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ASTROCHEMISTRY AND STAR FORMATION IN NEARBY GALAXIES: FROM GALAXY DISKS TO HOT NUCLEI

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Abstract. Studying the molecular phase of the interstellar medium in galaxies is fundamental for the understanding of the onset and evolution of star formation in nuclei and disks, and the growth of supermassive black holes(SMBHs) . Molecular line emission is an excellent tracer of chemical, physical and dynamical conditions. Key molecules in extragalactic studies are e.g. HCN, HCO^+, HC_3N, SiO, CH_3OH, H_2O. Furthermore, we can use IR excited molecular emission to probe the very inner regions of luminous infrared galaxies (LIRGs) allowing us to get past the optically thick dust barrier of the compact obscured nuclei where lines of CO, HCN and HCO^+ in their vibrational ground state (ν=0) may be self-absorbed. Finally, molecular outflows and their chemistry are briefly discussed - including the new ALMA discovery of a highly collimated precessing molecular jet in the lenticular, extremely radio quiet galaxy NGC1377.

1 Extragalactic astrochemistry

Molecular emission and absorption lines are very useful tools to study the nature and evolution of luminous ($L_{\rm FIR}$=$10^{10} - 10^{11}$ $L_\odot$) and ultraluminous ($L_{\rm FIR} \gtrsim 10^{12}$ $L_\odot$) infrared galaxies (U/LIRGs). Molecular gas serves as fuel for the evolution of galaxies through star formation and the growth of SMBHs. Molecular emission (from mm to FIR wavelengths) can penetrate highly obscured regions allowing us to probe the dusty nuclei of U/LIRGs revealing the nature of the buried activity. In addition, the starbursts and AGNs power massive large-scale molecular outflows that can help regulate the growth of the galaxy - both in the nucleus and on larger scales.

The CO 1–0 line is often used to trace H_2 mass (e.g. Wada and Tomisaka, 2005; Narayanan et al., 2012) and gas dynamics. The line intensity ratio between CO

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and the polar molecule HCN is a popular measure of the mass fraction of dense ($n > 10^4\,\mathrm{cm}^{-3}$) molecular gas (e.g. Gao and Solomon, 2004). Astrochemistry offers an additional new tool to study galaxy evolution where the radiative, dynamical and chemical impact on the gas can be explored.

There are a number of standard scenarios often referred to when discussing extragalactic astrochemistry (see (e.g. Aalto, 2013)): **Photon (or Photo) dominated region (PDR)** Regions affected by far-ultraviolet photons (hν=6 - 13.6 eV) with large surface temperatures (300 - 1000 K) and moderate (20 - 50 K) bulk temperatures (due to the layered structure of the PDR) . The chemistry is dominated by photo-chemistry (e.g. Hollenbach and Tielens, 1997); **X-ray dominated regions (XDR)** are affected by X-rays with hν=1-100 keV with larger penetration depth than in PDRs. Thus XDRs are signified by large bulk temperatures $>$ 100 K and a chemical structure typical of the special ion-neutral chemistry triggered by the irradiation of X-rays. (e.g. Maloney et al., 1996; Meijerink and Spaans, 2005); **Cosmic ray dominated region (CDR or CRDR)** are regions of elevated ($> 10^3 \times$ Galactic value) cosmic ray energy density (e.g. Suchkov et al., 1993; Meijerink et al., 2011) primarily originating from supernovae; **Dense shielded regions** Hot core-like chemistry can dominate in warm, shielded regions with temperatures ranging from 50 to 500 K (e.g. Nomura and Millar, 2004; Viti, 2005). Icy grain mantles are released affecting chemistry and the intense infrared (IR) radiation fields impact the molecular excitation (Costagliola and Aalto, 2010; Sakamoto et al., 2010); **Mechanically dominated region** The chemistry reflects the speed of the shock and thus the level of grain processing (e.g. Viti et al., 2011; Kazandjian et al., 2012). Milder shocks results in evaporation of icy mantles and in more violent shocks the grain cores may be affected. There will be a mixture of scenarios in galaxies even at high spatial resolution and it is a challenge to identify dominant conditions and key tracers.

1.1 Some useful molecular emission lines and ratios

By 2015 at total of 60 molecular species have been detected in external galaxies (see http://www.astro.uni-koeln.de/cdms/molecules). Intensity ratios of emission lines are often used to identify various astrochemical scenarios and/or physical conditions in the gas. Below is a short list of a few popular molecular lines and ratios (for a longer account see Aalto (2013)).

HCN, HCO^+ and HNC: In the molecular cores around some AGNs elevated HCN/HCO^+ 1–0 intensity ratios have been found (e.g. Kohno, 2003; Imanishi et al., 2009) and also in some ULIRGs (Graciá-Carpio et al., 2006, e.g.). It is not clear if the HCO^+ abundance is suppressed or enhanced relative to HCN in XDRs (e.g. Maloney et al., 1996; Meijerink and Spaans, 2005), but HCN is expected to be enhanced in warm and shocked environments (e.g. Aalto et al., 2012a; Kazandjian et al., 2012). Thus, it is possible that HCN/HCO^+ 1–0 ratios are generally elevated in compact molecular regions towards galaxy nuclei regardless of the nature of the buried activity. Recently, the detection of self-absorbed HCN and HCO^+ towards compact obscured nuclei shows that the line ratio may be difficult to interpret in environments with large $N(H_2)> 10^{24}$ cm^{-2} (Aalto et al., 2015b). In addition, elevated HCN/HCO$^+$ ratios are also found in galaxies with no obvious AGN component (Privon et al., 2015).

In cold ($T < 24$ K) gas HNC/HCN abundance ratios are expected to be greater than unity while in dense, warmer gas and in shocked gas X(HCN)>X(HNC) (Schilke et al., 1992). However, in XDRs and PDRs X(HCN)$\gtrsim X$(HNC) also in warm gas (Meijerink and Spaans, 2005) which complicates the use of the HCN/HNC abundance ratio as a tracer of gas temperature. Surveys reveal that global HCN/HNC 1–0 intensity ratios in luminous galaxies often range between 1 and 6 (e.g. Aalto et al., 2002; Baan et al., 2010), but there are cases where the HNC/HCN 3–2 intensity ratio exceeds unity (Aalto et al., 2007b, 2009). The cause for this "overluminosity" of HNC (e.g. in Arp 220) has been debated and studies of isotopomers of HCN and HNC in Arp220 suggest that HNC is somewhat underabundant and its overluminosity is due to excitation and radiative transport effects (Tunnard et al., 2015).

HC_3N and CN Surveys have revealed a subset of luminous galaxies with unusually bright HC_3N 10–9 emission compared to HCN 1–0 (Lindberg et al., 2011; Costagliola et al., 2011). HC_3N is destroyed by UV and particle radiation and in the Galaxy it can be found in high abundance in hot cores and in general in dense and shielded gas. Interestingly, luminous HC_3N emission has also been found near AGN nuclei such as Mrk231 (Aalto et al., 2012a) and NGC1097 (Martín et al., 2015). In contrast to HC_3N, enhancement of CN is expected in XDRs and in PDRs (e.g. Aalto et al., 2002; Baan et al., 2010; Meijerink and Spaans, 2005). CN is also chemically linked to HCN via photodissociation. The abundance enhancement of CN over HCN is greater in an XDR (factors 40 - 1000) than in a PDR (CN/HCN abundance ratio range from 0.5 to 2) (Meijerink and Spaans, 2005).

SiO, H_2O, HNCO, CH_3OH Shocks can form SiO through the sputtering of Si from silicate grain cores, followed by reactions between the released Si and O_2 or OH (Guillet et al., 2009). The shock must therefore be strong enough to get the Si off the grains while species such as H_2O, HNCO, CH_3OH can be released in milder events resulting in mantle evaporation. Luminous lines of H_2O are found in many U/LIRGs (González-Alfonso et al., 2010; Yang et al., 2013; Falstad et al., 2015) and see González-Alfonso et al. (2014) on modelling of H_2O in galaxies.

1.2 Observational astrochemistry

There are a large number of studies using global molecular line ratios to attempt to classify galaxies in terms of nuclear activity and evolutionary status (e.g. Aalto et al., 1995, 2002; Gao and Solomon, 2004; Graciá-Carpio et al., 2006; Krips et al., 2008; Baan et al., 2010; Lindberg et al., 2011; Costagliola et al., 2011; Privon et al., 2015). Although effects of radiative transfer and excitation are difficult to account for in these surveys, they are useful in identifying trends and searching for correlations. The new broadband receivers allow several lines to be measured simultaneously improving the accuracy of the line ratios. One such example is the EVOLUTION study of U/LIRGs with the EMIR receiver at the IRAM 30m telescope (Costagliola et al., 2011). Simultaneous observations of HCN, HCO^+, HNC, HC_3N, C_2H, SiO and CO, ^{13}CO, $C^{18}O$, CN were correlated with nature of activity, PAH EW and silicate strength. The Herschel satellite also provied an unprecedented view of the molecular ISM of galaxies - for example through surveys of high-J lines of CO (e.g. Greve et al., 2014; Rosenberg et al., 2015).

Combining many lines simultaneously in a spectral scan will give a more complete (and complex) picture of the chemical status of a galaxy. This includes emission from rarer species with clearer diagnostic value. Spectral scans of U/LIRGs including NGC253, M82, M83, M51, NGC7469, NGC1097, NGC1068, Arp220, Mrk231 have been carried out at 1, 2 and 3 mm wavelengths with the IRAM 30m, the Nobeyama 45m telescope, the SMA and ALMA (e.g. Martín et al., 2006; Nakajima et al., 2011; Aladro et al., 2011; Martín et al., 2011; Aladro et al., 2012, 2015; Martín et al., 2015; Meier et al., 2015). An ALMA spectral scan of the LIRG NGC4418 (band 3,6,7) (Costagliola et al., 2015) reveal a rich spectrum dominated by vibrationally excited species of e.g. HCN and HC_3N (Aalto et al., 2007a; Costagliola and Aalto, 2010; Sakamoto et al., 2010, 2013; Costagliola et al., 2013). Herschel has targeted many U/LIRGs including Arp220, Mrk231, Zw049.057 (e.g. van der Werf et al., 2010; Rangwala et al., 2011; Falstad et al., 2015).

1.2.1 Astrochemistry at high spatial resolution

Interferometric studies provide both spatial resolution and sufficient pointing accuracy to allow us to separate regions of different dominant chemical processes. Studies of starbursts, bars and disks include IC 342 and Maffei 2 (Meier and Turner, 2005, 2012), M51 (Watanabe et al., 2014) and M33 (Buchbender et al., 2013). ALMA high resolution astrochemistry studies are now beginning to appear in the literature. One example is the nucleus of the nearby Seyfert/starburst NGC1068 (García-Burillo et al., 2014; Viti et al., 2014; Takano et al., 2014; Nakajima et al., 2015).

2 Molecular excitation - IR pumping of molecules

When we interpret mm and submm molecular spectra from external galaxies we usually assume that the excitation is dominated by collisions with H_2. However, there are also other possible mechanisms including IR radiative excitation where molecules absorb IR continuum which affects the excitation of the rotational levels in the vibrational ground state. For example, HCN can absorb IR-photons to the bending mode (its first vibrational state) and then it decays back to the ground state via its P-branch (ν = 1-0, ΔJ = +1) or R-branch (ν = 1-0, ΔJ = -1). In this way, a vibrational excitation may produce a change in the rotational state in the ground level and can be treated (effectively) as a collisional excitation in the statistical equations (Aalto et al., 2007b; Matsushita et al., 2015). For HCN the mode occurs at $\lambda = 14$ μm (713.5 cm^{-1}), energy level $h\nu/k = 1027$ K.

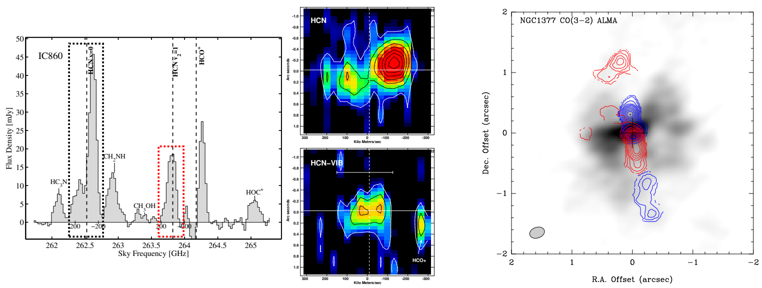

Fig. 1. Right: IRAM HCN, HCN-VIB and HCO^+ spectra and PV diagrams of the LIRG IC860 (Aalto et al., 2015b). Note the extremely bright emission from the HCN-VIB line. Left: ALMA Cycle2 CO 3–2 integrated intensity image of NGC1377 where systemic velocity (0 to ± 60 $\mathrm{km\,s^{-1}}$) emissionis shown in gray scale and the high velocity (±60 to ±180 $\mathrm{km\,s^{-1}}$) emission in red and blue contours (showing the velocity reversals) (Aalto et al., 2015a)

Recent results toward dust obscured galaxies show the presence of rotational lines from vibrationally excited HCN, HC_3N and HNC (Aalto et al., 2007a; Costagliola and Aalto, 2010; Sakamoto et al., 2010; Martín et al., 2011; Sakamoto et al., 2013; Costagliola et al., 2013; Aalto et al., 2015c,b; Costagliola et al., 2015). *These lines appear near the lines in the vibrational ground state (Fig.1) and can be used to probe inside the optically thick dust cocoons in the nuclei of deeply obscured galaxies.* Therefore, vibrationally excited lines open up a new interesting avenue to gain access to the most obscured AGNs and starbursts.

2.1 Vibrationally excited HCN in extremely obscured nuclei.

High resolution IRAM PdBI and ALMA mm and submm observations of the U/LIRGs IRAS17208-0014, Arp220, IC860 (Fig.1) and Zw049.057 show intense line emission from vibrationally excited (ν_2=1) J=3–2 and 4–3 HCN (Aalto et al., 2015b). The emission is emerging from buried, compact (r <17-70 pc) nuclei that have very high implied mid-infrared surface brightness $>5 \times 10^{13}$ $L_\odot$ $\mathrm{kpc^{-2}}$. These nuclei are likely powered by accreting supermassive black holes (SMBHs) and/or hot (>200 K) extreme starbursts. In contrast, the ground vibrational state (ν=0), J=3–2 and 4–3 rotational lines of HCN and HCO^+ fail to probe these highly enshrouded, compact nuclear regions due to strong self- and continuum absorption.

3 Molecular outflows

Outflows driven by AGNs and/or starbursts represent a strong and direct mechanism for feedback that may clear central regions of fuel for star formation or black hole (BH) growth. Many galactic winds and outflows carry large amounts of molecular gas and dust with them and there is a growing list of examples of molecular gas in outflows in nearby galaxies (e.g. Nakai et al., 1987; García-Burillo et al., 2000, 2001; Walter et al., 2002; Sakamoto et al., 2006; Tsai et al., 2009; Fischer et al., 2010; Feruglio et al., 2010; Alatalo et al., 2011; Sturm et al., 2011; Aalto et al., 2012a,b; Bolatto et al., 2013; Sakamoto et al., 2014; Veilleux et al., 2013; Cicone et al., 2014; García-Burillo et al., 2014; Matsushita et al., 2015; Aalto et al., 2015c). Studying the physical and chemical conditions of the outflowing molecular gas will help us understand the driving mechanism, origin of the gas and its fate in the wind. *Interestingly, the Mrk231 outflow has very bright HCN emission* (Aalto et al., 2012a, 2015c). This can be explained by the presence of dense ($n > 10^4$ cm^{-3}) gas in the outflow and with an elevated HCN abundance (possibly due to shocks). HCN enhancements have also been seen in other AGN-driven outflows such as M51 (Matsushita et al., 2015); NGC1068 (García-Burillo et al., 2014), NGC7469 (Izumi et al submitted). Recently, emission from the CN radical is found to be luminous in the NGC3256 outflow (Sakamoto et al., 2014) and in Mrk231 (Cicone, priv. com.). Mrk231 also show evidence of chemical differentiation it the outflow (Lindberg et al. submitted).

With the high resolution, high sensitivity capacity of ALMA it is possible to image molecular outflows in unprecedented detail (e.g. NGC253 (Bolatto et al., 2013)). With ALMA Cycle 2 CO 3–2 imaging we have discovered an extremely collimated, 200 pc scale, molecular outflow in the nearby lenticular galaxy NGC1377. *Remarkably, the outflow reverses direction near the nucleus* - apparently along the same line of sight (Fig. 1). A molecular bipolar jet precessing around an axis near the plane of the sky can reproduce observations.

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