Hunt for Molecules
F. Combes, F. Casoli, E. Falgarone, L. Pagani (eds)

HUNT FOR MOLECULES IN LOCAL UNIVERSE GALAXIES

García-Burillo, S.[1], Fuente, A.[1], Martín-Pintado, J.[2], Usero, A.[1], Graciá-Carpio, J.[1] and Planesas, P.[1]

Abstract. A complete understanding of the physical and chemical evolution of molecular gas in starbursts and active galaxies (AGN) requires the use of specific tracers of the relevant energetic phenomena that are known to be at work in these galaxies: large-scale shocks, strong UV fields, cosmic rays and X-rays. Results of a combined survey using the IRAM 30m and Plateau de Bure interferometer(PdBI) to study the chemistry of molecular gas in a sample of starbursts and AGN of the local Universe are presented.

1 Extragalactic chemistry at z=0

The correct interpretation of mm-observations of the high-z Universe galaxies, to be made with future mm interferometers (e.g., ALMA), will depend on the availability of multi-wavelength studies made in a number of local Universe galaxies used as templates. Current mm-interferometers can zoom in on the scales of individual GMCs or GMAs in nearby galaxies, and provide a complete view of the physical and chemical status of their dense molecular gas reservoirs. In particular, detailed studies of starbursts in the

---

[1] Observatorio Astronómico Nacional-OAN, Observatorio de Madrid, Alfonso XII, 3, E-28014, Madrid, SPAIN

[2] Departamento de Astrofisíca Molecular e Infrarroja, Instituto de Estructura de la Materia, CSIC, Serrano 121, E-28006 Madrid, SPAIN

local Universe are a prerequisite to interpret how feedback processes driven by star formation operate at higher redshift galaxies (Springel & Hernquist, 2003). The spectacular energies injected in the gas reservoirs of starbursts and AGN can create a particularly harsh environment for the neutral ISM.

We report below on the results of a combined survey using the IRAM 30m and Plateau de Bure interferometer devoted to study the chemistry of molecular gas in a sample of starbursts and AGN of the local Universe. These observations track down the relevant energetic phenomena that are at work all the way along the starburst/AGN sequence: large-scale shocks, strong UV fields, and X-rays. The survey includes protoypical starbursts and AGN such as M 82, NGC 253, NGC 1068 and IC 342, as well as a sample of 16 Luminous and Ultraluminous Infrared Galaxies (LIGs and ULIGs).

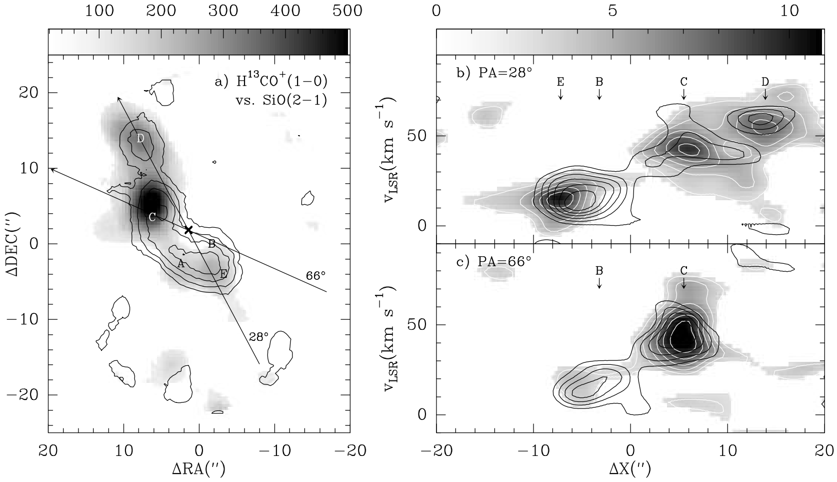

Fig. 1. SiO(2–1) and $H^{13}CO^+(1–0)$ p–v diagrams (**b** and **c**, respectively) taken along the 1D–strips highlighted in panel **a** where we overlay the SiO(2–1) (grey scale) and $H^{13}CO^+(1–0)$ (contours) intensity maps of IC 342. The p–v diagrams illustrate the contrast between the different linewidths measured for SiO and $H^{13}CO^+$ in the northern spiral arm and in the nuclear ring (see discussion of Usero et al. (2005)).

1.1 Large-scale molecular shocks in galaxies

The first SiO(v = 0, J = 2 − 1) maps made with the Plateau de Bure Interferometer (PdBI) in the nuclei of the prototypical starbursts NGC 253 and M 82 have revealed the existence of large-scale molecular shocks in galaxy disks (García-Burillo et al., 2000, 2001). In M 82, virtually all of the SiO emission traces the disk-halo interface where episodes of mass injection are building up the gaseous halo (García-Burillo et al., 2001). García-Burillo et al. (2000) have discussed the role of bar resonances at inducing shocks in the ∼600 pc circumnuclear disk (CND) of NGC 253. More recently, the high-resolution images showing the emission of SiO in the inner r∼200 pc disk of IC 342 reveal the onset of large-scale molecular shocks driven by the bar potential of this galaxy (Usero et al., 2005). The shocks arise during cloud-cloud collisions at the stage when kinetic energy has partly dissipated in turbulent motions. This explains the markedly different gas kinematics revealed by SiO and $H^{13}CO^+$ in IC 342 (see Fig. 1). The rate of energy dissipated in the shocks could be comparable to the corresponding rate of energy typically transferred by gravity torques in barred galaxies (García-Burillo et al., 2005).

Taken together, these results underline the relevant role that large-scale molecular shocks can play at shaping the evolution of gas disks. High-resolution SiO imaging is key to discern the different sources of shock chemistry which are activated at different locations and at different moments in galaxy disks during a starburst event. Being more than a mere tracer of *exotic* chemistry, SiO allows to unambiguously probe the regions where dust grains are being destroyed in galaxies due to the action of density waves, star formation and galactic outflows (García-Burillo et al., 2000, 2001; Usero et al., 2005).

1.2 PDR chemistry in starbursts: the M 82 laboratory

M 82 is one of the nearest and brightest starburst galaxies studied in virtually all wavebands. The pervasive UV field produced by the starburst episode has heavily influenced the interstellar medium in M 82 (Lord et al., 1996; Mao et al., 2000). Widespread emission of HCO has been detected in the nuclear disk of M 82 (García-Burillo et al., 2002). HCO is known to be enhanced in the interfaces between the ionized and molecular gas, making it a privileged tracer of photo-dissociation regions (PDR). The 5” HCO map

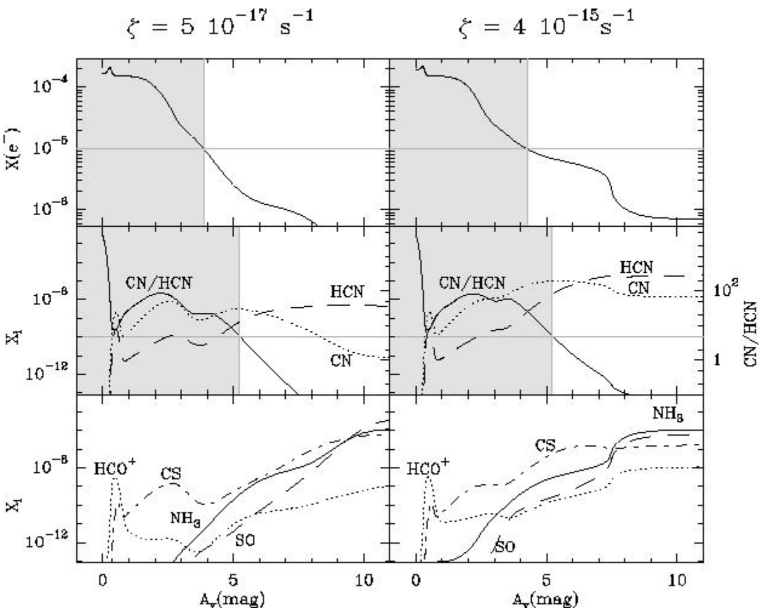

Fig. 2. Predictions for the abundances of various species derived by Fuente et al. (2005) for M 82. The calculations have been carried out for n=4×10^{5}cm^{-3} and G$_0$=10^4 in units of the Habing field. The cosmic-ray flux is set to ζ=5×10^{-17}s^{-1} (galactic value) in the left panels and ζ=4×10^{-15}s^{-1} in the right panels. We have shadowed the region of the plot in agreement with the observational results in M 82.

of M 82, the first obtained in an external galaxy, shows a ring-like distribution, also displayed by other molecular/ionized gas tracers in this galaxy. The high overall abundance of HCO in M 82 (∼4×10^{-10}) indicates that its nuclear disk has become a giant PDR of ∼650 pc size. Furthermore, the existence of a nested ring pattern, with the highest HCO abundance in the outer ring, suggests that PDR chemistry is propagating in the disk.

More recently, Fuente et al. (2005) has mapped the nucleus of M 82 in several mm-lines of CN, HCN, C_2H, c-C_3H_2, CH_3C_2H, HC_3N and HOC^+, using the IRAM 30m telescope. Most remarkably, Fuente et al. (2005) derived a high [CN]/[HCN] ratio (∼5) in all observed positions across the

M 82 nucleus. These results have been interpreted by Fuente et al. (2005) in the frame of the PDR models of Le Bourlot et al. (1993). Adopting $G_0 \sim 10^4$ and a total hydrogen nuclei density $\sim 4\times10^5$ cm^{-3}, the model predicts that [CN]/[HCN] ratios ∼5 are only reached in regions at $A_v < 5$–6 mag (Fig. 2). This sets a stringent limit to the cloud sizes in the nuclear disk of M 82. Furthermore, Fuente et al. (2005) detected the HOC^+(1–0) line with an intensity similar to that of the $H^{13}CO^+$(1–0) line. This implies a $[HCO^+]/[HOC^+]$ ratio of ∼ 40. These results corroborate the existence of a giant PDR in the nucleus of M 82.

Our studies suggest that UV-rays could be shaping the chemistry of molecular gas of extreme starbursts which are postulated to be more likely found in the high-redshift Universe. The study of local templates such as M 82 can guide the interpretation of future mm-observations to be made in higher redshift galaxies.

1.3 XDR chemistry in AGN

Molecular gas can be exposed to strong X-ray irradiation close to the central engine of active galaxies. In contrast to UV-photons, hard X-rays are efficient at penetrating huge gas column densities out to A_v=100-1000 (Maloney et al., 1996). First evidence that the chemistry of molecular gas in the CND of AGN departs from normalcy came from the large HCN/CO abundance ratio measured in the nucleus of the Seyfert 2 galaxy NGC 1068 (Sternberg et al., 1994). Later observations by Usero et al. (2004) detected SiO emission coming from the CND of NGC 1068. The derived SiO abundances are enhanced out to $\sim10^{-9}$. Silicon chemistry in the CND is driven either by X-rays or by violent shocks near the central engine. To bring some light into the 'obscuring torus chemistry' Usero et al. (2004) made complementary observations with the 30m telescope and PdBI for eight molecular species, chosen to explore the predictions of XDR models for molecular gas. Observations included several lines of CN, HCO, $H^{13}CO^+$, $H^{12}CO^+$, HOC^+, HCN, CS and CO. A first analysis of this survey has shown that the bulk of the molecular gas emission in the CND of NGC 1068 can be interpreted as coming from a giant XDR (Usero et al., 2004).

2 Extragalactic chemistry in ULIGs: the way to the high-z Universe

ULIGs may represent the local examples of the high redshift galaxies that dominate the IR and submm backgrounds (e.g., Blain et al., 1999). LIGs and ULIGs possess large amounts of molecular gas as derived from CO(1–0) observations (Sanders et al., 1991). Sanders et al. (1988) reported that the infrared–to–CO luminosity ratio in ULIGs is anomalously high compared to that of normal galaxies and interpreted this result as evidence of the AGN power source scenario for ULIGs. On the other hand, Gao & Solomon (2004) used HCN(1–0) observations to probe the dense molecular gas content of a sample of 65 nearby galaxies, including 25 LIGs and 6 ULIGs. Their results, showing a tight linear correlation between the IR and HCN luminosities over 3 orders of magnitude in $L_{\rm IR}$, were interpreted in terms of star formation as being the main power source in ULIGs. However, doubts have been casted on the reliability of HCN as an unbiased tracer of dense molecular gas in LIGs and ULIGs. First, X-rays may significantly enhance HCN abundances in enshrouded AGN (Maloney et al., 1996; Kohno et al., 2001; Usero et al., 2004). Furthermore the excitation of HCN lines in LIGs and ULIGs might be affected by IR pumping through a $14\,\mu$m vibrational transition (Aalto et al., 1995). Taking together, the possible caveats on the use of HCN observations call for the use of alternative tracers of dense gas in LIGs and ULIGs.

Graciá-Carpio et al. (2005) completed recently observations with the IRAM 30m telescope in the 1–0 line of HCO^+ of a sample of 16 galaxies including 10 LIGs and 6 ULIGs. Preliminary results of this HCO^+ survey, the first ever conducted in LIGs and ULIGs, indicate that the HCN/HCO^+ luminosity ratio sharply increases with $L_{\rm IR}$ for LIGs and ULIGs (Fig. 3). This intriguing trend provides indicative evidence that HCN is not a fair tracer of dense gas in the most extreme LIGs. In particular, the application to our sample of the diagnostic tool originally designed by Kohno (2005) to distinguish between 'pure' AGN and 'composite' starbursts+AGN in nearby Seyferts, reveals that a large number of embedded AGN lie in LIGs and ULIGs (Fig. 3). The most plausible scenario accounting for the observed trends implies that X-rays shapes the chemistry of molecular gas at $L_{\rm IR} > 10^{12}\,L_\odot$ (see discussion in Graciá-Carpio et al. (2005)).

The future extension of this work to galaxies with higher $L_{\rm IR}$ (HyLIGs and high-z submm sources) will help to shed light on the relative contribution of star formation and AGN to the huge infrared luminosity of higher redshift objects.

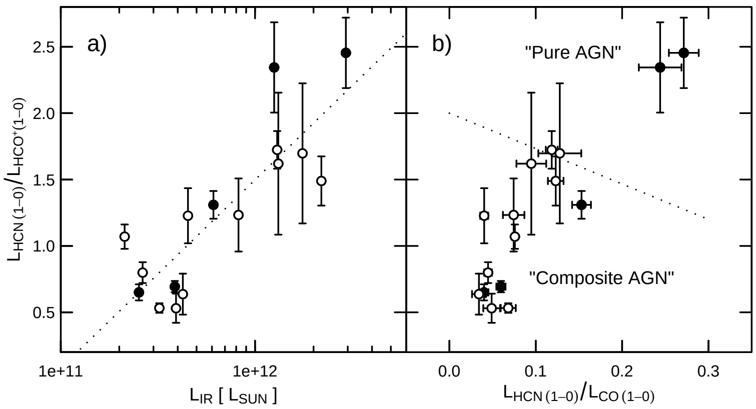

Fig. 3. a) The correlation between the HCN(1–0)/HCO$^+$(1–0) luminosity ratio and $L_{\rm IR}$ is displayed for the sample of LIGs and ULIGs analyzed by Graciá-Carpio et al. (2005). **b)** We show the location of LIGs and ULIGs in the 2D diagnostic diagram of Kohno (2005), distinguishing 'pure' from 'composite' AGN. Filled symbols represent LIGs and ULIGs for which secure identification of embedded AGN are obtained in at least two wavelengths.

References

Aalto, S., Booth, R. S., Black, J. H., & Johansson, L. E. B. 1995, A&A, 300, 369

Blain, A. W., Smail, I., Ivison, R. J., & Kneib, J.-P. 1999, MNRAS, 302, 632

Fuente A., García-Burillo, S., Gerin, M., Teyssier, D., Usero, A., Rizzo, J. R., & de Vicente, P. 2005, ApJL, 619, L155

Gao, Y., & Solomon, P. M. 2004, ApJ, 606, 271

García-Burillo, S., Martín-Pintado, J., Fuente, A., & Neri, R. 2000, A&A, 355, 499

García-Burillo, S., Martín-Pintado, J., Fuente, A., & Neri, R. 2001, ApJL, 563, L27

García-Burillo, S., Martín-Pintado, J., Fuente, A., Usero, A., & Neri, R. 2002, ApJL, 575, L55

García-Burillo, S., Combes, F., Schinnerer, E., Boone, F., & Hunt, L. K. 2005, A&A, 441, 1011

Graciá-Carpio, J., García-Burillo, S., Planesas, P. & Colina. L. 2006, ApJL, 640, 135

Kohno, K., Matsushita, S., Vila-Vilaró, B., Okumura, S. K., Shibatsuka, T., Okiura, M., Ishizuki, S., & Kawabe, R. 2001, ASP Conf. Ser. 249: The Central Kiloparsec of Starbursts and AGN: 249, 672

Kohno, K. 2005, AIP Conf. Proc. 783: The Evolution of Starbursts, 783, 203

Le Bourlot, J., Pineau Des Forets, G., Roueff, E., & Flower, D. R. 1993, A&A, 267, 233

Lord S.D., Hollenbach D.J., Haas M.R., Rubin R.H., Colgan S.W.J., Erickson E.F. 1996, ApJ, 465, 703

Mao R.Q., Henkel C., Schulz A. et al. 2000, A&A 358, 433

Maloney, P. R., Hollenbach, D. J., & Tielens, A.G.G.M., 1996, ApJ, 466, 561

Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z. 1988, ApJ, 325, 74

Sanders, D. B., Scoville, N. Z., & Soifer, B. T. 1991, ApJ, 370, 158

Springel, V., & Hernquist, L. 2003, MNRAS, 339, 312

Sternberg, A., Genzel, R., Tacconi, L. J., 1994 ApJ, 436, L131

Usero, A., García-Burillo, S., Fuente A., Martín-Pintado, J., & Rodríguez-Fernndez, N. J., 2004, A&A, 419, 897

Usero, A., García-Burillo, S., Martín-Pintado, J., Fuente, A., & Neri, R. 2006, A&A, 448, 457