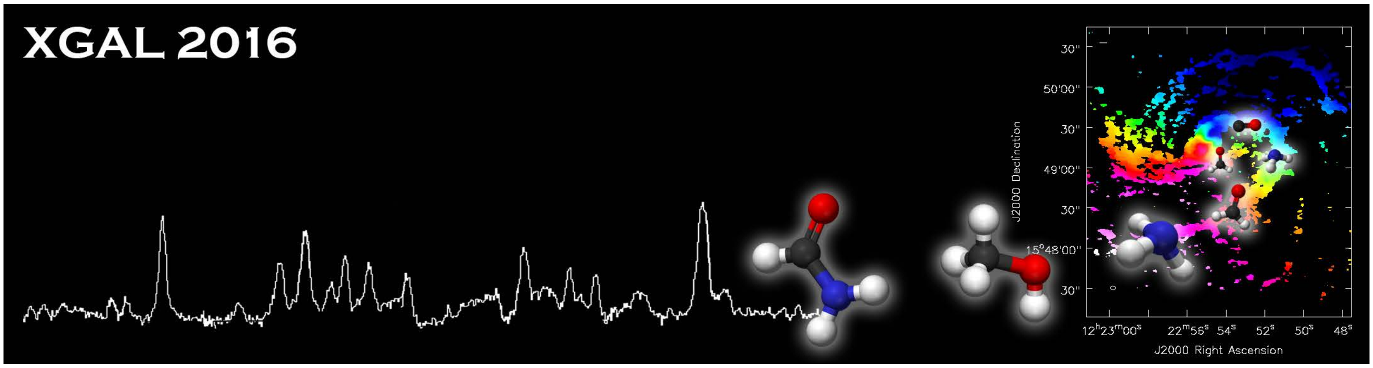

Molecular Gas in Galactic Environments Abstracts

Charlottesville, Virginia, USA
April 4-7, 2016

Monday, April 4, 2016		
Session A: Modeling I		
Gergö Popping	Sub-mm Emission in Cosmological Simulations: Theoretical Challenges and Predictions	Invited
Rebeca Aladro	Chemical Characterisation of Nearby Active Galaxies	Contributed
Johan Lindberg	Evidence for a Chemically Differentiated Outflow in the Quasar Mrk 231	Contributed
Session B: Modeling II		
Nanase Harada	Chemical Models of the Circumnuclear Disk around an Active Galactic Nucleus	Invited
Eric Herbst	Gas and Grain Chemistry in the Small Magellanic Cloud	Contributed
Tyler Pauly	Models of Interstellar Ice Formation in the Large Magellanic Cloud	Contributed
Session C: Nearby Galaxies I		
Angus Mok	Resolved Analysis of the ISM and Star Formation Properties of Spiral Galaxies in Different Environments	Contributed
Min-Young Lee	A High-Resolution Study on the Radiative and Mechanical Feedback into the Warm Molecular Gas in the LMC Star-Forming Region N159W	Contributed
Takashi Shimonishi	ALMA Observations of a Hot Molecular Core in the Large Magellanic Cloud	Contributed
Natalie Butterfield	High Resolution Observations of Regions of Massive Star Formation in the Galactic Center: Molecular and Ionized Gas in the Radio Arc and G0.10-0.08	Contributed
Frank Bigiel	The EMPIRE Survey – Dense Gas and Star Formation Across Nearby	Contributed
Session D: Nearby Galaxies II		
Adam Leroy	Molecular Gas in High Detail in Nearby Galaxies	Invited
Julia Kamenetzky	Warm and Cold Molecular Gas Conditions of Galaxies Observed by the Herschel FTS	Contributed
Mark Gorski	Extragalactic Ecology of Star Forming Galaxies with SWAM: The Starburst Anatomy of NGC253	Contributed

Gergo Popping (ESO - Garching)

Sub-mm Emission in Cosmological Simulations: Theoretical Challenges and Predictions

The newest generation of radio- and sub-mm instruments open up a new molecular window on the formation and evolution of galaxies. The observations expected from these facilities present a new and stringent challenge to theoretical models of galaxy formation. In this talk I will discuss my efforts to model the sub-mm line emission of galaxies at different redshifts and environments and how this sheds light on our understanding of ISM physics and galaxy formation. To do so I use semi-analytic and hydrodynamic models of galaxy formation and couple these with PDR chemistry and radiative transfer codes. I will first discuss how to overcome some of the sub-grid challenges when introducing small scale ISM physics within cosmological simulations. I will then discuss predictions made by my models, including scaling relations for CO and [CII], CO SLEDs of galaxies over cosmic time, and predictions for CO and [CII] deep fields. I will compare these predictions to observational samples and demonstrate how the combination of sub-mm predictions and observations can help to reveal caveats in our understanding of galaxy formation.

Rebeca Aladro (ESO Chalmers University)

S Martin (ESO ALMA)
D Riquelme (Max-Planck-Institut für Radioastronomie)
C Henkel (Max-Planck-Institut für Radioastronomie Astron Dept King Abdu)
R Mauersberger (ESO)
J Martin-Pintado (CSIC-INTA)

Chemical Characterisation of Nearby Active Galaxies

I will present a 3mm survey of eight nearby galaxies done with the IRAM 30m telescope, which includes starbursts in different stages of evolution, Seyfert 1 and 2 AGN types, and nearby ULIRGs (starburst + AGN activities). A comparison of 27 molecules and 10 isotopologues allows the chemical differentiation of active nucleus types. I will discuss the key species that characterise each galaxy/type of galaxy, as well the differences among them. This aims to provide useful chemical templates to further study similar objects at high resolution with interferometers such as ALMA or NOEMA.

Johan Lindberg (NASA Goddard Space Flight Center)

Aalto
Muller
Mart -Vidal
Falstad
Costagliola

Evidence for a Chemically Differentiated Outflow in the Quasar Mrk 231

We report high-resolution (0."3-2") interferometric IRAM Plateau de Bure Interferometer observations of HCN, HCO+, and HNC emission in the high-velocity molecular outflow of he nearby quasar Mrk 231. We find that the three species have distinct, and differing, velocity structure consistent with chemical differentiation in the outflow. The most significant clump of each species appears in the same order in the red and the blue outflow (HCO+ at 600 and -450 km/s); (HCN at 500 and -400 km/s); (HNC at 350 km/s and -340 km/s). As the outflow appears to slow down with increasing radius, it suggests that the HCO+ gas is enhanced close to the nucleus and HNC farthest out in the outflow. A possible interpretation is that HCN emission is tracing the recently ejected gas which is interacting with the surrounding gas in a shock, HNC is primarily found in the slower post-shock gas, while HCO+ is found in faster gas closer to the nucleus before the shock. It is interesting to note that (again under the assumption of a decelerating outflow) the HCO+ enhancement is closest to the AGN - in contrast to more common interpretations of the HCN/HCO+ line ratio. In other outflows HCN-enhancements have been found (e.g. M51, NGC1068) and the enhancement is attributed to the interaction with a radio jet. If jet interaction occurs in Mrk231 and is causing the HCN-peak - it appears to happen a distance away from the nucleus.

Chemical structure is common in Galactic outflows - mainly from protostars. But this is the first time chemical differentiation between HCN, HNC, HCO+ is seen in an extragalactic molecular outflow. Our result shows that studies of the chemistry in large-scale galactic outflows can be used to better understand the physical properties of such outflows and their effects on the interstellar medium in the galaxy.

Nanase Harada (ASIAA)

Todd Thompson (Ohio State)
Eric Herbst (University of Virginia)

Chemical Model of the Circumnuclear Disk around an Active Galactic Nucleus

Chemical compositions can be affected by the strong irradiation of X-rays from an active galactic nuclei. To investigate how much of the gas is affected by the X-ray dominated regions (XDRs) and what are the chemical abundances of different molecular tracers, we calculate the chemical abundances in these regions. We use an axisymmetric accretion disk model around an AGN using a simplified physical model in 1+1 dimension while irradiating X-rays from the central region. Chemical abundances and temperatures are calculated using a chemical network including high-temperature gas-phase reactions.

Our results show that the X-ray irradiated surface shows the enhancement of radicals such as CN and ionic species such as OH^+ and H_3O^+. At the same time, there is a significant amount of gas in the midplane shielded from X-rays. In this shielded region, species such as HC_3N can be enhanced. These results are compared with ALMA observations of NGC 1068. I also briefly talk about effects of other factors on the chemistry such as shocks and dust temperatures.

Eric Herbst (Unversity of Virginia)

Kinsuk Acharyya (University of Virginia)

Gas and Grain Chemistry in the Small Magellanic Cloud

We report a new study of the gas-grain chemistry of dense regions in the Small Magellanic Cloud. The chemistry in the SMC is influenced by the low metallicity and the surprisingly high temperature of dust particles. We are able to explain the gas-phase molecular abundances seen in the dense sources N27 and LIRS reasonably well. Our calculated abundances of molecules in interstellar ice mantles can be compared with limited observations of material in front of young stellar objects.

Tyler Pauly (Cornell University)

Robin Garrod (University of Virginia)

Models of Interstellar Ice Formation in the Large Magellanic Cloud

Observations of the dense interstellar medium in the Large Magellanic Cloud (LMC) show chemical variation with respect to galactic star-forming regions. We have collated mid-infrared spectra for fifteen young stellar objects in the LMC and present new optimally-extracted spectra from Spitzer IRS for nine of the fifteen sources. These spectra provide detections or upper limits for solid state water, CO, CO_2 and CH_3OH. We compare these solid-state absorption features to our state-of-the-art gas-grain chemical model, implementing a grain-size distribution and a grain temperature distribution. Measurements of the LMC radiation field are used to define an LMC-specific grain temperature treatment. The preliminary results of our models indicate a simple explanation for the as-yet unsolved problem of the shortfall in solid-phase CO abundance in the LMC as compared with galactic values.

Angus Mok (McMaster University)

Christine Wilson (McMaster University)

Resolved Analysis of the ISM and Star Formation Properties of Spiral Galaxies in Different Environments

Using a sample of gas-rich spiral galaxies from the Nearby Galaxies Legacy Survey (NGLS), we explore the effects of environment on their distribution of atomic gas, molecular gas, and star formation. We combine CO(3-2) data from the JCMT with new VLA 21 cm observations and archival VLA data to determine radial trends in both their molecular and atomic gas surface densities and the H2 to HI ratios. For Virgo galaxies, the average size of their molecular gas disk is larger than that of the galaxies in less dense environments, such as in groups. With complementary H measurements, we can also perform resolved measurements of their star formation efficiencies and the corresponding gas depletion times.

Min-Young Lee (CEA-Saclay France)

Suzanne Madden (CEA-Saclay France)
Vianney Lebouteiller (CEA-Saclay France)
Antoine Gusdorf (LERMA Observatoire de Paris France)
Benjamin Godard (LERMA Observatoire de Paris France)
Ronin Wu (University of Tokyo Japan)

A High-resolution Study on the Radiative and Mechanical Feedback into the Warm Molecular Gas in the LMC Star-forming Region N159W

By virtue of a wide range of critical densities, CO rotational lines are powerful diagnostic tools to probe the physical conditions of molecular gas in diverse environments (kinetic temperature Tk 10-1000 K and hydrogen density n $10^3 - 10^8 cm^{-3}$). In the past several years, Herschel spectroscopic observations have been combined with ground-based telescope data to extensively examine CO spectral line energy distributions (SLEDs) of various Galactic and extragalactic sources, revealing the ubiquitous presence of warm molecular gas (Tk > 100 K). While a range of excitation sources, e.g., UV photons, X-rays, cosmic-rays, and mechanical heating, have been invoked to reproduce the properties of this warm molecular gas, most of the previous studies lack proper spatial resolution, as well as important complementary data (e.g., tracers of UV-dominated photodissociation regions (PDRs) and characteristics of X-ray sources), to probe relative contributions from various energy sources and their spatial variations.

In this contribution, we present our high-resolution study (7 pc scales) on the physical properties and excitation mechanisms of warm molecular gas in N159W (Lee et al. submitted), a region of particular interest in the LMC due to the presence of active star formation, shocks, and a strong X-ray source. CO observations obtained with the Herschel SPIRE FTS and ground-based telescopes (from J = 1 to 13) are analyzed with a non-LTE radiative transfer code, showing that the CO-emitting gas is very warm (400 K) and moderately dense (10^3 cm^{-3}). To examine the origin of this warm molecular gas, we then compare the CO observations with state-of-the-art PDR and shock models ("Meudon PDR" and "Paris-Durham shock" codes). We first constrain the properties of PDRs by modeling Herschel observations of [OI] 145 micron, [CII] 158 micron, and [CI] 370 micron fine-structure lines and find that the constrained PDR component emits very weak CO emission. X-rays and cosmic-rays are also found to provide a negligible contribution to CO emission, essentially ruling out ionizing sources as the dominant heating source for CO. On the other hand, mechanical heating by low-velocity C-type shocks with 10 km/s appears sufficient to reproduce the observed warm CO across the entire N159W region. Several sources are considered as possible shock drivers and large-scale processes involving powerful stellar winds/supernova explosions and Milky-Way-Magellanic Clouds interactions are found to be the primary energy source.

Our work supports the emerging picture that mechanical heating plays an important role in the excitation of molecular gas. In the future, systematic studies of various atomic and molecular species at high spatial and spectral resolutions will be crucial to probe the drivers of mechanical heating and the detailed processes of energy dissipation in the ISM, which will be possible particularly with ALMA and JWST.

Takashi Shimonishi (Tohoku University)

Takashi Onaka (The University of Tokyo)
Akiko Kawamura (NAOJ)
Yuri Aikawa (Tsukuba University)

ALMA Observations of a Hot Molecular Core in the Large Magellanic Cloud

Observations of chemically-rich objects such as hot molecular cores in nearby low metallicity galaxies play a crucial role for understanding of chemical complexity in the past metal-poor universe. However, observations of hot cores have been so far limited to Galactic sources due to lack of spatial resolution and sensitivity of radio telescopes. The Large Magellanic Cloud (LMC), the nearest metal-poor star-forming galaxy, is an excellent target to investigate chemical processes in low metallicity environments. We here report the detection of a hot core outside our Galaxy based on interferometric observations towards a high-mass young stellar object (YSO) in the LMC with ALMA. We detected multiple high excitation lines of SO_2 and its isotopomers from a compact region ($\sim$0.1 pc) associated with a high-mass YSO. We also detected other molecular species including CO, HCO^+, H_2CO, NO, SiO, SO, and H_2CS. The gas temperature is estimated to be higher than 100 K based on rotational diagram analysis of SO_2 lines. The compact size of the emitting source, warm gas temperature, and rich molecular lines suggest that ST11 is associated with a hot molecular core. Most of the detected molecules show the lower abundances compared to Galactic hot cores mainly due to the low metallicity of the LMC. CH_3OH lines, which are common in Galactic hot cores, were not detected although the gas temperature is warm enough for the sublimation of ice mantles. We found that chemical compositions of the observed source are well characterized by the deficiency of molecules which require the hydrogenation of CO on grain surfaces for the formation. On the other hand, it is interesting that NO shows the higher abundance in the LMC than in our Galaxy despite the low nitrogen abundance in the LMC. In this presentation, we discuss the characteristics of warm and dense gas around a high-mass YSO in low metallicity environments.

Natalie Butterfield (University of Iowa)

Cornelia Lang (University of Iowa)
Dominic Ludovici (University of Iowa)
Betsy Mills (NRAO)

High Resolution Observations of Regions of Massive Star Formation in the Galactic Center: Molecular and Ionized Gas in the Radio Arc and G0.10-0.08

The central 200 parsecs of the galaxy provides a unique laboratory to study the effects of extreme physical conditions (e.g., strong tidal forces, high energy cosmic rays, well organized magnetic field) on properties of molecular clouds and ultimately, to study how these clouds may undergo massive star formation. We will discuss the interplay between the interstellar and stellar components in two regions that represent different evolutionary stages of star formation: (1) The Radio Arc region represents an evolved region of massive star formation and (2) the dense and compact molecular cloud G0.10-0.08. We have used the new high frequency and broadband capabilities of the upgraded Very Large Array, to make high angular resolution (2) observations in both deep continuum and spectral lines at 24-25 GHz (K band) and 27 & 36 GHz (Ka band). We are able to observe more than 12 different spectral line transitions, including: tracers of dense molecular gas (NH3, HC3N), tracers of ionized gas (RRL), and a methanol maser line. In the Radio Arc region we have observed complex kinematic motions and arrangement of both the ionized and molecular gas. Molecular properties of G0.10-0.08 suggest that this compact molecular cloud shows similarities to the dense M0.25+0.01 (Brick) cloud, with no evidence of current star formation. In both regions we detect abundant Class I (collisionally excited) compact methanol sources. By comparing the brightness and distribution of these methanol sources in different evolutionary stages of star formation can give insight on the mechanism for excitation.

Frank Bigiel (ZAH Univ of Heidelberg)

The EMPIRE Survey - Dense Gas and Star Formation across Nearby Galaxy Disks

I will present first results from EMPIRE, a large program (500 hr) with the EMIR receiver at the IRAM 30m telescope to map high critical density gas and shock tracers (e.g., HCN, HCO+, HNC, N2H+, C2H) as well as the optically thin 1-0 lines of 13CO and C18O for the first time systematically across the disks of 9 prominent, nearby (distances of a few Mpc) spiral galaxies. Building on a large suite of available ancillary data from the radio to the UV, we are able to study, among other things, dense gas fractions and star formation efficiencies and how they vary with local conditions within and among nearby disk galaxies. I will focus on our recent study of M51, where we find substantial variation of both, dense gas fraction and star formation efficiency across its disk, with the surprising sense of a decreasing dense gas star formation efficiency towards smaller radi. I will place these results in context with other work, including our previous study of dense gas and star formation in the Antennae galaxies, earlier studies of dense gas tracers in other galaxies and the Milky Way, and present details of the EMPIRE survey and report on additional ongoing projects and future directions in our survey.

Adam Leroy (Ohio State University)

Molecular Gas in High Detail in Nearby Galaxies

I will show how new high physical resolution mapping and sensitive spectroscopy reveal a strong dependence of the physical state of the ISM on local environment in nearby galaxies. From ALMA, the PdBI, and CARMA imaging, we see a strong dependence of the cloud scale surface density, turbulent line width, and apparent gravitational boundedness on environment. New, sensitive spectroscopy of faint high dipole moment lines (HCN, HCO+, HNC, CS) across large areas also reveals strong, physically driven dependences of gas density on environment. I will highlight likely underlying physical drivers for these variations and also describe new, simple but powerful methods to access the cloud-scale state of the ISM and approach the underlying density distribution from line ratio patterns. Finally, I will discuss how these changing physical conditions affect the ability of the gas to form stars.

Julia Kamenetzky (University of Arizona)

Jason Glenn (University of Colorado)
Naseem Rangwala (NASA Ames Research Center)

Warm and Cold Molecular Gas Conditions of Galaxies Observed by the Herschel FTS

We follow-up on a catalog of CO J=4-3 to J=13-12, [CI], and [NII] 205 micron line fluxes in 200 galaxies observed with the Herschel FTS by modeling the physical conditions of the warm and cold CO gas. This catalog is a window into the warm molecular gas traced by mid- to high-J CO lines, blocked by the atmosphere but revealed with Herschel. Such gas offers a window into the feedback interactions among molecular gas, star formation, and galaxy evolution, including the important role of mechanical heating. We will present a statistical view of the molecular gas conditions (temperature, density, pressure, mass) that can be ascertained from two-component modeling of galaxy-integrated CO SLEDs among a variety of galaxy types. ALMA studies of individual galaxies can offer more information on gas morphology and excitation gradients, but with fewer CO lines than were visible with Herschel.

Mark Gorski (NRAO University of New Mexico)

Juergen Ott (NRAO)
David Meier (NMT NRAO)
Emmanuel Momjian Emmanuel Momjian (NRAO)
Richard Rand (UNM)
Fabian Walter (MPIA)

Extragalactic Ecology of Star Forming Galaxies with SWAN: The Starburst Anatomy of NGC253

Energetic processes in galaxies (outflows from massive stars and AGN, density waves, mergers, etc.) largely control the evolution and star formation capabilities of a galaxy. A major limitation in our understanding of galaxy evolution is a physical description of feedback and thermodynamic evolution of gas. It is thus vital to understand the interplay between those processes and the dense gas reservoirs where stars ultimately form. We present results from the Survey of Water and Ammonia in Nearby galaxies (SWAN). In this program, we have observed a range of molecular tracers in four nearby star forming galaxies (NGC253, IC342, NGC6946, and NGC2146) using the VLA K and Ka band receivers. Our measurements reveal the structure, kinematics, temperature, densities, and pressures of the molecular ISM. Analysis of the metastable ammonia lines reveals a relatively uniform 140K temperature across the central kpc of NGC253. Furthermore, the ammonia (3,3) line appears to be masing in the centermost 200pc. Water masers are largely concentrated in the central 100pc and extended along the minor axis. The velocities and morphologies of the water masers suggest a relation with the starburst driven outflow or other strong shocks in the nuclear disk of NGC253. Methanol is tracing shocks located 500pc away from the nuclear starburst possibly driven by expanding super bubbles. These locations also form the footprint of extended CO outflows as observed with ALMA. The maser locations also agree with ALMA detections of HNCO, which is a more widespread, thermal tracer for shocks in the ISM. The combination of VLA and ALMA data thus provides unprecedented tools for a deep analysis of the physical parameters within galaxy cores that control their star formation efficiencies.

Tuesday, April 5, 2016		
Session E: Isotopes		
Christian Henkel	Nucleosynthesis and Molecular Isotope Ratios in Extragalactic Systems	Invited
Yixian Cao	Spatially Resolved $^{13}CO(1\text{-}0)$ in Spiral Galaxies from the CARMA Survey Toward Infrared-bright Nearby Galaxies (STING)	Contributed
Maria J Jiminez-Donaire	Analysing Optically Thin Isotopologues of Dense Gas Tracers in EMPIRE	Contributed
Session F: Overluminous HCN		
Sergio Martin	The Unbearable Opaqueness of Obscured Nuclei	Invited
Elisabeth Mills	HCN 1-0 is Not a Linear Tracer of Dense Gas Mass in the Galactic Center	Contributed
Masatoshi Imanishi	ALMA Molecular Gas Observations of Luminous Infrared Galaxies as a Tool to Scrutinize Elusive Deeply-Buried AGNs	Contributed
Kotaro Kohno	Ten Parsec Scale View of Dense Molecular Medium in the Active Nucleus of NGC 1097	Contributed
Francesco Costaglio	The Molecular Complexity of Galaxies: Opportunities and New Challenges in the ALMA Era	Invited

Christian Johann Henkel (MPIfR)

Nucleosynthesis and Molecular Isotope Ratios in Extragalactic Systems

Nucleosynthesis, the creation of elements heavier than hydrogen, started in the dense hot medium soon after the big bang and is an ongoing process up to the present time. The resulting changes in abundances caused by energetic nuclear reactions, the so-called chemical evolution, is a measure of the gradual enrichment of heavy elements and thus serves as an indispensable tool to assess the past, present and future of the universe.

At optical, near-infrared, and ultraviolet wavelengths it is difficult to discriminate between an elementś various isotopes. The prospects are much better when considering molecules, which can be observed at radio, mm-, and submm-wavelengths. Lines of different isotopologues of a given molecule are, with the exception of hydrogen, separated by only a small fraction of their rest frequencies. With the recent development of broadband spectrometers and the high sensitivity of ALMA and NOEMA we now possess the proper tools to explore isotope ratios outside the Milky Way in a systematic way. Here, molecular data from extragalactic sources, including carbon (C), nitrogen (N), oxygen (O), silicon (Si), and sulfur (S), are summarized and complemented (whenever possible) by interpretation, providing the basis for a so far almost unexplored new field of research.

Yixian Cao (University of Illinois)

Tony Wong (University of Illinois)
Rui Xue (Purdue University)
Alberto Bolatto (University of Maryland)
Leo Blitz (University of California Berkeley)
Stuart Vogel (University of Maryland)

Spatially Resolved 13CO(1-0) in Spiral Galaxies from the CARMA Survey Toward Infrared-bright Nearby Galaxies (STING)

We present a ^{13}CO$(1-0)$ mapping survey of 11 nearby galaxies from the CARMA STING sample. The line ratio between ^{12}CO$(1-0)$ and ^{13}CO$(1-0)$, $\mathcal{R} \equiv I[^{12}\mathrm{CO}(1-0)]/\mathrm{I}[^{13}\mathrm{CO}(1-0)]$, is derived to study its dependence on environmental properties. We find no strong dependence of mean values of $\mathcal{R}$ on global galaxy properties such as dust temperature, inclination or metallicity in our sample. The kilosparsec-resolution images show spatial variations in $\mathcal{R}$ up to a factor of 3. Lower values of resolved $\mathcal{R}$ are usually found in regions with weaker ^{12}CO emission. However, stacking ^{13}CO intensities below the detection threshold in regions with weak ^{12}CO emission results in similar average $\mathcal{R}$ to those regions with brighter ^{12}CO, suggesting the apparent increase of $\mathcal{R}$ with ^{12}CO intensity is due to a sensitivity bias in regions of low ^{12}CO. Limiting our analysis to the regions less affected by the sensitivity bias, we find no clear evidence that $\mathcal{R}$ values on kilosparsec scales depend on the velocity dispersion of the gas or the star formation rate surface density. There is also no general radial gradient in $\mathcal{R}$ for our sample. We discuss the interpretation of our results and the prospects for future observations with the GBT and ALMA.

Maria J Jimenez-Donaire (ITA-ZAH Heidelberg)

EMPIRE collaboration

Analysing Optically Thin Isotopologues of Dense Gas Tracers in EMPIRE

Spectroscopic tracers of dense gas offer our best way to study immediately star-forming gas, but their optical depth remains a major unknown. I will present the first results of our on-going IRAM 30m large program EMPIRE and ancillary ALMA data, where we map dense gas tracers (in particular HCN, HCO^+, HNC) and their ^{13}C isotopologues in the disks of several nearby galaxies. We have obtained complete maps of those galaxies and studied the optical depth and fraction of the dense gas. We find that the very dense gas emission comes mostly from the very central parts of the galaxies: the HCN and HCO^+ emissions are the brightest among our tracers, the HCN being more compact and significantly brighter than HCO^+. The ratios of these lines with their optically thin ^{13}C isotopologues (detected in stacked spectra) depend on the galaxy considered and show the largest variations in the centers and spiral arms within one galaxy. We derived optical depths for the dense gas tracers and used these to derive column densities and dense gas masses. I will present these results and also discuss the line shapes of the stacked spectra of our dense gas tracers across our galaxies. Some of these line profiles show a notable broadening, likely related to the presence of an AGN in their center.

Sergio Martin (Joint ALMA Observatory - European Southern Observatory)

The Unbearable Opaqueness of Compact Obscured Nuclei

Probing the inners regions behind the optically thick dust layer of heavily obscured LIRGs and ULIRGs are a major observational challenge. The obscuration of Av>1000 mag prevent the direct observation at all wavelenghts. Understanding the nuclear engines of these galaxies may be key for a complete AGN and starburst census as well as understanding nuclear growth and feedback mechanisms. Molecular observations has been usually exploited as a way to circunvent obscuration, however this might not be a valid approach towards this objects. The prototypical ULIRG Arp 220, usual suspect and closest example of CON, has been the target of multiple ALMA observations showing that obscuration and absorption (both self-absorption and continuum absorption) may actually be preventing direct observation of the nuclear few tenths of parsercs even with high density molecular probes. Molecular transitions in particular excitation conditions might be the answer to peer into these objects. That is the case of the vibrationally excited transitions of dense molecular tracers such as HCN and HC3N. Here i will summarize the latest observational results towards Arp 220 which illustrates the observational difficulties inherent to such obscured nuclei. I will also present the recent results on vibrationally excited emission in (U)LIRGs which have gain relevance during the last few years.

Elisabeth Mills (University of Arizona)

HCN 1-0 is Not a Linear Tracer of Dense Gas Mass in the Galactic Center

I present an investigation of the correlation of HCN 1-0 with dense gas mass in the Galactic center, inspired by the use of HCN 1-0 as a proxy for the amount of dense gas in extragalactic systems. I find that in the extreme environment of the Galactic center, on size scales up to those of individual giant molecular clouds, the HCN 1-0 luminosity is not correlated with the dense gas mass as measured from a Herschel column density map. The core of the massive cloud Sgr B2 with 10% of the total molecular gas mass in the Galactic center has less HCN 1-0 emission than clouds up to five times less massive due to self-absorption in this line, while several other clouds show an enhancement of HCN 1-0 by a factor of 2-3 relative to clouds of comparable mass. Although I do not perform a detailed comparison of infrared luminosity and HCN 1-0 luminosity, I find that HCN 1-0 enhancements are not solely seen toward regions of strong infrared emission, and suggest instead that sh! ock chemistry may be the primary driver of enhanced HCN 1-0 emission. I also investigate other tracers having transitions near 3 mm, finding that HNC and HCO+ largely behave like HCN, while HC3N and CH3CN are higher fidelity tracers of the amount of gas in denser clouds like Sgr B2. As HCN 1-0 appears to be both over- and under-luminous in Galactic center clouds, future work is necessary to assess the fidelity of HCN 1-0 as a tracer of gas mass in extreme environments and to determine which effect dominates in systems such as ULIRGs and high-redshift galaxies.

Masatoshi Imanishi (Subaru Telescope)

Kouichiro Nakanishi
Takuma Izumi
Kazushi Sakamoto

ALMA Molecular Gas Observations of Luminous Infrared Galaxies as a Tool to Scrutinize Elusive Deeply Buried AGNs

We present the results of our ALMA Cycles 0, 1, 2 observations of dusty luminous infrared galaxies (LIRGs) using dense gas tracers, HCN, HCO+, and HNC, at J=4-3 and 3-2. We selected targets with different levels of AGNś bolometric contributions estimated from infrared spectroscopic energy diagnostic methods. We aim to establish a reliable method to scrutinize elusive, deeply buried AGNs in the dusty LIRG population, based on molecular line flux ratios, at the dust-extinction-free (sub)millimeter wavelength range. We confirmed a trend that LIRGs with infrared-identified AGNs show higher HCN-to-HCO+ flux ratios at J=3-2 and J=4-3, than starburst-dominated LIRGs. Two LIRGs without infrared-identified AGNs show high observed HCN-to-HCO+ flux ratios. We detected vibrationally-excited (v2=1f) HCN J=3-2 emission lines in both of the two, suggesting the presence of luminous infrared 14 micron continuum emitting energy sources (=AGNs) to vibrationally excite to the v2=1f level by infrared radiative pumping. These LIRGs may contain extremely deeply buried AGNs which are still elusive in the infrared energy diagnostic methods, but are first detected at (sub)millimeter wavelength range, due to even lower dust extinction effects. In one AGN-hosting LIRG with small molecular line widths, we clearly detected v2=1f HCN and HNC J=3-2 emission lines, with no-detection of HCO+ v2=1f J=3-2 emission line. Comparison of these v2=1f emission line fluxes with an infrared radiative pumping model, using available infrared 5-35 micron spectrum and H13CN 3-2 (HCN isotopologue) flux suggests that (1) higher HCN abundance than HCO+, and (2) sufficient HCN excitation to J=4, can naturally explain the observed high HCN-to-HCO+ flux ratio in this LIRG, rather than substantially higher infrared radiative pumping rate of HCN than HCO+. We also found that line-opacity-corrected intrinsic HCN-to-HCO+ flux ratios will be an even more solid energy diagnostic method than observed ratios.

Kotaro Kohno (The University of Tokyo)

NGC 1097 collaboration

Ten Parsec Scale View of Dense Molecular Medium in the Active Nucleus of NGC 1097

We present 0".13 - 0".20 (or 9 - 14 pc) resolution observations of HCN(4-3), HCO+(4-3), CO(3-2), and 870 um continuum in the central kpc region of NGC 1097 hosting a low-luminosity type-1 active galactic nucleus. With this spatial resolution we are about to resolve the sphere of influence (SoI) of the super massive black hole in NGC 1097 (r(SoI) 12 pc for M(BH) = $1.2x10^8 M_\odot$). We find S-shaped or bar-like distributions of HCN, HCO+, and CO lines with a size of 1.5" (dense gas bar hereafter) with two-armed spiral arms (especially visible in CO). Overall HCN(4-3)/HCO+(4-3) flux ratios are enhanced (larger than unity) across the dense gas bar, but we find two prominent peaks exhibiting high HCN(4-3)/HCO+(4-3) ratio (exceeding 2) and they are not at the very center but at a distance of 0".5 or 35 pc. This is very similar to the distribution of high HCN(4-3)/HCO+(4-3) ratio gas at the vicinity of active nucleus in NGC 1068 reported by Garcia-Burillo et al. (2014) and Viti et al. (2014), suggesting that high HCN/HCO+ ratios are not caused by X-ray radiation, although it could be related to the presence of an active nucleus. We find that the 870 um continuum emission from the active nucleus is highly time variable (a factor of 7) during the observing period (August 2014 to July 2015), indicating that most of the 870 um emission is originated from non-thermal activities of the nucleus.

Francesco Costagliola (Chalmers University of Technology)

The Molecular Complexity of Galaxies: Opportunities and New Challenges in the ALMA Era

Until recently, the study of the molecular interstellar medium of galaxies has been mostly focused on a few, relatively abundant, molecular species. Recent attempts at modeling the molecular emission of active galaxies have shown that standard high-density tracers do not provide univocal results and are not able to discriminate between different relevant environments (e.g., star-formation vs AGN). Spectral lines surveys allow us to explore the richness of the molecular spectrum of galaxies, provide tighter constrains to astrochemical models, and find new more sensitive tracers of specific gas properties. What started as a time-consuming pioneering work has become now routinely accessible with the advent of ALMA. Here I will report some recent results of molecular line observations in local galaxies, focusing on the use of non-standard molecular tracers as diagnostics of the ISM properties in extremely obscured galactic nuclei.

Wednesday, April 6, 2016		
Session G: High-z I		
Dominik Riechers	Detailed Studies of Cold Gas and Star Formation in the Early Universe	Invited
Lisa Young	Molecular and PDR Gas in Nearby Spiral Galaxies	Contributed
Karen Olsen	Simulations of [CII] at High Redshift: What Does [CII] trace?	Contributed
Session H: High-z II		
Chelsea Sharon	Molecular Gas Excitation and the Evolutionary Connection Between z 2-3 Sub-millimeter Galaxies and AGN	Contributed
Roberto Decarli	The ALMA Molecular Deep Field in the Hubble UDF	Contributed
Eric Murphy	Baryon Cycling within Galaxies: the View with a Next-Generation Radio-mm Interferometer	Contributed
Nick Scoville	90 mas Imaging of Arp 220 and ISM and Star Formation at z > 1	Invited
Session I: Dwarf Galaxies I		
Leslie Hunt	Molecules in Low-Metallicity Starbursts	Invited
Amanda Kepley	Revealing the Molecular Gas Content of Dwarf Starburst Galaxies	Contributed
Vianney Lebouteiller	The Quest for Cold Molecular Gas in Extremely Metal-Poor Galaxies: Insights from the Thermal Balance in the Neutral Gas of IZw18	Contributed
Marco Grossi	Star-forming Dwarf Galaxies in the Virgo Cluster: the Link between Molecular Gas, Atomic Gas, and Dust	Contributed
Session J: Dwarf Galaxies II		
Suzanne Madden	Unveiling the CO-dark Gas in Galaxies	Contributed
Lauren Bittle	Internal Molecular Gas Properties in the Local Group Dwarf Starburst IC 10	Contributed
Kelsey Johnson	The Relationship Between Super Star Clusters and Molecular Gas	Contributed
Omanarayani Nayak	NGC159 Region of the LMC Using Dendrograms to Explore the Relation Between CO and CS Molecular Gas to Star Formation in a Low Metallicity Environment	Contributed

Dominik Riechers (Cornell University)

Detailed Studies of Cold Gas and Star Formation in the Early Universe

Over the past decade, great progress has been made in studies of the atomic and molecular interstellar medium and dust-obscured star formation in high-redshift galaxies, resulting in a vastly improved picture of the physical properties and chemical composition of the gas and dust in galaxies in the early universe. With the recent completion of the Karl G. Jansky Very Large Array (VLA) and the Atacama Large (sub)Millimeter Array (ALMA), it has now become possible to advance these studies to the next level through sensitive, broad-band molecular line spectroscopy, spatially-resolved imaging of the gas and dust, and deep field surveys of considerable cosmic volumes in both line and continuum emission back to the earliest cosmic epochs. I will present a suite of new scientific investigations that exemplify the range of the exciting new research enabled by the VLA and ALMA as we are approaching the 2020s.

Lisa Young (New Mexico Tech)

Molecular and PDR Gas in Nearby Spiral Galaxies

Several recent observing projects enable us to study the atomic and molecular ISM in nearby galaxies through their CO, HI, and FIR fine structure line emission. As numerical simulations of galaxy formation are now modeling the atomic and molecular phases, and predicting the emission in these lines, it is particularly important to have a good understanding of their behavior locally. Thus, we present some exploratory work on the radial profiles and kpc-scale spatial distributions of CO, HI, [C II], and [O I]63micron emission in nearby spirals. For example, if [C II] largely traces photodissociated molecular gas, then [C II]/CO and [O I]/[C II] can be rough indicators of the PDR gas density and the strength of the incident UV field. Local galaxies sometimes show strong radial gradients in [C II]/CO and [O I]/[C II], in the sense of having a [C II] deficit in their nuclei compared to their disks; these strong gradients occur in galaxies with AGN, but the converse is not true (galaxies with AGN sometimes show no gradient in these line ratios). In addition to providing more detailed zero points for simulations, these results should be folded in to the interpretations of high redshift data which use [C II] as a proxy for molecular gas and a tracer for star forming material.

Karen Olsen (SESE ASU)

Thomas Greve (UCL)
Desika Narayanan (Haverford College)
Robert Thompson (NCSA)
Christian Brinch (NBI)
Sune Toft (NBI)

Simulations of [CII] at High Redshift: What does [CII] Trace?

The fine structure line of [CII] at 158μm can arise throughout the interstellar medium (ISM) and has been proposed as a tracer of star formation rate (SFR). But the origin of [CII] and how it depends on e.g. metallicity and radiation field of a galaxy remain uncertain. Simulating [CII] can be done by combining the output from galaxy simulations with prescriptions for the subgrid physics, as has now been demonstrated by several groups. However, these models are either built on analytical discs or contain other simplifying assumptions. SÍGAME (Simulator of GAlaxy Millimeter/submillimeter emission) avoids this by taking galaxies from cosmological simulations and calculating [CII] emission reliably on resolved scales within each galaxy. The local metallicity is that of the simulation, whereas far-ultraviolet radiation field and cosmic rays are scaled with local star formation rate. I will show results for $z = 2$ star-forming galaxies yet to be observed, as well as preliminary results for galaxies at $z \sim 6-7$ where observations have presented contradictory detections and non-detections of star-forming galaxies.

Chelsea Sharon (Cornell University)

Dominik Riechers (Cornell University)
Jacqueline Hodge (Leiden Observatory)
Chris Carilli (NRAO)
Fabian Walter (MPIA)
Axel Weiss (MPIR)

Molecular Gas Excitation and the Evolutionary Connection Between z 2-3 Submillimeter Galaxies and AGN

Theoretical work suggests that AGN play an important role in quenching star formation in massive galaxies. Direct evidence for AGN affecting the molecular ISM has so far been limited to detections of molecular outflows in low-redshift systems and extreme excitation regions that represent a tiny fraction of their host galaxyś total gas. At the peak epoch of star formation and AGN activity, previous CO(1-0) observations revealed that submillimeter galaxies (SMGs) have multi-phase molecular gas, including substantial reservoirs of cold-phase gas. However, the entirety of the molecular gas in AGN-host galaxies appears highly excited. This difference potentially provides indirect evidence of AGNś impact on star-forming molecular gas and supports an evolutionary connection between these two populations. I will present a VLA survey that significantly increases the number of CO(1-0) detections in z 2-3 SMGs and AGN-host galaxies, allowing us to better compare the cold gas properties of these systems and investigate the effects of AGN on star-forming molecular gas.

Roberto Decarli (MPIA)

Fabian Walter (MPIA)
Manuel Aravena (UDP)

The ALMA Molecular Deep Field in the Hubble UDF

Multi-wavelength studies have accurately constrained the growth of galaxies through cosmic time: The rate of star formation per unit of cosmological volume increased from the earliest epochs until z=1-3 (Universe age: 2-6 Gyr), when it peaked (the ”epoch of galaxy assembly”), then steeply declined by more than an order of magnitude until z=0 (today). What drives this evolution? In order to address this fundamental question, we need to target the fuel for star formation, i.e., the dense phase of the interstellar medium in high-z galaxies beyond the ”tip of the iceberg” of extremely luminous galaxies, thus in the bulk of the galaxy population. This is possible only now, in particular thanks to the advent of the Atacama Large Millimeter Array (ALMA). We obtained ALMA cycle 2 observations to scan the 3mm and 1mm transparent windows of the atmosphere in a region of the Hubble Ultra Deep Field (UDF). We searched for molecular gas as traced by the carbon monoxide (C! O) lines, as well as for ionized carbon ([CII]) at z¿6 and for dust continuum. Our analysis is supported by a wealth of ancillary information at virtually any wavelengths (the field is one of the most studied regions in the sky). We can now for the first time directly gauge the molecular gas content of galaxies throughout cosmic time. The results of this project provide new constraints on theoretical models of the evolution of galaxies throughout cosmic time.

Eric Murphy (NRAO)

Adam Leroy (OSU)
Juergen Ott (NRAO)
Chris Carilli (NRAO)
ngVLA Science Working Groups (USA)

Baryon Cycling within Galaxies: the View with a Next-Generation Radio-mm Interferometer

Objects in the nearby universe provide the best means to obtain a complete picture of baryon cycling for a heterogenous set of astrophysical conditions. This includes the inflow of atomic gas into galaxies, the formation of molecular structures, the birth of stars, and the expulsion of gas from galaxies due to associated feedback processes. Moving into the next decade, this will continue to remain true and our knowledge of galaxy formation and evolution will be fundamentally improved by having higher resolution/sensitivity observations of nearby galaxies to better interpret high-z observations of sources that were rapidly evolving at epochs soon after the Big Bang. The radio-to-mm part of the spectrum provides critical diagnostics for each of these processes and access to almost all phases of gas in galaxies: cool and cold gas (via emission and absorption lines), ionized gas (via free-free continuum and recombination lines), cosmic rays and hot gas (via synchrotron emission and the Sunyaev-Zeldovich effect) each of these is free from dust extinction, which plagues shorter wavelengths. In this talk we highlight a number key science problems that will remain relevant going into the next decade and are best answered by a next-generation radio-mm interferometer.

Nick Scoville (Caltech)

90 mas Imaging of Arp 220 and ISM and Star Formation at z > 1

I discuss the calibration and use of the long wavelength dust continuum as a tracer of galactic scale gas contents in the early universe. For samples of normal star forming galaxies and ULIRGs at low redshift and lensed SMGs at z 2 there exists a linear scaling between the dust flux and the gas mass determined from CO (1-0). In Cycle 2, we measured the continuum in 2 min observations in Bd 7 for 145 galaxies at z = 1 to 4, and find an approximately linear dependence of the SFR (determined from optical, UV and IR) on the derived ISM gas contents with a depletion time 500 Myr. We also find little evidence for higher star formation efficiencies above the main sequence compared to the main sequence. An additional 360 galaxies are scheduled for Cycle 3.

Leslie Hunt (INAF-Osservatorio di Arcetri)

Christian Henkel (MPIfR Bonn)
Viviana Casasola (INAF-OAA Firenze)
Francoise Combes (LERMA Observatoire di Paris)
Santiago Garcia-Burillo (OAN Madrid)
Paola Caselli (MPIfE Garching)

Molecules in Low-Metallicity Starbursts

Metal-poor dwarf galaxies are known to be deficient in molecules, despite prodigious star formation. However, our new data show that CO can trace the interstellar medium (ISM) and star formation processes to metallicities as low as 1/10 solar (the Small Magellanic Cloud is 1/4 solar). Here we present an analysis of molecular depletion times in low-metallicity blue galaxies, together with a new derivation of the dependence of the CO-to-H2 conversion factor on metallicity. We also focus on a detailed characterization of a metal-poor ISM in a dwarf starburst, NGC 1140. With single-dish detections of 6 CO transitions, including 13CO, we have used radiation-transfer models to infer temperature, density, and abundances in the ISM of this low-metallicity galaxy. Our results confirm observationally the notion that in metal-poor environments, atomic carbon is more abundant than carbon monoxide, and that feedback from the massive super-star clusters may substantially alter isotopic abundances.

Amanda Kepley (National Radio Astronomy Observatory)

Adam Leroy (Ohio State University)
Kelsey Johnson (University of Virginia)
Lauren Bittle (University of Virginia)
Karin Sandstrom (University of California San Diego)
Rosie Chen (Max Planck Institute for Radio Astronomy)

Revealing the Molecular Gas Content of Dwarf Starburst Galaxies

With their high star formation rate surface densities and low metallicities, dwarf starburst galaxies represent one of the most extreme environments in the local universe. Until the advent of telescopes like ALMA and the GBT, however, the molecular gas fueling the prodigious star formation in these systems was difficult to observe because of their weak CO emission and the presumably even fainter emission from other commonly used molecular tracers. In this talk, I will present two examples of how new instrumentation is expanding molecular gas studies to previously inaccessible dwarf starbursts. I will begin by presenting the first detailed study of the molecular gas content (as traced by CO) in the prototypical nearby blue compact dwarf galaxy II Zw 40. Using the extraordinary resolution and sensitivity of our ALMA Cycle 1 observations, we have separated the molecular gas emission with II Zw 40 into discrete giant molecular clouds and measured their properties. We find that molecular clouds within this galaxy have linewidths and surface densities similar to molecular clouds in more massive starburst galaxies, suggesting that the on-going merger within II Zw 40 is driving the properties of molecular gas. I will conclude by reporting on new GBT detections of the dense molecular gas tracers HCN/HCO+ in a Local Group dwarf starburst galaxy and how the properties of its dense molecular gas compare to those in more massive spiral galaxies.

Vianney Lebouteiller (Laboratoire AIM - CEA Saclay)

D Pequignot (LUTh Observatoire de Paris-Meudon France)

The Quest for Cold Molecular Gas in Extremely Metal-poor Galaxies: Insights from the Thermal Balance in the Neutral Gas of IZw18

The lack of detection of cold molecular gas in blue compact dwarf (BCD) galaxies is at variance with the intense star-formation episode in these objects. In particular, CO is not detected in galaxies with metallicities below 1/8 the solar value, which is both a direct consequence of low metal abundance and indirect consequence of enhanced CO photodissociation due to a low dust-to-gas mass ratio. In theory, a potentially large fraction of molecular gas is expected to reside in the so-called CO-free gas, where it could be traced by warm neutral atomic tracers [CI], [CII], and [OI] in the far-infrared/sub-millimeter. Although the fraction of CO-free gas to total molecular gas is expected to be especially large in metal-poor galaxies, a definite evidence is still lacking because of the difficulty in associating cooling lines with any given heating mechanism. In the most metal-poor BCD IZw18 (1/35 solar), molecular gas, cold or warm, has never been detected. I will present new observations with the Herschel Space Telescope, thanks to which we succesfully detected [CII] 157um and [OI] 63um. I will show how these lines along with observations in the optical and in the mid-infrared can be used to constrain the physical conditions in the HII region + HI region within a consistent photoionization and photodissociation model. I will compare various heating mechanisms and show that the HI region is mostly heated by a known ultraluminous XR source. This result has important implications for using FIR cooling lines as star-formation rate tracers and, in general, for using any diagnostic involving FIR cooling lines in such extreme objects. I will then quantify the molecular gas under two assumptions, molecular gas distributed either in the HI shells or in tiny dense clumps, and examine the reliability of [CII] and other FIR lines as molecular gas tracers. The end of the talk will dedicated to possible future observations with existing/new facilities to detect cold molecular gas directly for the first time in this object and in other extremely metal-poor systems.

Marco Grossi (Observat rio do Valongo UFRJ)

M Grossi (Observat rio do Valongo UFRJ)
E Corbelli (INAF - Osservatorio Astrofisico di Arcetri)
L Bizzocchi (Center for Astrochemical Studies MPE)
C Giovanardi (INAF - Osservatorio Astrofisico di Arcetri)
I De Looze (University College London)

Star-forming Dwarf Galaxies in the Virgo Cluster: the Link between Molecular Gas, Atomic Gas, and Dust

We present IRAM 30-m telescope observations of a sample of 20 star-forming dwarfs selected from the Herschel Virgo Cluster Survey, with oxygen abundances $12 + \log(\mathrm{O/H}) > 8.1$. CO emission is observed in 10 galaxies and marginally detected in another one. CO fluxes correlate with the far-infrared emission at 250
mum and the dwarfs follow the same linear relation that holds for more massive spiral galaxies. H2 molecular masses are estimated comparing different methods, namely a metallicity-dependent CO-to-H2 conversion factor and one dependent on H-band luminosity. The molecular-to-stellar mass ratio remains nearly constant at stellar masses $< 10^9$ M_{odot}, contrary to the atomic hydrogen fraction, $\mathrm{M}_{HI}/\mathrm{M}_*$, which increases inversely with M_*. The flattening of the $\mathrm{M}_{H_2}/\mathrm{M}_*$ ratio at low stellar masses is predicted by models of the evolution of the gas content of galaxies and it does not seem to be related to the effects of the cluster nvironment, because it occurs for both HI-deficient and HI-normal dwarfs. The molecular-to-atomic ratio is more tightly correlated with stellar surface density rather than metallicity, confirming that the interstellar gas pressure plays a key role in determining the balance between the two gaseous components of the interstellar medium. The mechanism removing atomic gas and dust appears to have left intact the molecular component at the current stage of evolution of the dwarfs within the cluster. However, the correlation between HI deficiency and the molecular gas depletion time suggests that the lack of gas replenishment from the outer regions of the disc is lowering the star formation activity.

Suzanne Madden (CEA Saclay France)

Unveiling the CO-dark Gas in Galaxies

From the local to the high-z universe, we often rely on CO observations to determine the H2 reservoir in galaxies. Dwarf galaxies, however, are notoriously deficient in CO, leaving us with an uncomfortable uncertainty in quantifying the total molecular gas reservoir, compounding the difficulty in understanding the process of star formation in low metallicity environments. While CO is difficult to observe, the MIR and FIR fine structure lines are relatively luminous, providing us with a means to get at the photodissociation (PDR)/ molecular cloud properties. Cormier et al (2015) have modeled the rich array of ionized and PDR gas tracers from the Spitzer and Herschel Dwarf Galaxy Survey and from these models we quantify the total molecular gas reserrvoir. Comparison of the H2 reservoir predicted from the self-consistent modeling, with the molecular gas determined from CO observations, we have quantified the CO-dark gas reservoir present in the low metallicity galaxies. We find a potentially significant mass of H2 residing in the C^+ and C^o-emitting regions, not traced by CO.

Lauren Bittle (University of Virginia)

Internal Molecular Gas Properties in the Local Group Dwarf Starburst IC 10

Dwarf starburst galaxies provide an ideal environment to study the impact of low metallicity, high gas fraction, and extreme feedback on the cool, star-forming molecular gas. We present new multi-transition observations of the molecular gas in the nearest dwarf starburst galaxy, the Local Group dwarf IC 10. Using the IRAM 30-m telescope, we have mapped the CO (1-0), CO (2-1), and ^{13}CO (1-0) transitions over the whole area of the disk. We followed up these observations with targeted ARO SMT spectroscopy of the CO (2-1) and ^{13}CO (2-1) transitions. Together these give the most complete and sensitive view of the internal conditions in the molecular gas of a dwarf starburst galaxy to date. We present the resolved CO line ratios for this dwarf starburst and discuss their implications for the excitation, density, and optical thickness of the CO-emitting molecular gas considering both basic LTE calculations and comparing to the results of LVG (Radex) modeling. We compare these physical properties within molecular clouds that occupy the starburst complex in the southeast, the more quiescent clouds associated with the edges of supernova-carved shells, and the infalling gas streamer in the east of the galaxy. Studying IC 10 in such detail will provide an unprecedented exploration of the molecular gas in a low-metallicity dwarf starburst.

Kelsey Johnson (University of Virginia)

The Relationship Between Super Star Clusters and Molecular Gas

Observationally constraining the physical conditions that give rise to massive star clusters has been a long-standing challenge. Now with the ALMA Observatory coming on-line, we can probe the birth environments of massive clusters in a variety of galaxies with sufficient angular resolution. ALMA observations enable an assessment of the molecular cloud chemical abundances in the regions surrounding super star clusters. For example, based on our ALMA observations of Henize 2-10, Molecular clouds associated with existing super star clusters are strongly correlated with HCO+ emission, but appear to have relatively low ratio of CO/HCO+ emission compared to other clouds, indicating that the super star clusters are impacting the molecular abundances in their vicinity. Thus, these line ratios could potentially provide a mechanism for identifying newly formed massive clusters.

Omnarayani Nayak (Johns Hopkins University)

Margaret Meixner (STScI)
Yasuo Fukui (Nagoya University)
Kengo Tachihara (Nagoya University)
Toshikazu Onishi (Osaka Prefecture University)
Kazuya Saigo (Osaka Prefecture University)

N159 Region of the LMC Using Dendrograms to Explore the Relation Between CO and CS Molecular Gas to Star Formation in a Low Metallicity Environment

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 2). N159 is located south of the massive star formation region 30 Doradus. Out of all the 12CO (3-2) observations that have been done so far of the LMC, N159 is the most intense molecular cloud in 12CO (3-2). 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 pc x 0.3 pc. We measure the molecular cloud complexes in 13CO (1-0), 12CO (2-1), 13CO (2-1), and CS (2-1) lines. We study the heirarchical structure of the clumps using dendrogram analysis. Dendrogram analysis is a novel way to study the large and small scale structure in a contiguous manner that is inherent in the ISM. We compare the size-linewidth relation, mass distribution, and other CO clump properties in N159 to previous studies in 30 Doradus and in the Milky Way. N159 is currently forming massive stars. Over a dozen young stellar object candidates and about 100 pre-main sequence stars have been identified by color-magnitude cuts, SED fitting, and isochrone fitting. Analysis of the dense molecular gas in N159 will shed light on the conditions necessary for star formation.

Thursday, April 7, 2016		
Session K: AGN		
Takuma Izumi	ALMA Observations of Circumnuclear Feedback and Feeding in Nearby Seyfert Galaxies	Invited
Satoki Matsushita	Shocked Outflowing HCN Gas Along the Radio Jets of the Seyfert 2 Galaxy M51	Contributed
Laura Zschaechner	Galactic Scale Feedback: The AGN and Starburst Driven Molecular Outflows in Circinus and NGC 258	Contributed
Session L: Black Holes		
Benjamin Boizelle	Accurately Measuring Black Hole Masses with ALMA	Contributed
Martin Bureau	WISDOM: mm-Wave Interferometric Survey of Dark Object Masses	Contributed
Kyoko Onishi	WISDOM: Supermassive Black Hole Mass Measurements in NGC 1097 and NGC 3665	Contributed
Session M: Dwarf Galaxies III		
Jean Turner	Massive Star Clusters and Dusty Clouds	Invited
Oskar Karczewski	NGC 4449: Understanding Star Formation in Environments Subjected to Large-scale Gravitational Perturbations	Contributed
Melanie Chevance	Quantifying the CO-dark Molecular Gas in the Extreme Environment of LMC/30 Doradus	Contributed

Takuma Izumi (University of Tokyo)

ALMA Observations of Circumnuclear Feedback and Feeding in Nearby Seyfert Galaxies

We will present 10s−100 pc scale view of submm dense gas tracers such as HCN(4-3), HCO^+(4-3), and CS(7-6) in some nearby Seyfert galaxies (active galactic nuclei = AGNs) mainly provided by ALMA. Enhanced HCN(4-3)/HCO^+(4-3) and/or HCN(4-3)/CS(7-6) line ratios in circumnuclear gas of AGNs compared to those in starburst galaxies (submm-HCN enhancement), especially when observed at high spatial resolutions, are shown at first. Non-LTE radiative transfer modelings of the above lines involving both collisional and radiative excitation were conducted to investigate the cause of the high line ratios in AGNs. As a result, we suggest that enhanced abundance ratios of [HCN]/[HCO^+] and [HCN]/[CS] in AGNs than in starburst galaxies by a factor of a few to even ¿ 10 are a plausible origin of the feature. These high abundance ratios are hard to be reproduced by ionisation-dominated chemistry. Alternatively, we might have to take into account hot gas-phase chemistry (e.g., mechanical heating).

We also talk about possible fueling processes operating at 10s-100 pc regions around AGNs. We especially discuss a physical/causal link between AGN activities and surrounding star formation that can now be investigated in detail with ALMA. Circumnuclear dense gas disks seem to drive further mass accretion onto supermassive black holes. The talk will be closed by introducing prospects on high-resolution studies of circumnuclear dense gas to probe the nature of a putative molecular/dusty torus.

Satoki Matsushita (ASIAA)

Dinh-V-Trung (Vietnamese Academy of Science Technology)
Frederic Boone (Univ Toulouse CNRS)
Melanie Krips (IRAM)
Jeremy Lim (Univ Hong Kong)
Sebastien Muller (OSO)

Shocked Outflowing HCN Gas along the Radio Jets of the Seyfert 2 Galaxy M51

Recent interferometric molecular gas observations toward AGNs and U/LIRGs revealed outflowing molecular gas from nuclear regions. However, very few data spatially resolved the molecular gas, so that it is still unclear what is actually ongoing at the molecular outflows. We observed Seyfert 2 nucleus of the nearby galaxy M51 with multiple CO transition and the HCN(1-0) lines at 1 (34 pc) or higher resolution using the IRAM Plateau de Bure Interferometer (PdBI) and the Submillimeter Array (SMA). All the images show very similar overall molecular gas distribution and dynamics; there are two discrete clouds at the eastern and western sides of the nucleus, and the western cloud exhibits elongated distribution and velocity gradient along the radio jets. High HCN(1-0)/CO(1-0) brightness temperature ratio of about unity has been observed along the radio jet, similar ratio to that observed at the shocked molecular gas in our Galaxy. This indicates that the molecular gas along the jet is shocked, and both diffuse (CO) and dense (HCN) molecular gas are outflowing from the Seyfert 2 nucleus by the radio jets. This is the first clear evidence of spatially resolved outflowing molecular gas due to radio jets, and showing the detailed physical status of it. Our results will help to understand the nature of molecular gas outflows from AGNs and U/LIRGs, and high HCN/CO ratios at the nuclear regions.

Laura Zschaechner (MPIA)

Fabian Walter (MPIA)
Alberto Bolatto (University of Maryland)
Sylvain Vellieux (University of Maryland)
Juergen Ott (NRAO)
David S Meier (New Mexico Institute of Mining and Technology)

Galactic Scale Feedback: The AGN and Starburst Driven Molecular Outflows in Circinus and NGC 253

Galactic outflows are poorly understood although they are essential to feedback processes that quench star formation and limit the total mass of large galaxies. Thus, insufficient understanding of feedback associated with them - in particular molecular phase, which likely dominates the mass budget - is one of the greatest shortcomings in our knowledge of galaxy evolution. Multiphase outflows associated with galactic winds have been well-studied at a range of wavelengths, but detailed observations of the molecular phase are only now feasible with new instruments such as ALMA. We present ALMA observations and kinematic models of the molecular outflows in Circinus galaxy and NGC 253. Using these data, we constrain the molecular mass of the winds and outflow rates - both crucial to future star formation. We compare the AGN-driven molecular wind in Circinus to the starburst-driven wind in NGC 253 and note key differences in the ways each type of wind impacts star formation.

Benjamin Boizelle (UC Irvine)

Aaron Barth (UC Irvine)
Jeremy Darling (University of Colorado)
Andrew Baker (Rutgers)
Jonelle Walsh (Texas A&M)
Luis Ho (Kavli Institute)

Accurately Measuring Black Hole Masses with ALMA

ALMA has a revolutionary ability to resolve molecular gas kinematics within the gravitational radius of influence of supermassive black holes in galactic nuclei. We are pursuing a two-stage program to accurately measure black hole masses in nearby early-type galaxies: first obtaining CO(2-1) observations at 0.3"resolution to test for the presence of rapidly rotating gas within the black hole sphere of influence, and when it is identified, then proposing higher-resolution observations to map the gas kinematics in exquisite detail and obtain accurate black hole masses via dynamical modeling. In Cycle 2 we obtained 0.3"-resolution observations of seven galaxies selected based on the presence of circumnuclear dust disks seen in HST images. ALMA observations reveal clear evidence of rapid central rotation in four of these. We present kinematic measurements and dynamical modeling results, including detailed model fits for NGC 1332. Dynamical models demonstrate that degeneracy between black hole mass and other parameters can preclude the derivation of strong constraints on black hole mass when the black hole's sphere of influence is not highly resolved. We also present new Cycle 3, 0.04"-resolution observations of NGC 1332 that highly resolve the black hole sphere of influence, and new constraints on the black hole mass derived from dynamical modeling of the high-resolution data.

Martin Bureau (University of Oxford)

WISDOM: mm-Wave Interferometric Survey of Dark Object Masses

Correlations between galaxy properties and the masses of their central supermassive black holes (SMBHs) currently underly a vast number of observational and theoretical studies. The number of reliably measured SMBHs is however still relatively small, and only a handful of measurement techniques exist. Here we report on WISDOM, a multi-pronged effort to dynamically measure SMBH masses using molecular gas in the nuclear regions of galaxies, by simply probing the near-Keplerian rotation of molecular disks at high angular resolution. Molecular gas is particularly useful as it is present across the Hubble sequence, it is unaffected by dust, it can be observed with sufficient angular resolution to relatively large distances, and its kinematics is generally regular to the smallest spatial scales probed. First, we present our background optical and millimetre work to identify promising targets, with regular nuclear molecular gas distributions and kinematics. Second, we present our first SMBH mass measurements, from both CARMA (NGC4526) and ALMA (NGC3351, 4429, 4826 and others), this for galaxies across a range of morphological types. The observations reveal the molecular gas kinematics well within the spheres of influence of the SMBHs, putting extremely tight constraints on the SMBH masses, but also highlighting the observational and modeling challenges of such programmes. Third, we show how ALMA opens up the possibility of easily and rapidly measuring hundreds of SMBHs masses across all galaxy types, and discuss the feasibility of a dedicated ALMA large programme. Finally, we discuss how the same data allow to study the spatially-resolved properties of giant molecular cloud populations in the galaxies targeted, thus testing the universality of cloud scaling relations beyond local late-type galaxies.

[I note that a complementary abstract has been submitted by Kyoko Onishi, discussing in much more details two other SMBH mass measurements (NGC1097 and 3665).]

Kyoko Onishi (SOKENDAI The Graduate University for Advanced Studies)

Timothy Davis (Cardiff University)
Martin Bureau (University of Oxford)
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WISDOM: Supermassive Black Hole Mass Measurements in NGC1097 and NGC3665

Using molecular gas kinematics, we measure the supermassive black hole (SMBH) mass in two nearby galaxies, NGC1097 and NGC3665. The masses are both measured to good accuracy, $1.40^{+0.27}_{-0.32} \times 10^8 M_\odot$ for NGC1097 and $3.80^{+0.77}_{-0.71} \times 10^8 M_\odot$ for NGC3665, and both follow the M-sigma relation. Unlike other direct SMBH mass measurement techniques, molecular gas kinematics is applicable to all galaxy types – NGC1097 is a Seyfert 1 barred spiral galaxy while NGC3665 is a powerful early-type radio galaxy with a jet. We further show how the accuracy of the measurements is improved by the use of interferometric (3D) data, and discuss a statistical method yielding reliable uncertainties. With the large samples allowed by molecular gas kinematics, detailed studies of the M-sigma relation are now possible, that will shed light on the co-evolution of galaxies and SMBHs.

(This abstract is complimentary to the more general WISDOM abstract submitted by Martin Bureau.)

Jean Turner (UCLA)

Massive Star Clusters and Dusty Clouds

High resolution submillimeter images allow us to observe gas and dust on the parsec scales of star formation in local galaxies. Observations of young massive star clusters suggest significant localized metal enrichment during early stages of cluster evolution, as expected from massive stellar evolution. This enrichment can potentially have significant dynamical consequences for the host molecular clouds and their evolution. Gas masses near large clusters are difficult to constrain, even in the absence of CO-dark H2, but dynamical constraints indicate that star formation efficiencies can be quite high, exceeding 50%, a value favorable to long term cluster survival. As expected, high radiation fields from luminous clusters produce very warm, PDR conditions in the gas but may not have the expected chemical effects.

Oskar Karczewski (CEA Saclay)

Suzanne Madden (CEA Saclay)
Deidre Hunter (Lowell Observatory)
Frederic Galliano (CEA Saclay)
Vianney Lebouteiller (CEA Saclay)
Serena Viti (UCL)

NGC 4449: Understanding Star Formation in Environments Subjected to Large-Scale Gravitational Perturbations

NGC 4449 is a nearby dwarf galaxy involved in an on-going merger with a low mass companion. With its thin disc and the face-on orientation on the sky, NGC 4449 gives us a detailed view of the interstellar medium (ISM) across the entire galaxy. This isolated galaxy-galaxy system forms a unique laboratory which we can use to study the effects of large-scale gravitational processes on the local conditions in the ISM.

In my talk I will present spatially resolved multiwavelength observations from *Spitzer*, *Herschel* and ground-based telescopes covering the emission from ionised, atomic and molecular gas. I will present our model of gas and dust emission in NGC 4449 constructed with the radiative transfer code MOCASSIN and based on our photometric and spectroscopic observations. I will also discuss the properties of the neutral ISM suggested by our analysis of $[\text{Si II}]_{35}$, $[\text{O I}]_{63}$, $[\text{C II}]_{158}$ and the CO transitions observed in the photo-dissociation regions (PDRs). Finally, I will present the emerging picture of the star formation processes in perturbed environments and its relevance for studies of more distant galaxies which are likely to be involved in mergers, such as ULIRGs.

Melanie Chevance (CEA SAp AIM)

Suzanne Madden (CEA SAp AIM)
Vianey Lebouteiller (CEA SAp AIM)
Benjamin Godard (LERMA)
Diane Cormier (Heidelberg University)
Frederic Galliano (CEA SAp AIM)

Quantifying the CO-dark Molecular Gas in the Extreme Environment of LMC/30 Doradus

I will present a far-infrared (FIR) view of the extreme star-forming region 30 Doradus in the Large Magellanic Cloud (LMC). The 30 Doradus region offers the best laboratory to examine in detail the interplay between stellar activity and a metal-poor interstellar medium (ISM). The main stellar source of radiation, provided by the closest example of a super star cluster, R136, shapes the surrounding half-solar metallicity ISM. The proximity of 30 Doradus (50kpc) makes it possible to study gas and dust over large scales in this dramatic environment. The new Herschel/PACS and SPIRE/FTS observations of FIR fine structure lines, combined with Spitzer/IRS spectroscopic maps, are used to constrain the physical conditions in the photo-dissociation regions (PDR) with the Meudon PDR code (Le Petit et al., 2006). This allows us to construct a comprehensive, self-consistent picture of the density, radiation field, and ISM structure. We quantify the effect of intense radiation field on this low metallicity ISM. In particular, we bring constraints to the fraction of molecular dark gas not traced by CO, the so-called CO-dark gas and find that a large reservoir of H2 is not traced by CO in this extreme environment. Our follow-up observations with ALMA reveal the CO structures at 0.1pc scale.