHD simulations and detailed mono-dimensional codes coupling the physics, chemistry and thermodynamics of the gas. This talk will review the recent observational results, and the parallel advances in the modeling.

REFERENCES

Neufeld D. (2015) This conference
Chemical probes of turbulence in the diffuse medium: the TDR model

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Because it is predominantly heated by the UV radiation field, the diffuse interstellar medium (ISM) has long been thought to behave like a photo-dissociation region (PDR). Yet, for the last 30 years, absorption spectroscopy has revealed a gas with a chemical richness that was unexpected from the sole predictions of PDR-type models. This problem has recently been deepened by the observations of large abundances of small hydrides using the Herschel/HIFI instrument. Since their production pathways are blocked by highly endo-energetic reactions, it has been proposed that several of these species are nothing else but a signature of another powerful energy source, such as the dissipation of magnetized turbulence (Godard 2009).

Among all the molecules, CH\(^+\) and SH\(^+\) are a unique couple (Godard 2012) because the energies involved in their formation are large (\(\Delta E/k \sim 4640\) K and 9860 K respectively). Their presence in the cold diffuse ISM is therefore much more than a chemical riddle: it is rooted in the physics of the diffuse ISM, the intermittency of the turbulent cascade and the rate of its dissipation, and it connects with the broader issues of star formation and galaxy evolution.

The informations inferred from the absorption spectra are analysed (Godard 2014) in the framework of the TDR (Turbulent Dissipation Regions) model which follows the dynamical and chemical evolutions of the gas in intermittent regions of turbulent dissipation. By comparing the predictions of the TDR model with multiwavelength observations of seven atomic and molecular species (C\(^+\), CH\(^+\), SH\(^+\), H, H\(_2\), HCO\(^+\) and CO) we are able, for the first time, to measure five essential properties of the interstellar turbulence: (1) the dissipation rate (\(\sim 10^{-24}\) erg cm\(^{-3}\) s\(^{-1}\)), (2) how it varies across the Galactic disk, (3) the size of the dissipative structures (\(\sim 100\) AU), (4) their lifetime (\(\sim\) a few hundred years), and (5) the dominant dissipative process (viscous friction or ion-neutral friction).

REFERENCES

How we can constrain the transition from atomic to molecular hydrogen; a Planck-based approach to the “optically thick” HI 21cm spectrum

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The HI 21 cm emission in the Galaxy is assumed to be optically thin. Recent works (Fukui et al. 2014; 2015) indicate that the 21 cm spectrum is usually optically thick with an average HI optical depth around 2 by assuming that the dust optical properties are uniform in the local interstellar volume near the sun. I will discuss the implications of the results on the interstellar physics.

REFERENCES

Spatially resolved physical conditions of molecular gas: a zoom-in from circumnuclear region of M83 to Carina nebula

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Since the launch of the Herschel Space Observatory (Pilbratt et al. 2010), our understanding about the photodissociation regions (PDR) has taken a step forward. In the bandwidth of the Fourier Transform Spectrometer (FTS) of the Spectral and Photometric Imaging REceiver (SPIRE) on board Herschel, ten CO rotational transitions, including $J = 4 - 3$ to $J = 13 - 12$, and three fine structure lines, including [CI] 609, [CI] 370, and [NII] 250 μm, are covered. This presentation focuses on the physical conditions of molecular gas probed by the Herschel SPIRE/FTS.

Based on the spatially resolved physical parameters derived from the CO spectral line energy distribution (SLED) map and the comparisons with the dust properties and starformation tracers, I will first present our findings at the circumnuclear region of M83 (Wu et al. 2015), and then zoom in toward the molecular cloud near a young open cluster, Trumpler 14, in Carina nebula. I will discuss (1) the potential of using [NII] 250 and [CI] 370 micron as starformation tracers; (2) the reliability of tracing molecular gas with CO (3) the excitation mechanisms of warm CO (4) the possibility of studying stellar feedback by tracing the thermal pressure of interstellar molecular gas.

REFERENCES

PDRs in Low Metallicity Environments

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I will discuss PDR structures, H/H₂, and C⁺/C/CO transitions from outer FUV dominated zones to the inner cosmic-ray controlled cores, for normal but especially to low-metallicity environments. My emphasis will be on theoretical physical principles as guides to ISM observations on small and large scales in galaxies.
Tracing and characterizing PDRs in nearby galaxies

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I will review the emission characteristics of photodissociation region tracers on a galactic scale within the context of the main gas heating and cooling mechanisms at work. The morphology and topology of the interstellar medium have been successfully probed by observations of nearby galaxies (within a few dozens of Mpc), in particular with Spitzer, SOFIA, Herschel, and ground-based sub-millimeter/radio facilities. Nearby galaxies have proven to be invaluable laboratories to understand the physical conditions in which infrared cooling lines emit, with strong implications for studies of unresolved objects. In that vein I will discuss recent results obtained in several samples spanning a wide range of galaxy types, showing also the influence of the ISM metallicity. I will emphasize results concerning the origin of the ubiquitous [CII] 158\,\mu m cooling line, which potentially arises from several important phases of the ISM (warm/cold neutral medium, warm ionized medium, dense molecular cloud surfaces), as well as the identification of the gas heating processes in different environments.

REFERENCES
I present an examination of PDR properties driven by resolved stellar populations in three regions of NGC 6822. This Local Group dwarf galaxy has a metallicity less than half Solar and lies 490 kpc away. It is close enough that stellar populations are resolved; we can see that our three PDRs are driven by massive stars and model the radiation field directly from the stellar content. The resultant G₀ estimates are significantly higher than that estimated from far-infrared (FIR) dust maps, leading us to postulate that unresolved clumps composing the PDR occupy only a small percentage of each observed spatial element. Detailed analysis rests on the FIR maps in combination with Herschel/PACS spectral maps in [CII] and [OI] 63, 145 µm. We apply PDR modeling results from (Kaufman et al. 1999, 2006, and Wolfire et al. 1990) but incorporate a clumpiness factor into the fits to refine G₀ and derive clump density and filling factor across each PDR map. We further estimate average clump sizes and the number of clumps in each spatial element of our maps. We compare our results to ionized gas densities derived from mid-IR [SIII] line ratios and traced by [OIII] 88 µm to determine whether our PDR clumps and ionized gas are in approximate equilibrium. Finally, we comment on the implications for unresolved PDRs in more distant galaxies.

REFERENCES
The Herschel Dwarf Galaxy Survey: Gas properties at low metallicity

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I will present recent results on the gas properties of the galaxies from the Herschel Dwarf Galaxy Survey. In low-metallicity environments, molecular tracers are rare and the far-IR lines, detected down to metallicities of 1/40$^{1}$solar thanks to Herschel, may be our best handle on their star formation properties.

We analyze observations of the mid-IR and far-IR cooling lines together with detailed Cloudy spectral synthesis models to characterize the physical conditions in the ISM of those galaxies. We find that the low-metallicity ISM differs dramatically from that of more metal-rich objects. It is characterized by harder radiation fields and a porous structure, with larger filling factors of ionized gas, the [O$^{\text{iii}}$] 88$\mu$m line being the brightest far-IR line. The C$^{+}$ emission arises mostly from PDRs, which are dense, of low covering factors, and have moderate UV field strengths. The high [C$^{\text{ii}}$/L$_{\text{TIR}}$ and [C$^{\text{ii}}$]/CO ratios also suggest efficient photoelectric heating caused by UV field dilution and strong effects of photodissociation, leaving a possibly large reservoir of CO-dark gas in those dwarf galaxies.

REFERENCES

PDRs and Molecular Gas at Low-Metallicity in the Small Magellanic Cloud

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The Small Magellanic Cloud (SMC) provides the only laboratory to test the physics of the low-metallicity ISM and photodissociation regions at low metallicity. We present results from the Herschel mapping of key FIR cooling lines ([C\textsc{ii}], [O\textsc{i}], [N\textsc{ii}], [O\textsc{iii}]) in photodissociation regions in the Small Magellanic Cloud (HS\textsuperscript{3}), and compare our measurements to normal local galaxies. Our dust-based estimates of the molecular gas in the SMC show more extended structure than what is traced by CO (including new ALMA observations), and we use of [C\textsc{ii}] measurements to trace this translucent molecular gas. We discuss the relation between [C\textsc{ii}] and CO (from new APEX observations) at low metallicity.
PDRs in Starburst, (U)LIRG, and High-z Environments
Witnessing the Effects of Massive Star Formation in 30Do-radus of the LMC

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We will present a far infrared view of the spectacular nearby star forming region, 30 Doradus in the Large Magellanic Cloud (LMC), commonly considered to contain our nearest super star cluster, R136. This region offers the best laboratory to zoom into the interplay between stellar activity and metal-poor ISM due to its proximity (50kpc) and half-solar metallicity. The new Herschel/PACS and SPIRE/FTS observation of far infrared (FIR) fine structure lines, combined with Spitzer IRS spectroscopic maps, provide constraints for modeling the gas in the photodissociation regions (PDR) with the Meudon PDR code (Le Petit et al., 2006), as well as the ionized gas, thus allowing us to construct a comprehensive, self-consistent picture of the density, radiation field, and ISM structure in this well-studied region and to quantify the effect of intense star formation on the low metallicity ISM. Effects of the intense star formation activity and lowering the metal abundance, hence decreasing the shielding necessary for the formation of molecular gas, can be witnessed throughout.

The extreme luminosity of the 30Dor region makes it the only region of the Magellanic Clouds that can be extensively studied on large scales. Observations of the FIR fine structure lines in 30Dor ([CII] 157 μm, [OI] 63 μm, [OII] 145 μm and [OIII] 88 μm) over the entire 6′×5′ region (90pc × 75pc), covering the full range of contiguous PDR and ionized conditions influenced by the massive cluster will provide the most complete 3D picture of a well-resolved (4pc scales) star-forming region divulging the structure and physical conditions of the diverse gas phases throughout the low metallicity ISM in a powerful starburst.

REFERENCES

Molecular gas in luminous galaxies

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We have investigated the minimum line information needed to determine molecular gas properties in galaxy centers, by collecting line fluxes (one \textsuperscript{13}CO, two [CI], three CO transitions) in 76 galaxies. We find that a useful analysis of the simplest cases requires a minimum of five of these lines. The CO lines do not provide much information on the ISM in the parent galaxies, nor do the [CI] lines by themselves. Their luminosities poorly predict H\textsubscript{2} mass in any particular galaxy. However, taken together, they can be used to classify the parent galaxies in terms of ISM gas pressure, and the (U)LIRGs) with the highest pressure are well described by single-gas-phase models. They are dominated by dense (10\textsuperscript{4}-10\textsuperscript{5} cm\textsuperscript{-3}) and warm gas (35 K) with low [\textsuperscript{13}CO]/[\textsuperscript{12}CO] and [C]/[CO] abundances. This analysis can also be used to determine molecular gas temperature, density, and mass in high-redshift galaxies and we have identified six redshift ranges for which all five lines required fall in atmospheric windows. In the more numerous, less luminous galaxies, lower-density gas is more important and a multiple-gas-phase analysis is needed, requiring better coverage of at least the \textsuperscript{12}CO and \textsuperscript{13}CO ladders, and preferably also the HCN, HNC, HCO\textsuperscript{+} etc ladders for a more sophisticated treatment of the gas heating process (UV photons, X-ray photons, CRs, shocks etc) as pure-PDR models are no longer sufficient.
PDRs in starburst and (U)LIRG environments

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With the recent developments in far-infrared and (sub-)millimeter spectroscopy, provided, for instance, by the Herschel Space Observatory, the ALMA and NOEMA interferometers and the single dish CSO-ZEUS instrument, the studies of extragalactic PDRs in infrared-bright galaxies like starbursts and (U)LIRGs have made tremendous progress and now range from the local universe all the way back to the era when galaxies were assembled. In this review I will provide an overview of recent results in this area and address questions such as: What are the characteristics of PDRs in galactic nuclei, starburst galaxies, and (U)LIRGS and how does that differ from local PDRs? How can observations of PDRs be used to probe the conditions in extreme environments?
Probing the star forming ISM in high-z quasars

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In local massive galaxies there is an amazing correlation between the mass of supermassive black holes and the mass of the stellar component. Through observations of dust infrared emission and molecular and fine structure line emission from high-redshift quasars, we have been exploring the relation between both components at the time of their formation. The vastly improved interferometric capabilities of the VLA, IRAM-PdBI and ALMA allow us to resolve the star formation regions, thus revealing the physical characteristics of the dense, star forming gas.

REFERENCES
Tracers of PDRs at High Redshift

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I plan to cover the current state of the knowledge and future prospects for tracing the physical conditions of the photodissociation regions in high redshift systems. The workhorse line is the 158 um [CII] transition which has now been reported from about 50 high redshift galaxies. The [CII]/far-IR continuum luminosity ratio is a measure of the strength of the ambient FUV radiation fields, which together with the source luminosity yields the size of the emitting regions. This ratio varies by about a factor of 100 from the low ratios seen in local ULIRG galaxies and distant AGN dominated systems to very high values (in excess of 0.01) seen in luminous star formation dominated systems. This simple tracer has already been used to demonstrate that unlike the collision-induced, confined and very intense starbursts found in local ULIRG galaxies, many of the highest luminosity star forming systems at intermediate redshifts (z ∼ 1-3) are dominated by very extensive, but moderate intensity star formation regions. Star formation in these systems likely arises from within massive molecular disks in a “quiescent” Schmidt-Kennicutt law mode.

I will also cover high redshift surveys in the [OI] line and the mid-IR PAH features and discuss their added value in constraining the heating and cooling of PDRs at high redshift, prospects for other tracers (e.g. molecular hydrogen rotational line emission), and the utility of the [NII] line for constraining the fraction of the [CII] emission that arises from ionized gas. I will finish with speculations on the expected brightness of the [CII] line from very early times.
HELLO-PDR: FIR Lines from local and z=1-3 Galaxies

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Are the physical conditions of star-forming interstellar medium (ISM) in high redshift galaxies different from those in low redshift galaxies? And are these differences responsible for the prolific star-formation at $z\approx2$? We address these questions with a relatively unbiased survey of [CII] line emission of highly lensed galaxies at redshift $z=1-3$ from the Herschel Extreme Lensing Line Observations (HELLO) survey. Those lensed galaxies are bright in rest-frame UV and represent the star-forming galaxies with modest intrinsic luminosities ($L_{\text{FIR}} \approx 10^{10-11}L_\odot$). We compare their FIR lines ([CII], [OI], [CI]) with PDR models and derive gas densities $n$ and UV fluxes $G_0$ at PDRs. We also explore model independent correlations amongst star formation, FIR continuum, FIR emission lines, and metallicities for this sample. We will also discuss comparison with a sample of local galaxies with a suite of [CII]158$\mu$m, [OI]63$\mu$m, [CI]370$\mu$m, and multi-J CO emission lines detected.

REFERENCES
We illustrate the power of CH\textsuperscript{+} spectroscopy at high spectral resolution with the first detection by ALMA of a CH\textsuperscript{+} (J=1-0) line in an hyper-luminous galaxy, SDP17b at z = 2.3. It is a weakly lensed galaxy (μ = 3.56) of intrinsic FIR luminosity $L_{\text{FIR}} = 2.07 \times 10^{13} L_\odot$, implying an extreme star formation rate $SFR = 2325 M_\odot \text{yr}^{-1}$ (Negrello et al. 2014). Unlike other molecular tracers, the unique chemical and spectroscopic properties of the CH\textsuperscript{+} cation make it a tracer of the turbulent energy trail, from its scale of injection to that of dissipation at which CH\textsuperscript{+} forms (Godard et al. 2014). In SDP17b, CH\textsuperscript{+} (1-0) absorption is detected against the dust continuum and a broad emission line. The absorption probes a massive turbulent halo of low density and the emission possibly originates in a large number of irradiated low-velocity shocks.

REFERENCES

Posters
The 11.2 $\mu$m PAH emission in astrophysical objects

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The 11.2 $\mu$m emission band belongs to the family of the Aromatic Infrared Bands (AIBs), seen in emission in many astronomical environments, e.g. photodissociation regions. In this work, we present a theoretical interpretation of the band characteristics and profile variation for a number of astrophysical sources in which the carriers are subject to a range of physical conditions. The results of Density Functional Theory calculations for the solo out-of-plane vibrational bending modes of large polycyclic aromatic hydrocarbon (PAH) molecules are used as input for a detailed emission model which includes the treatment of the temperature dependence of the band position, and the physical condition of the astronomical sources. Comparison of the model with astronomical spectra indicates that the characteristic asymmetry of the 11.2$\mu$m band and its profile variation can be explained principally in terms of the mass distribution of neutral PAHs with a small contribution from anharmonic effects (Candian & Sarre, 2015).

REFERENCES

Far infrared observations of externally illuminated protoplanetary disks with the *Herschel space observatory*

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Most low and intermediate mass stars seem to be born within transient OB associations (Lada and Lada 2003), and very likely the Solar System too. In such environments, protoplanetary disks around young stars are ionized and photoevaporated by ultraviolet photons arising from nearby massive stars, forming objects known as "proplyds" (O’Dell et al. 1993). These harsh conditions likely have an impact on the formation of planets within such disks. Here, we present the first infrared observations of such objects obtained with the *Herschel space telescope* as part of an open time program dedicated to proplyds (PI: O. Berné). Our study focused on a candidate proplyd located in the Carina nebula, for which several gas lines ([CII], [OI] and some high-J CO lines) have been detected with PACS and HIFI. We also derived the spectral energy distribution of dust emission from PACS data. We modelled the gas emission using the Meudon photodissociation region code (Le Petit et al. 2003) while the dust emission was modelled with simple modified black-bodies plus a component from the polycyclic aromatic hydrocarbon (PAH) emission based on the DustEM model (Compiègne et al. 2011). This study suggests the presence of a diffuse atomic envelope, surrounding a massive (few tenth of a solar mass) and hot molecular region which could correspond to a photoevaporating protoplanetary disk. We will discuss the implications of our results on the understanding of the physical conditions and evolution of proplyds in the context of planet formation.

REFERENCES

Cometary Photodissociation Regions

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Cometary ices contain material left over from the birth of the solar system, and studying their composition provides an important source of information regarding the physical and chemical conditions of the early Solar Nebula. Sublimation of nuclear ices near perihelion generates a large photodissociation region - the coma of gas and dust. Modeling of this multi-fluid plasma requires consideration of a variety of chemical processes, such as photodissociation, photoionization and ion-molecule reactions. Compositional studies, from ground and space, especially of organic molecules, isotopologues, and ortho-para ratios can provide important clues as to their origins. This presentation will summarize recent observational and theoretical developments in cometary chemistry.

REFERENCES

Formation of Organic Molecules in the Interstellar Medium

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This work presents the study of some molecules of the interstellar medium that could useful for the bookkeeping of the organic content of the universe and for the assessment of prebiotic conditions on Earth and in other environments in the universe. The Horsehead Nebula was chosen as test object, due to its simple geometry, its moderate distance to us, its well-known ultraviolet radiation field resulting from the star Orionis, and due the fact that it has been extensively studied in several works.

The main tool used in the present work was the Meudon PDR code due the fact that it is widely used as one of the legacy data analysis programs of current astronomy projects, e.g. the Herschel project, and it is public. The code can reliably model the Horsehead Nebula, since this object is a prototypic PDR (photodissociation region). We have updated the chemical sector of the code - at least a hundred more molecules - in order to test several scenarios of molecule production.

We derived the abundances of several molecules, including some of potential prebiotic importance and we investigated the role of PAHs. We explored production channels for astrobiologically relevant nitrogenated heterocycles, such as pyrrole and pyridine. PAHs are important as intermediary species that favor the production of N-heterocycle. Furthermore, we have checked the role of the cosmic rays flux, within a scenario in which cosmic rays could raise the cation abundances, therewith increasing the abundances of complex molecules.

This presents simulations show us how the exploration of only a small number of possible paths of production of heterocycles already resulted in significants abundances at least one N-heterocycle species, pyridine. Systematic tours along other productions paths are expected to reveal more species with abundances high enough to be targeted in future observational surveys.

REFERENCES

Mapping PAH emission in NGC 7023 with SOFIA

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NGC 7023 is a well-known reflection nebula which shows strong emission from Polycyclic Aromatic Hydrocarbon (PAH) molecules in the form of Aromatic Infrared Bands (e.g. Berné et al., 2007; Boersma, Bregman and Allamandola, 2013). The spectral variations of the AIBs in this region are connected to the chemical evolution of the PAH molecules which, in turn, depends on the local physical conditions.

We exploited the unique capabilities of The Stratospheric Observatory for Infrared Astronomy (SOFIA) to image a 3.2’ x 3.4’ region of this nebula in the PAH bands with high spatial resolution (2.7’). Specifically, we look at the 3.3 µm and 11.2 µm emission in the north and south PDR using the PAH filter ($\lambda_c = 3.3 \mu m$, $\Delta \lambda = 0.09 \mu m$) of FLITECAM and the LWC filter ($\lambda_c = 11.1 \mu m$, $\Delta \lambda = 0.95 \mu m$) of FORCAST (PI Berné).

We compare the SOFIA images with existing images of other PAH bands (Spitzer 8.0 µm), the Extended Red Emission (Hubble and Canadian French Hawaiian Telescope) and H₂ (2.12 µm).

We create maps of the 3.3/11.2 ratio to probe the PAH size distribution and of the 8.0/11.2 to probe the PAH ionization.

We analyze our maps with a emission model based of spectra from the NASA Ames PAH database (Boersma et al, 2014) to determine the physical conditions in the emitting regions and to understand the chemical evolution of PAH molecules in region.

REFERENCES

Revealing the chemical richness of the Orion Bar PDR

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The Orion Bar is the prototypical photodissociation region (PDR) with a far-UV radiation field of a few $10^4$ times the mean interstellar field. Because of its proximity ($\sim 414$ pc) and nearly edge-on orientation, the Orion Bar provides an excellent laboratory to study the chemical content and molecular formation-destruction routes in strongly UV-illuminated gas. Indeed, observations of the Orion Bar across the electromagnetic spectrum have been historically used in the development of PDR models (e.g., Tielens & Hollenbach 1985, ApJ, 291, 722) and today they are used as a template to understand the unresolved emission from sources as different as the nuclei of distant starburst galaxies or the illuminated surfaces of protoplanetary disks. In the context of investigating the chemistry prevailing in molecular gas directly exposed to strong far-UV fields, we have performed the first complete millimeter line survey toward the edge of Orion Bar using the IRAM-30m telescope. The survey is complemented with $\sim 2' \times 2'$ maps of the 0.8 mm emission from several molecules at 7" angular resolution.

Our survey covers $\sim 220$ GHz of bandwidth, between 80 GHz and 360 GHz, in which more than 500 lines have been detected. To the date, over 60 molecular species with up to 6 atoms have been identified, including main isotopologues ($D$, $^{13}C$, $^{18}O$, $^{17}O$, $^{34}S$, $^{33}S$, and $^{15}N$).

$\sim 40\%$ of the lines in the survey arise from small hydrocarbons ($C_2H$, $C_3H$, $^{13}C_2H_2$, $^{13}C_3H$, $^{13}CH$, $^{13}CCH$, $^{13}C_2H$ and $^{13}H_2C_3$ in decreasing order of abundance (Cuadrado et al. 2015, A&A, arXiv:1412.0417). We detect new lines from $^{13}C_3H^+$ and improve its rotational spectroscopic constants. Anions or deuterated hydrocarbons are not detected but we provide accurate upper limit abundances. Despite being a very harsh environment, our observations show a relatively rich and distinctive chemistry: radicals (e.g. $C_2H$, $CN$, $HCO$), ions (e.g. $CF^+$, $CO^+$, $HOC^+$, $SO^+$), complex organics (e.g. $HNCO$, $CH_3OH$, $CH_3CN$), isotopologues and isotopomers (e.g. $HCN$, $HNC$, $DCN$). We have also identified tens of hydrogen, helium, and carbon recombination lines arising from the H II region/PDR interfaces.

In this contribution we summarize our ongoing work and show the perspectives for much higher sensitivity and angular resolution observations of the Orion Bar with ALMA.
High Spectral and Spatial Resolution Observations of $H_2$ Emission in Planetary Nebulae with IGRINS

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Near-infrared emission lines from vibrationally-excited $H_2$ were first detected in a planetary nebula (PN), NGC 7027, four decades ago. The PN environment hosts multiple potential excitation mechanisms for these transitions: shocks at the interfaces of differentially expanding nebular layers, and a strong UV radiation field from the hot central star that can drive radiative excitation. The first PN in which a “pure fluorescent” $H_2$ spectrum (Black & van Dishoeck 1987) was detected was Hubble 12 (Dinerstein et al. 1988). Other PNe display $H_2$ spectra with thermal (collisionally-dominated) spectra or line ratios intermediate between fluorescent and thermal cases. Departures from pure fluorescent line ratios in a radiatively-excited gas can result from collisional modification at high densities (Sternberg & Dalgarno 1989), superposition of fluorescent and collisional components (Davis et al. 2003), a hard UV radiation field, and/or advective effects (Henney et al. 2007), but it is often difficult to determine which of these are relevant. Here we present observations of $H_2$ emission in PNe obtained with the high-spectral resolution (R = 40,000) IGRINS spectrometer, which covers the entire H and K bands simultaneously (Park et al. 2014). We measure over 100 individual $H_2$ emission lines in the original fluorescent PN Hubble 12, and also observed the PN M 1-11, which displays two distinct $H_2$ components: a highly fluorescent $H_2$ ring expanding at $\pm 10$ km/s; and two compact blobs expanding at $\pm 30$ km/s. The latter are seen only in the $v = 1-0$ lines, emit a thermal spectrum with $T_{\text{rot}} \sim 1000$ K, and resemble “molecular bullets” seen in CO in the PN BD+30$^\circ$3639 (Bachiller et al. 2000). Our observations demonstrate the ability of instruments with high spectral resolution and broad spectral grasp to resolve $H_2$ components with different excitation, as well as to reveal hidden spatio-kinematical structure within complex sources by utilizing velocity information.

REFERENCES

A far-ultraviolet and X-ray dominated region code including dust grain chemistry

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Understanding Astrochemistry is essential for disentangling the complex physical processes taking place in very different environments, such as regions where the energetic balance is dominated by UV radiation and AGNs. Meijerink & Spaans (2005) developed a PDR/XDR code (considering gas-phase chemistry only) to study this type of regions. Recently, we have significantly improved this code by including dust grain chemistry in order to determine the different conditions of the interstellar medium (gas/ice/dust) in regions characterised by high molecular gas densities and by the presence of strong radiation fields. In particular, we have included more than 100 reactions covering many processes, such as chemical desorption, freeze out, evaporation, reactivity on surfaces or in the ices and photo-desorption. Here we present the first results obtained with this new code and we discuss the impact of dust grains on the chemical composition of environments powered by UV/X-rays.

REFERENCES

The Distribution, Excitation, and Abundance Of C⁺, CH⁺, and CH in Orion KL

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The CH⁺ ion was one of the first molecules identified in the interstellar gas over 75 years ago, and is postulated to be a key species in the initial steps of interstellar carbon chemistry. The high observed abundances of CH⁺ in the interstellar gas remain a puzzle, because the main production pathway of CH⁺, viz., C⁺ + H₂ → CH⁺ + H, is so endothermic (4640 K), that it is unlikely to proceed at the typical temperatures of molecular clouds. One way in which the high endothermicity may be overcome, is if a significant fraction of the H₂ is vibrationally excited, as is the case in molecular gas exposed to intense far-ultraviolet radiation fields. Elucidating the formation of CH⁺ in molecular clouds requires characterization of its spatial distribution, as well as that of the key participants in the chemical pathways yielding CH⁺. Here we present high-resolution spectral maps of the two lowest rotational transitions of CH⁺, the fine structure transition of C⁺, and the hyperfine-split fine structure transitions of CH in a ~ 3′ × 3′ region around the Orion Kleinmann-Low (KL) nebula, obtained with the Herschel Space Observatory’s Heterodyne Instrument for the Far-Infrared (HIFI).¹ We compare these maps to those of CH⁺ and C⁺ in the Orion Bar photodissociation region (PDR), and discuss the excitation and abundance of CH⁺ toward Orion KL in the context of chemical and radiative transfer models, which have recently been successfully applied to the Orion Bar PDR (Nagy et al. 2013).

REFERENCES


¹These observations were done as part of the Herschel observations of EXtraordinary sources: the Orion and Sagittarius star-forming regions (HEXOS) Key Programme, led by E. A. Bergin at the University of Michigan, Ann Arbor, MI.
Kinematic Study of Ionized and Molecular Gases in Ultra-Compact HII Region Monoceros R2

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Monoceros R2 (Mon R2) is a ultra compact HII region (UCHII; diameter < 0.1pc; density $> 10^4$ cm$^{-3}$; Churchwell 2002) surrounded by PhotoDissociation Regions (PDRs), and an excellent example to investigate the chemistry and physics of early stage of massive star formation due to its proximity (830pc) and brightness. Previous studies by Jaffe et al. (2003) and Zhu et al. (2005, 2008), based on the 12.8\(\mu\)m [Ne II] observations of 16 UCHII regions, suggest that (a) essentially all of the different UCHII morphologies were the same (flows along cometary shells) but appeared different depending on viewing angle and (b) that these wind-driven cometary shells could have much longer lifetimes than classical UCHII regions. In this picture, the wind from the star holds the ionized gas up against the dense molecular core and the higher pressure at the head drives the ionized gas along the shell. In order for the model to work, there should be evidence for dense molecular gas along the shell walls, irradiated by the UCHII region and perhaps entrained into the flow along the walls.

We obtained the Immersion Grating INfrared Spectrograph (IGRINS) spectra of Mon R2 to study the kinematic patterns in the areas where ionized and molecular gases interact. The position-velocity maps from the high resolution H- and K-band (1.4-2.5\(\mu\)m) IGRINS spectra demonstrate that the ionized gases (Brackett and Pfund series, He and Fe emission lines; $\Delta v \approx 40$ km/s) flow along the walls of the surrounding clouds. This is consistent with the model by Zhu et al. (2008). In the PV maps of the H$_2$ emission lines there is no obvious motion ($\Delta v \approx 10$ km/s) of the molecular hydrogen right at the ionization boundary. This implies that the molecular gas is not taking part in the flow as the ionized gas is moving along the cavity walls.

REFERENCES

Large Scale Surveys of [Cl] and [CII] from the HEAT & STO Telescopes in Antarctica

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The largest scientific impact of photodissociation regions may be still to come, even after 30 years of study. If star formation in dense gas is relatively prompt on average, then cloud formation may be the rate-limiting process governing star formation in galaxies. The construction of (giant) molecular clouds from lower column, diffuse components lies firmly in the PDR regime. It is especially remarkable that this process has yet to be identified observationally!

Observing the principal forms of gas-phase carbon (C\textsuperscript{+}, C, and CO) at terahertz frequencies provides a more complete census of material in PDRs and molecular clouds, and therefore probes the full life cycle of interstellar clouds. Here, we report on two dedicated spectroscopic mapping missions with the express goal of exploring the full carbon life cycle over large swaths of the southern Milky Way.

(1) The High Elevation Antarctic Terahertz (HEAT) telescope is a pioneering, robotic, 0.6-meter observatory near the 3-mile-high summit of the Antarctic plateau at a site called “Ridge A”. The unparalleled stability, exceptional dryness, low wind and extreme cold make Ridge A a site without equal for astronomy at infrared and submillimeter wavelengths. In its first three years, HEAT’s pilot surveys have focused on the 370 $\mu$m [Cl] line and high-J CO and [NII] emission at 200-205 $\mu$m. In this contribution, we will showcase new openly-available products from HEAT’s Galactic Plane Survey, new catalogs of clouds and PDRs, candidate cloud formation regions, and exciting prospects for observing [CII] from the ground!

(2) Providing a rapid mapping capability for terahertz [CII], [NII] and [OI] line emission is the principal goal of the Stratospheric Terahertz Observatory (STO), a 0.8-meter telescope on a long duration stratospheric balloon launched from Antarctica. STO is scheduled to perform a 2-4 week science mission in December 2015, providing spectroscopic mapping of $\sim$30 square degrees of the Galactic Plane from 63 to 205 $\mu$m. A preview of expected data products from STO and their impact on our understanding of the cold ISM and PDRs will be discussed.

REFERENCES
Physical conditions of the warm molecular gas in the star-forming region N159

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The interaction between stars and their surrounding interstellar medium is of critical importance for the evolution of galaxies (Hopkins et al. 2014). In this contribution, we present our investigation of the physical properties and excitation mechanisms of the warm molecular gas in N159, one of the most active star-forming regions in the Large Magellanic Cloud (LMC). CO rotational transitions up to CO(J = 12 → 11) have been detected in Herschel SPIRE FTS observations and our non-LTE radiative transfer analyses on ~10 pc scales have revealed the presence of very warm (~400 K) and moderately dense (~2 × 10³ cm⁻³) molecular gas in the LMC for the first time. In combination with other gas and dust tracers, we have examined the observed CO line ratios using Meudon PDR and XDR models (Le Petit et al. 2006), finding that both models fail to reproduce in particular high-J CO observations (upper J > 6). Our results suggest that UV and X-ray photons are not sufficient to heat the warm CO-emitting gas in N159 and shock likely dominates the gas excitation. Our study is one of the first attempts to examine the excitation mechanisms of the warm molecular gas on scales of individual molecular clouds and provides insights into the role of stellar feedback.

REFERENCES

Protostellar chemistry dominated by external irradiation

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In their youngest stages, protostars are deeply enshrouded by envelopes of gas and dust, material which later accretes onto the central object and the protoplanetary disc. The icy grain mantles in the envelope are the formation sites for many different complex organic molecules, a process which is strongly affected by external effects such as heating and irradiation, both due to changes in reaction rates and due to the evaporation of key species from the ice mantles (see e.g. Herbst & van Dishoeck 2009). To understand these effects, we have studied the molecular composition of irradiated protostars, and find that also moderate external irradiation levels can create PDR-like chemistry in a protostellar envelope.

We have performed an unbiased line survey of all deeply embedded sources in the nearby Corona Australis star-forming region using the APEX telescope. Many of the sources are located near the $\sim 3M_\odot$ Herbig Be star R CrA, which elevates the irradiation field to $G_0 \sim 1000$ in the protostellar envelopes (Lindberg & Jørgensen 2012). It heats the gas on $\sim 10000$ AU scales to $\sim 30-50$ K (Lindberg et al., submitted).

Towards R CrA-IRS7B, the most thoroughly investigated object in our study, we find that the chemistry differs greatly from other well-studied deeply embedded protostars. We find low abundances of complex organic molecules such as CH$_3$OCH$_3$ and CH$_3$CN, but instead elevated abundances of the photo-dissociation product CN and small carbon-chain species like HC$_3$N and C$_2$H. We interpret the observed chemical properties as a result of thermal evaporation of CO from the grain mantles and photo-dissociation reactions in the IRS7B envelope, both initiated by the irradiation from the intermediate-mass protostar R CrA.

REFERENCES

Characterizing the infrared spectra of small, neutral, fully dehydrogenated PAHs

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We present the results of a computational study to investigate the infrared spectroscopic properties of a large number of polycyclic aromatic hydrocarbon (PAH) molecules and their fully dehydrogenated counterparts. We constructed a database of fully optimized geometries for PAHs that is complete for eight or fewer fused benzene rings, thus containing 1550 PAHs and 805 fully dehydrogenated aromatics. A large fraction of the species in our database have clearly non-planar or curved geometries. For each species, we determined the frequencies and intensities of their normal modes using density functional theory calculations. Whereas most PAH spectra are fairly similar, the spectra of fully dehydrogenated aromatics are much more diverse. Nevertheless, these fully dehydrogenated species show characteristic emission features at 5.2\textmu m, 5.5\textmu m and 10.6\textmu m; at longer wavelengths, there is a forest of emission features in the 16-30\textmu m range that appears as a structured continuum, but with a clear peak centered around 19\textmu m. We searched for these features in Spitzer-IRS spectra of various positions in the reflection nebula NGC 7023. We find a weak emission feature at 10.68\textmu m in all positions except that closest to the central star. We also find evidence for a weak 19\textmu m feature at all positions that is not likely due to C\textsubscript{60}. We interpret these features as tentative evidence for the presence of a small population of fully dehydrogenated PAHs.

REFERENCES

The physics and chemistry of photon-dominated clouds in NGC 3603

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High-mass star-formation in the interstellar medium is one of the main open questions in astronomy. Stars are born within molecular clouds due to the perturbations of local physical and chemical processes. To investigate these perturbations, we observed one of the most prominent HII region, NGC 3603, in our Galaxy. This molecular cloud complex embraces a massive open cluster, which provides strong stellar winds and radiation field. These phenomena heavily interact with the neighbouring environment and govern the local physics and chemistry.

To investigate the aforementioned effects and their influence, we received spectroscopy data of molecules, ions and atoms via Herschel Space Observatory (Pilbratt et al., 2010). In addition, measurements of the same species with ground-based telescopes were also used as complementary data.

The observational results showed that the observed molecular clouds have gas components with different temperatures as well as vigorous gas movements. Different theoretical models were used (KOSMA-\(\tau\), Röllig et al. (2006) and RADEX, van der Tak et al. (2007)) to fit the observational results. We found that the observed line intensities and abundances of given species match with the model predictions and the model results are independent from the cloud geometry.

All the results we obtain, give the opportunity to characterize the physical conditions and chemical processes within NGC 3603. Based on our observations and our model calculations, we concluded that the observed molecular clouds (or part of them) are probably in gravitationally unstable stage. Hence, the star-formation process within NGC 3603 is still ongoing. This scenario is in agreement with previous studies. It is also likely, that the observed clouds do not rotate as a rigid rotor but have a torsional geometry. On the other hand, due to observational facts (e.g., large beam size, distance of NGC 3603), we were only be able to make statements about the chemistry/chemical stratification within certain limits.

REFERENCES

Staging Experiments for Studying Cometary Pillars

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The pillars of creation are stunningly beautiful and physically puzzling molecular cloud structure in the Eagle nebula. Formation of these pillars has been subject of debate since their observation. Although extensive observation and modeling have attempted to answer the creation of the observed pillars, experiments have not adequately tested the theoretical models surrounding the photoevaporation of the molecular clouds. Experiments on the Omega EP laser at the Laboratory for Laser Energetics in Rochester NY, developed a 30ns x-ray drive using a multiple hohlraum array (Gatling gun approach) to drive the photoevaporation process and test pillar formation. This proof of principle experiment imaged the initial stages of a pillar using Ti area backlighter through a driven 50mg/cc R/F foam with an embedded solid density CH ball. This experimental technique is now being adapted for the National ignition Facility (NIF) and this presentation will cover the initial staging experiments on Omega EP and the recent results from the NIF.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
High-mass star formation triggered by collision between CO filaments in N159 West in the Large Magellanic Cloud


The Large Magellanic Cloud has been the subject of star formation studies for decades due to its proximity to the Milky Way (50 kpc), a nearly face-on orientation, and a metallicity (0.5 solar) similar to that of galaxies at the peak of star formation in the universe ($z \sim 2$) (Kaufman et al. 1999; Wolfire et al. 2010). N159, located south of the massive star formation region 30 Doradus, is the most intense molecular cloud as shown by the brightest 12CO (3-2) source in the LMC. Numerical simulations show turbulent gas becomes filamentary and dense cores are formed at the intersection of colliding filaments; this leads to triggered star formation. Our ALMA observations (PI: Fukui) cover a region of 20 pc x 25 pc at a spatial resolution of 0.2
We measure the molecular cloud complexes in 12CO (1-0), 13CO (1-0), 13CO (2-1), and CS (2-1) lines. We use ratios of the CO lines to constrain the physical conditions (T and n) of the molecular gas in the N159 photodissociation region. The high resolution of ALMA provides information of the physical structure of the photodissociation region for the first time. We see filamentary structures and, for the first time outside our galaxy, detect outflows of 10-20 km/s associated with young stellar objects (YSOs). Typical length of each filament we observe is 5-10 pc long and 0.5-1.0 pc wide. We compare the molecular gas distribution to the known YSO population in order to understand star formation. The conditions in the photodissociation region gives us information about the environment in which YSOs are born.

REFERENCES

EUV/FUV-driven photo-evaporation flows

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Spitzer, Herschel, and WISE have revealed that interstellar bubbles, cavities, and H$\text{\textsuperscript{II}}$ regions often show infrared dust arcs near the star. These arcs, which we term as dust waves, trace the effects of radiation pressure acting on the dust component of photo-evaporation flows. Dust waves provide a natural explanation for the long-standing problem on the presence of dust inside H$\text{\textsuperscript{II}}$ regions, and offer a new method to study interstellar dust.

We have performed a thorough analysis of the dust emission from the Orion IC 434 H$\text{\textsuperscript{II}}$ region. Dust in the ionized gas from the IC 434 is very much different from that observed in the diffuse ISM, and bears the marks of the molecular cloud phase from which they are ‘freshly’ evaporated by EUV radiation of $\alpha$ Ori AB. Coulomb interactions between gas and dust in the flow are less efficient than predicted by theory, and questions our understanding on grain charging. PAH emission is observed from within the ionized gas. Similar configurations, where photo-evaporation flows eventually culminate in infrared arc-like structures may be discerned within well-known reflection nebulae such as NGC 2023 and NGC 7023, revealing the importance of dynamics in both EUV- and FUV dominated regions.

Photo-evaporation flows and thermal conduction gradually erode molecular clouds and may limit their star formation efficiency. For the Orion Molecular Clouds, we have inferred a total evaporation rate of $10^{-2} \text{ M}_\odot \text{ yr}^{-1}$, a $3 \times 10^5 \text{ M}_\odot$ mass for the ‘proto-Orion’ cloud, and a cloud lifetime of 20 - 30 Myr (Ochsendorf et al. 2015, in press). The evaporation from the clouds fuels the expansion of the Orion-Eridanus superbubble. However, it is not clear what the relative contributions from EUV photons, FUV photons, and thermal conduction are to the evaporation rate of the molecular clouds. Stars of spectral type B2 and later are far more numerous compared to their ionizing siblings, and the resulting FUV field may induce large mass-losses from the OMCs. Large-scale mapping of PDRs and comparison with tracers of ionized gas may constrain the relative importance FUV irradiation in the evaporation of molecular clouds.

REFERENCES
Molecular Pillars in the Sky and in the Lab (part 1)

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A collaboration between astronomers at the University of Maryland and scientists at Lawrence Livermore National Laboratory has been investigating the origin and dynamics of the famous Pillars of the Eagle Nebula and similar structures at the boundaries of HII regions and molecular clouds. This approach has combined observations, theory, and radiative hydrodynamic simulations.

A long-term goal of this work is to field a High Energy Density Laboratory Astrophysics (HEDLA) experiment on the National Ignition Facility (NIF) which can recreate pillars in the lab with the astrophysically relevant scaling parameters. More immediately, we are creating a robust target that can produce a pillar, testing our new long-duration radiation source, and developing improved experimental diagnostics.

In this talk, I will review the theories of how molecular pillars may form, present results from recent CARMA observations of the pillars in Eagle and Pelican nebulae, and compare the data to results from numerical simulations. Finally, I will motivate the insights that a HEDLA experiment can provide in understanding the formation and dynamics of molecular pillars.

A follow-on talk by Jave Kane will present results of recent Eagle HEDLA experiments, and a related poster by David Martinez gives some detail on the experiment platform.
Characterizing the Molecular Interstellar Medium of Nearby Galaxies with Herschel, ALMA and SOFIA

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From Herschel observations of molecular gas in nearby galaxies, we find that high-excitation warm molecular gas, traced by high-J CO lines, is ubiquitous in star-forming galaxies and dominates the total CO luminosity and hence the energy budget (Rangwala et al. 2011, Kamenetzky et al. 2014). The pressure of the warm gas is about two orders of magnitude higher than the cold molecular gas, which dominates the total mass of the molecular gas. The heating source of this warm gas is still unclear. Comparison of the observed CO spectral line energy distributions and far-infrared luminosities to theoretical models indicates that the gas heating is dominated by some mechanism other than UV or X-ray photons (as in photon-dominated and X-ray dominated regions) or cosmic rays. Mechanical energy, from shocks generated by SNe and stellar winds, is the most plausible source of heating of the warm gas (e.g., Panuzzo et al. 2010, Rangwala et al. 2011, Kamenetzky et al. 2014, Meijerink et al. 2013, Greve et al. 2014, Rosenberg et al. 2014).

We will present results from our ongoing archival survey, which is systematically modeling CO rotational ladders for all the galaxies (∼300) observed by the SPIRE-FTS instrument on Herschel. This analysis is providing robust determinations of the physical conditions of the molecular gas, which are essential for understanding star-formation in galaxies and effects of feedback into the interstellar medium by star formation and AGN.

We will also present recent high-resolution observations of the highly-excited warm molecular gas in the nearby ULIRG, Arp 220, taken from the Atacama Large Millimeter Array (ALMA) (Rangwala et al. 2015). The exceptional sensitivity and spatial resolution of ALMA has allowed us to probe the detailed morphology and kinematics of the warm molecular gas associated with the two merging nuclei, which are in the final merger stage. We find strong evidence for foreground absorbing gas that is causing an apparent offset between the peak of the line and continuum emission. We also clearly detect highly redshifted CO absorption, a possible signature of an infalling molecular filament.

We will also briefly discuss our accepted Cycle-2 proposal SOFIA EXES, which will provide
the first direct comparison between the warm CO observed by Herschel/ALMA and warm $H_2$
observed by EXES.

REFERENCES

Probing the Cold Neutral Medium with Carbon Radio Recombination Lines

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The interstellar medium (ISM) plays a central role in the evolution of galaxies. The interplay of stars and their surrounding gas leads to the presence of distinct phases. Diffuse atomic clouds (the Cold Neutral Medium, CNM) where atomic hydrogen is largely neutral but carbon is singly ionized by photons with energy less than 13.6 eV, but larger than the ionization potential of carbon (11.2 eV). Watson, Western & Christensen (1980) and Walmsley & Watson (1982) showed that at low temperatures (\(\sim 100\) K) electrons can recombine via dielectronic recombination to high quantum levels (\(n \approx 1000\), Stepkin et al. 2007). Transitions between high quantum levels produce Carbon Radio Recombination Lines (CRRLs). These CRRLs have been observed in the interstellar medium of our Galaxy towards two types of clouds: diffuse clouds (e.g.: Roshi et al. 2002, Oonk et al. 2014) and photodissociation regions (PDRs), the boundaries of HII regions and their parent molecular clouds (e.g.: Natta et al. 1994, Quireza et al. 2006).

Here, we present new theoretical models of low frequency CRRLs (<350 MHz) under the physical conditions of cold diffuse clouds (Salgado et al. 2015a). We show that detailed modeling of the level population of carbon atoms (Salgado et al. 2015b) together with radiative transfer allow us to determine the temperature and density of the diffuse clouds from observations. Furthermore, combined observations of CRRLs with HI 21 cm can be used to constrain the carbon abundance and the cosmic ray ionization rate (Oonk et al. 2015).

In the coming years, we will use the Low Frequency Array (LOFAR) to carry out a full northern hemisphere survey of CRRL emitting clouds in the Milky Way. Observations and models will allow us to study the thermal balance, chemical enrichment and ionization rate of the cold neutral medium from degree-scales down to scales corresponding to individual clouds and filaments in our Galaxy. Furthermore, following the first detection of low-frequency CRRLs in an extragalactic source (i.e. M82; Morabito et al. 2014) we will also use LOFAR to perform the first flux limited survey of CRRLs in extragalactic sources. As new observations are performed, detailed modeling is necessary to determine the physical properties of the clouds. Low frequency CRRLs provide a unique window on the ISM and allow us to study diffuse clouds with new tools.

REFERENCES

Salgado, F., et al. (2015a) in preparation
Salgado, F., et al. (2015a) in preparation
We report detections of new correlations between the 15-20 µm emission bands of poly-cyclic aromatic hydrocarbons (PAHs). These molecules lie on the small end of the dust grain size distribution and are very abundant, containing up to 15-20% of the cosmic carbon. PAHs are present in PDRs and play key roles in chemical and physical processes, such as charge exchange reactions and gas heating through photoelectric ejection. We observe PAH emission bands at 15.8, 16.4, 17.4 and 17.8 µm in a variety of PDR environments, including HII regions, reflection nebulae, planetary nebulae and the interstellar medium of galaxies. Correlations between band intensities are detected, which we interpret in terms of molecular charge and structure with the aid of spatial maps. We find the 15.8 µm band is consistent with neutral molecules, the 17.4 µm band with cations, and the 16.4 and 17.8 µm bands a combination of the two. Radial cuts in the maps show that the spatial profiles of the 12.7, 16.4 and 17.8 µm bands can be reconstructed by summing the 11.2 µm (neutral) and 11.0 µm (cationic) bands. These results highlight the importance of ionization state in driving emission variability.
The mid-infrared appearance of the Galactic Mini-Starburst W49A

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The massive star forming region W49A represents one of the largest complexes of massive star formation present in the Milky Way and contains at least fifty young massive stars and their PDRs which are still enshrouded in their natal molecular cloud. We employ Spitzer/IRS spectral mapping observations of the northern part of W49A to investigate the mid-infrared (MIR) spatial appearance of the polycyclic aromatic hydrocarbon (PAH) bands, PAH plateau features, atomic lines and continuum emission. We examine the spatial variations of the MIR emission components in slices through two of the ultra compact-H II (UC-H II) regions. We find that the PAH bands reproduce known trends, with the caveat that the 6.2 µm PAH band seems to decouple from the other ionized PAH bands in some of the UC-H II regions – an effect previously observed only in one other object: the giant star forming region N66 in the LMC. Additionally, we examine the MIR appearance of star formation on various scales from UC-H II regions to starburst galaxies, including a discussion of the fraction of PAH emission in the 8 µm IRAC filter. We find that the MIR appearance of W49A is that of a starburst on large scales yet its individual components are consistent with other galactic H II regions.
Velocity-resolved large scale mapping of the ionized and warm neutral gas in OMC 1


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We present a large scale mapping (~7.5′×11.5′) of OMC 1 taken in the framework of an Open Time Project (P.I. J. Goicoechea) using the Herschel/HIFI instrument. Velocity-resolved (~0.2 km s⁻¹) maps of various tracers of the ionized and warm neutral gas ([C ii], CO J=10-9 and J=8-7, HCN J=6-5, HCO⁺ J=6-5 and CH⁺ J=1-0) offer an unprecedented view of the intricate small-scale kinematics of the ionized/PDR/molecular gas and of the radiative feedback from massive stars. We show that the main contribution (~85 %) to [C ii] is from dense PDRs at the interface between OMC 1 and the H II blister created by the Trapezium cluster. Around ~15 % of the [C ii] luminosity arises from gas without CO counterpart. We also study the physico-chemical properties of the gas and analyze the kinematics of the various tracers in the distinct environments probed over the map. In particular, channel maps of the [C ii] reveal blue-shifted filamentary structures that likely stem from the neutral cloud. Others can be associated with foreground H I absorption components in the Orion’s Veil.
A Zero Energy Scaling Technique for Predicting Collisional Rate Coefficients

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Collisional excitation rate coefficients of carbon monoxide due to light colliders such as H, H\textsubscript{2}, He, and electrons are necessary to produce accurate models of many astrophysical environments. CO is easily collisionally excited to high rotational levels in moderately energetic environments, but in these regions it is not appropriate to assume a thermal population of levels. Therefore, in order to model the non-thermal gas, collisional rate coefficients must be provided. The calculation of inelastic collisional rate coefficients for CO has been the focus of many studies (e.g. Yang et al. 2006, Yang et al. 2013). However, where explicit calculations have not been performed, a common approach is to estimate unknown values from known rate coefficients, such as in reduced potential scaling (Walker et al. 2014). Here we present a zero energy scaling technique for predicting inelastic collisional rate coefficients of rotationally excited CO\((v = 0, j)\) in collisions with H. Our predicted state-to-state rates are compared with explicit quantum scattering calculations for temperatures below 3000 K, and when combined, these data form an extensive set of collisional excitation rate coefficients for the H-CO system.

REFERENCES

Role of GMC Collisions in Dense Filament, Clump, and Star Formation

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We utilize magnetohydrodynamic (MHD) simulations with adaptive mesh refinement (AMR) to explore the process of GMC-GMC collisions as a potential trigger for dense filament, clump, and star formation. We implement new PDR-based density/temperature/extinction-dependent heating and cooling functions in Enzo that span the atomic to molecular transition and can return detailed diagnostic information. We initially perform a parameter space study via a suite of idealized 2D simulations for GMC-GMC collisions, which track the fate of an initially stable clump embedded within one of the clouds. We then extend these calculations to 3D, including introduction of initial turbulence into the clouds. Different turbulent spectra types, magnetic field strengths and orientations are considered, as is the role of cloud collisions. The density and kinematic structure are visualized and characterized, in addition to magnetic field configuration. We discuss observational diagnostics of cloud collisions, focusing on 13CO(J=2-1), 13CO(J=3-2), and 12CO(J=8-7) integrated intensity maps and spectra, which we synthesize from our simulation outputs. We find the ratio of J=8-7 to lower-J emission is a powerful diagnostic probe of GMC collisions.

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