GALAXIES

https://doi.org/10.1017/S0074180900009645 Published online by Cambridge University Press

PHYSICAL PROPERTIES AND KINEMATICS OF THE MOLECULAR GAS NEAR GALAXY NUCLEI

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Abstract. During the last decade there have been enormous steps forward in our understanding of the molecular gas properties of other galaxies, due to the huge increase in sensitivity and spatial resolution of instruments in the millimeter and submillimeter wavelength ranges. In particular, the emphasis has shifted from trying to *detect* CO in a variety of objects to studying the gas distributions and kinematics in a variety of species and transitions. For nearby galaxies, we are now able to study the physical and chemical processes occurring in the molecular gas over GMC size scales. Here I discuss a few examples of progress made in the study of galaxy nuclei.

1. Introduction

The increase in sensitivity and spatial resolution of instruments in the millimeter and submillimeter wavelength bands in the last 5–10 years has lead to a wealth of new information about the conditions of molecular gas in the nuclei of galaxies spanning a wide range of activity and redshift. Observations at very high spatial resolution are now being made in a variety of molecular species (such as HCN and CS in addition to CO) and transitions in nearby active galactic nuclei (AGN) and starburst galaxies (e.g Kohno et al. 1996; Tacconi et al. 1994, 1996a; Helfer & Blitz 1995; Paglione, Tosaki & Jackson 1995). One goal of these studies is to understand the kinematics of the gas in order to get accurate estimates of the enclosed mass in the circumnuclear regions and to identify the important mechanisms which are transporting the molecular fuel to feed the powerful AGN and starbursts. Another important aspect is that with the high spatial resolution now available, it is possible to estimate molecular gas densities, column

E. F. van Dishoeck (ed.), Molecules in Astrophysics: Probes and Processes, 489–500.

https://doi.org/10.1017/S0074180900009645 Published online by Cambridge University Press

densities, temperatures and abundances in the gas associated with narrow line regions and circumnuclear starbursts with little contamination from the more quiescent disk molecular gas. Moreover, high resolution and sensitivity molecular line observations are crucial to assess the validity of unified schemes for AGN, and to study the relationships among circumnuclear starbursts, AGN, and IR ultraluminous galaxies (ULIRGs). For example, major efforts have been devoted to determining whether the extreme FIR luminosity of the ULIRGs arises primarily from a dust-enshrouded quasar or other AGN (e.g., Sanders et al. 1988), an extreme starburst (e.g., Armus, Heckman & Miley 1989), or both.

This paper discusses high resolution, often multi-wavelength observations made over the last few years with an emphasis on how these observations of the molecular gas have improved our understanding of galaxy nuclei in general. I present results from "template" starburst and Seyfert nuclei in sections 2 and 3. Section 4 is a brief review of the wealth of new information on the IR luminous galaxies.

2. Starburst nuclei

2.1. NGC 253

Being one of the brightest and closest starburst galaxies, NGC 253 has been the subject of many molecular gas studies. Early interferometric CO observations by Canzian et al. (1988) made at $7''$ resolution show that the molecular gas is distributed in a central bar which is coincident with the bar seen in the optical, near- and mid-infrared (Forbes & DePoy 1992; Pina et al. 1992; Scoville et al. 1985), and is the location of a massive starburst. More recent observations of CS and HCN at higher spatial resolution show that much of the emission along the bar breaks up into many unresolved clumps (Peng et al. 1996; Paglione et al. 1995). Convolving their higher resolution HCN map to the $7''$ resolution of the CO, Paglione et al. (1995) find that the HCN $J = 1 \rightarrow 0$/CO $J = 1 \rightarrow 0$ ratio is 0.2 in many complexes along the bar. This ratio can be an indication of the amount of dense gas, and the high ratio in NGC 253 implies that the molecular clouds are much denser than standard Milky Way dark clouds. Combining the interferometric HCN and CO data with single dish observations of higher-J lines to make an excitation model for the HCN clouds in the bar, Paglione et al. find that $T \geq 100$ K and $n(H_2) \sim 10^4 - 10^5$ cm^{-3}. Although the distribution of these clouds is reminiscent of the HCN distribution in the central regions of the Milky Way, the clouds in NGC 253 are warmer and have much higher dense gas filling factors than Galactic Center clouds when viewed at 100 pc scales.

The kinematics of the central region of NGC 253 are strongly influenced

https://doi.org/10.1017/S0074180900009645 Published online by Cambridge University Press

by the bar potential. Peng et al. (1996) have modeled the gas motions along the bar and find that, within a radius of 10″ (145 pc) of the nucleus most of the gas moves along x_2 orbits whose major axes are perpendicular to the bar axis. They conclude that the most intense star formation occurs in the clouds which move on the x_2 orbits. Gas further out flows along a cuspy x_1 orbit aligned with the stellar bar. This conclusion is supported independently by the work of Anantharamaiah & Goss (1996) in their study of radio recombination line kinematics. They find three kinematic subsystems in NGC 253, including rotation in a plane perpendicular to the disk of the galaxy, and suggest that a central bar within the main bar could be one explanation for the complicated kinematics in this starburst galaxy.

2.2. M82

M82 is very similar to NGC 253 in many of its properties and has also been studied extensively at nearly all wavelength ranges. The molecular gas distribution is characterized by a double lobed structure and a weaker nuclear peak. Shen & Lo (1996) have studied the spatial variation of the HCN and CO emission in the central 600 pc of this starburst system, and find that the HCN/CO brightness temperature ratio gets as high as 0.2 in the central 150 pc. This is similar to the highest ratio found in NGC 253. Results from multi-transition studies of HCN and CO in the central regions of M82 show a dense gas mass fraction of 10% – 40% of the total molecular gas mass in these regions (Wild et al. 1992; Brouillet & Schilke 1993; Güsten et al. 1993), consistent with such a high HCN/CO ratio. Schilke, Brouillet & Pineau des Forêts (1996; see also poster abstract from Brouillet, Schilke and Pineau des Forêts, this conference) are studying the distributions of HCN, HNC and HCO^+ in the molecular lobe, or torus, and central regions of M82 at 2″ (30 pc) spatial resolution to study the spatial variations of the dense gas at GMC scales. Thus far in their work they have found that, averaged over several GMC sized clumps, the HCN/HNC line ratio is ~ 2, comparable to what one observes towards massive star forming regions in our own Galaxy.

3. Seyfert nuclei

The unified model of active galaxies interprets differences between Seyfert 1 and Seyfert 2 nuclei in light of different viewing angles. This implies that observational properties which do not depend heavily on orientation with the line of sight would be similar in both classes of AGN. One such property is the molecular gas content of the central regions. Thus it is crucial to determine the amount, distribution and physical conditions of the molecular gas present in AGNs of different types. In this section I present a few results from the Seyfert galaxies NGC 1068, NGC 7469, and I Zw 1.

3.1. NGC 1068

NGC 1068, the archetypal Seyfert 2 galaxy, has been the cornerstone for the unified models for Seyfert galaxies ever since optical emission from an obscured broad-line region was detected in scattered light by Antonucci & Miller (1985). It is relatively nearby (D=14 Mpc; $1''$=68 pc), has large quantities of molecular gas, and so it is also the best studied Seyfert galaxy at millimeter wavelengths. High resolution interferometric observations of isotopes of CO (Planesas et al. 1991, Kaneko et al. 1992; Helfer & Blitz 1995; Papadopoulos et al. 1996), and HCN (Jackson et al. 1993; Tacconi et al. 1994; Helfer & Blitz 1995) have delineated many features. A bright molecular bar coincident with the NIR stellar bar (Thronson et al. 1989; Quirrenbach et al. 1996), and tightly wound spiral arms emanating from the bar at a radius of 1 kpc from the center are seen most clearly in the CO maps, while the HCN emission, which is thermalized at much higher densities than CO, is concentrated mainly within the central few hundred parsecs of the galaxy. The striking difference in the distributions of the different molecular gas tracers is illustrated in Figure 1, which shows integrated maps of ^{12}CO and ^{13}CO $J = 1 \rightarrow 0$, HCN $J = 1 \rightarrow 0$, and CS $J = 2 \rightarrow 1$ emission made by our group at MPE at $2'' - 4''$ resolution with the IRAM interferometer.

The bar plays a major role in the kinematics of the central regions of NGC 1068. Kinematic analyses based on CO and HCN observations show that the observed velocities in the central few hundred parsecs cannot be due to pure circular rotation, but that very large (> 100 km/s) local turbulent velocities (Tacconi et al. 1994) and elliptical streaming motions along the stellar bar (Helfer & Blitz 1995; Tacconi et al. 1996b) are almost certainly dominating the kinematics in these regions. For example, the twisted isovelocity contours seen in both the HCN and CO velocity fields in the central few hundred parsecs are classical evidence of elliptical streaming motions. Moreover, higher spatial resolution ($1.5''$) CO $J = 2 \rightarrow 1$ observations which my collaborators and I have recently made at IRAM show that the central gas concentration has a clumpy structure which resembles a twin-peaked distribution, oriented roughly perpendicular to the large-scale bar. Such structures have been seen in other barred galaxies at several hundred parsec scales, and are believed to be evidence for gas orbit crowding near inner Lindblad resonances (Kenney et al. 1992). The above results all suggest that gas inflow along the bar could be an efficient mechanism to bring fuel to the center to feed the Seyfert nucleus. Future sub-arcsecond

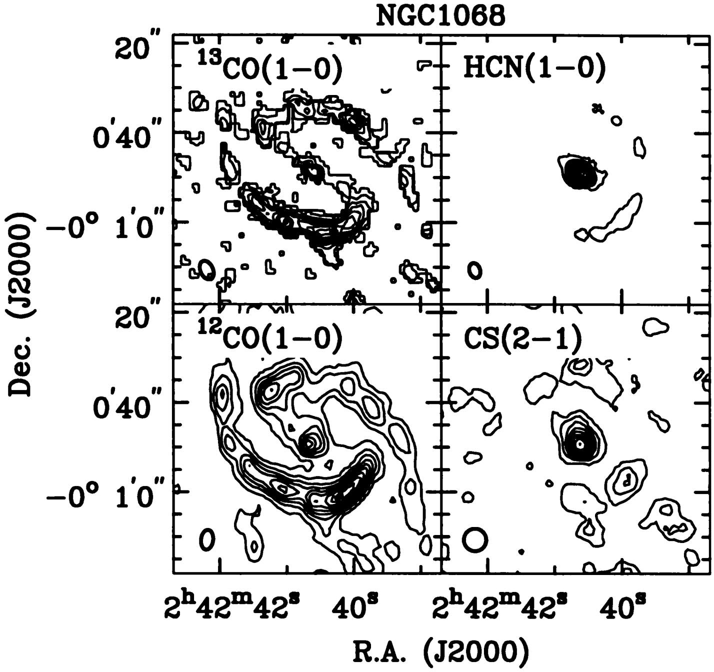

Figure 1. Contour maps of the integrated emission of CO, HCN and CS lines in NGC 1068 from Tacconi et al. (1996b), Sternberg et al. (1996), and Tacconi et al. (1994). The HCN map has been divided by 4, and the ^{12}CO J=1→0 map has been divided by 7 in order to show all the maps at the same relative scale. The observed beams are shown in the bottom left corner of each panel.

resolution CO observations will further study this important issue.

One of the most interesting properties of the molecular gas in NGC 1068 is the unusually high HCN/CO brightness temperature ratio of ~1 in the central few hundred parsecs (Jackson et al. 1993; Tacconi et al. 1994; Helfer & Blitz 1995). This ratio is higher than that seen anywhere in the Galaxy except in the cores of active star forming regions, but in the case of NGC 1068 we are measuring such a high ratio over a 300 pc region. One interpretation of the HCN/CO ratio is that most of the molecular gas is in dense clumps with little surrounding diffuse envelopes, such that the filling factors of the HCN and CO emission are comparable (Jackson et al. 1993; Tacconi et al. 1994). It is likely that the molecular clouds in the central few hundred parsecs are strongly affected by the nuclear wind and radiation, and the diffuse envelopes may be stripped away to leave only the dense cores. To be sure, non-LTE radiative transfer calculations combining the HCN and CO interferometric data with single dish observations of higher-J transitions indicate gas which is warm ($T \sim 50$ K) and dense ($n(H_2) \sim 10^5$ cm^{-3}) (Tacconi et al. 1994; Sternberg, Genzel & Tacconi 1994; Helfer & Blitz 1995). The calculations of Sternberg et al. indicate that the HCN/CO *abundance* ratio is also high in the central regions of NGC 1068. Recent calculations by Sternberg, Genzel & Tacconi (1994) and Shalabiea & Greenberg (1996) show that a selective depletion of gas-phase oxygen can lead to an overproduction of HCN relative to CO. X-ray and ultraviolet measurements both show that there is a depletion of oxygen relative to solar values of at least a factor of 5 in the ionized gas component of the nuclear region (e.g., Marshall et al. 1993; Kriss et al. 1992). Such a high depletion in the molecular gas is exactly what would be required by the Sternberg et al. and Shalabiea & Greenberg models to explain the observed HCN/CO abundance ratios. High resolution observations of other molecular species and transitions, particularly HCO^+, are needed to disentangle the density and abundance effects in the central region of NGC 1068.

3.2. NGC 7469

Another galaxy containing both an AGN and an intense circumnuclear starburst is the classical Seyfert 1 galaxy, NGC 7469. At a distance of 66 Mpc, it is roughly 4 times more distant than NGC 1068. Recently the millimeter CO line (Tacconi et al. 1996a) and NIR line and continuum emission (Genzel et al. 1995) have been studied in detail in this galaxy as a benchmark for the stellar and gas properties of a typical Seyfert 1 galaxy. The K-band continuum image shows both strong emission from a central component and the bright starburst ring separated by about 1.5″ (500 pc). At the 2.5″ resolution of the CO observations, the two components are not spatially resolved, but the data do show kinematic evidence of both a ring and a central source. Tacconi et al. (1996a) have made kinematic model fits to the data and find that the main kinematic structures and the dynamic range of the observed intensities are well fit by a modestly inclined Gaussian ring density distribution with a radius of 1.5″ and FWHM = 2.5″, combined with a compact central Gaussian source with FWHM = 0.3″. The central component has an intrinsic surface brightness which is 15–20 times greater than that of the ring. This intensity distribution is very similar to that seen in the 0.4″ resolution near-infrared K-band map of Genzel et al. (1995). The velocity field of this multi-component gas distribution has a rotation curve which is moderately constant at small radii, then rises steeply in the starburst ring. Comparing the molecular gas mass to the stellar mass in the region of the starburst ring, Tacconi et al. find that the molecular gas dominates the mass in this region of NGC 7469.

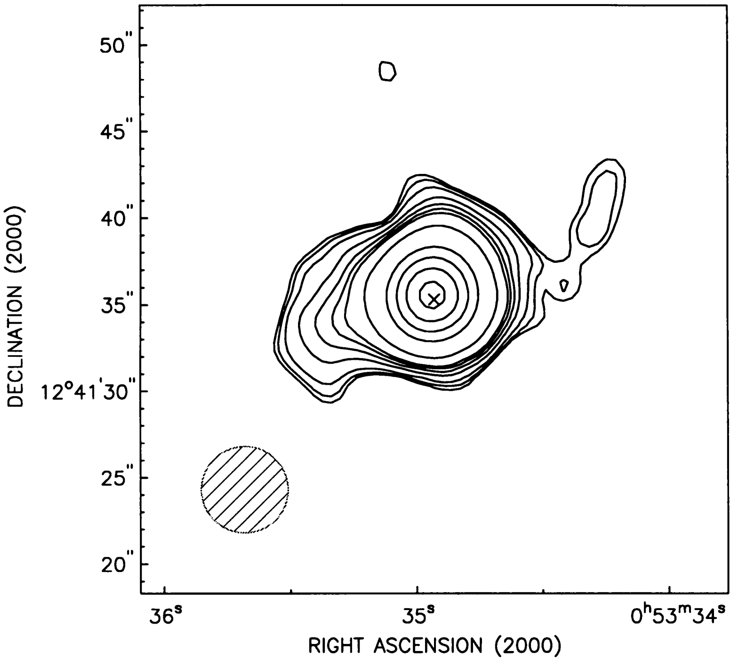

Figure 2. Contour map of the integrated emission of CO in I Zw 1 from Schinnerer et al. (1996), made at a spatial resolution of 5″. Contours are roughly logarithmically spaced and run from 3.1 to 16 Jy km s^{-1}.

3.3. I ZW 1

Extending studies of the connection between the molecular ISM and nuclear activity to more powerful active nuclei, such as QSOs, is a very important aspect for understanding the evolutionary sequences proposed for AGN. At a redshift of $z = 0.0611$ I Zw 1 is the closest QSO for which detailed studies of the host galaxy ISM are possible. I Zw 1 is a radio quiet QSO with an extremely bright optical nucleus ($M_V = -23.45$ mag), and a high x-ray luminosity (Kruper et al. 1990). The bright QSO nucleus lies in a gas-rich host galaxy, where strong CO and HI emission lines have been detected (Condon et al. 1985; Barvainis, Alloin & Antonucci 1989; Eckart et al. 1994). More recently Schinnerer et al. (1996) have mapped the CO $J = 1 \rightarrow 0$ distribution in I Zw 1 at 2″ resolution with the IRAM interferometer. In addition to a bright CO source associated with the nucleus, they detect molecular gas from the spiral arms of the host galaxy (Figure 2) for the first time. The nuclear source contains about 2/3 of the total CO flux, and has the structural and dynamical properties of a molecular gas disk

https://doi.org/10.1017/S0074180900009645 Published online by Cambridge University Press

with a diameter of about 4 kpc. Kinematic analysis of the CO maps shows that this circumnuclear disk in I Zw 1 is very much like those found in less active spiral galaxies. The peak rotational velocity in this disk is 290 ± 60 km s^{-1} and the disk is inclined to our line-of-sight by $\sim 38°$, implying a dynamical mass of 3.1×10^{10} $M_{\odot}$ for the central 4 kpc of I Zw 1. Over the same region, the inferred molecular mass is 5.5×10^{9} $M_{\odot}$. The studies made so far show the molecular gas properties in the host of this nearby QSO to be very similar to those found in the less luminous Seyfert and starburst galaxy central regions. Future studies with subarcsecond spatial resolution will determine whether this continues to be the case for gas closer to the QSO itself.

4. Infrared ultraluminous galaxies

4.1. NEARBY SYSTEMS

Infrared ultraluminous galaxies (ULIRGs) are unusual objects not only in their extreme infrared luminosities ($L_{\rm IR} > 10^{12}$ $L_{\odot}$), but also in their prodigious quantities of molecular gas as indicated from strong CO lines ($M(H_2) \sim 2 \times 10^{10}$ $M_{\odot}$; e.g., Sanders et al. 1986, 1988; Solomon et al. 1996). The ratio $L(\rm IR)/M(H_2)$, a measure of the rate of star formation per unit molecular mass, is an order of magnitude higher in these systems than in gas rich spirals (e.g., Sanders et al. 1986). In a survey of HCN emission from a large sample of ULIRGs, Solomon, Downes & Radford (1992) found that a large fraction of the molecular gas is at densities much larger than in typical Galactic giant molecular clouds. The nearest 10 ULIRGs are all either merging or have tidal tails indicative of a recent interaction or merger (Sanders et al. 1988). Moreover, Solomon et al. (1996) find that most of the galaxies in their sample of about 40 ULIRGs out to a redshift of 0.3 are interacting. The interactions likely influence the molecular gas, and may be at least partially responsible for the unusual molecular properties observed in these systems.

High resolution CO observations of the molecular gas of individual sources have now spatially resolved their gas distributions (e.g., Bryant & Scoville 1996; Downes, Solomon & Radford 1995; Scoville et al. 1995; Yun & Scoville 1995). In most cases the CO emission is found to be surprisingly compact, and extends over regions typically less than 1 kpc in size (e.g., Bryant & Scoville 1996; Scoville, Yun & Bryant 1996). Another interesting conclusion from high resolution studies of the molecular gas is that the four nearest systems all have central gas mass densities in excess of 10^{4} $M_{\odot}$ pc^{-2} (e.g., Yun and Scoville 1995). Such high gas densities could fuel starburst and/or AGN activity which is also often associated with ultraluminous galaxies. As more high resolution observations of a variety of

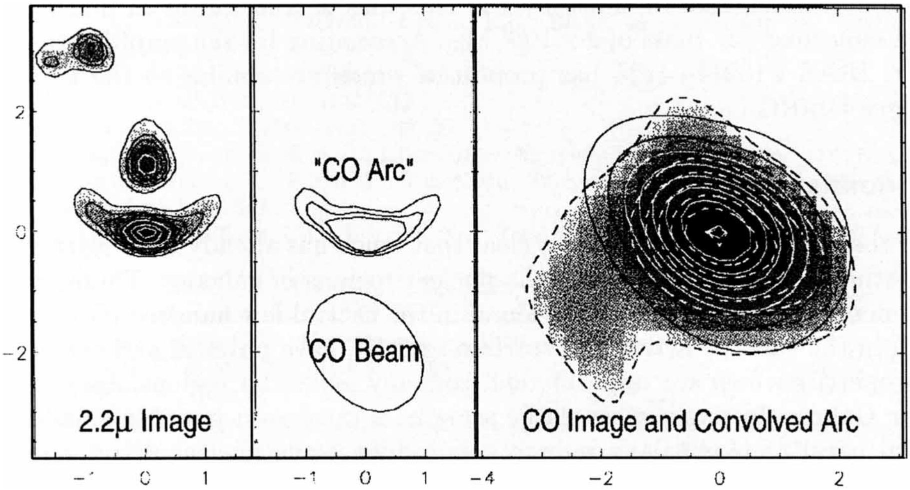

Figure 3. Figure 3 from Downes et al. (1995) showing the CO map of IRAS F10214+4724 in comparison with the 2.2μm image from the Keck. The left panel shows the Keck image in greyscale and contours; the center panel shows the arc model for the CO image; the right panel shows the CO map in greyscale and dashed contours, with CO model convolved to the CO resolution of $\sim 2''$ superposed in solid contours.

molecular species become available, there should be major breakthroughs in the understanding of these very complex systems.

4.2. ULIRGS AT HIGH Z: IRAS F10214+4724

Many observers first turned their millimeter telescopes to high redshift, luminous galaxies after the discovery of the extremely IR luminous object IRAS F10214+4724 at a redshift of 2.23 by Rowan-Robinson et al. (1991). The first CO detection followed shortly after by Brown & Vanden Bout (1991). In the last year or so, there have been many important breakthroughs in the understanding of this unusual object. Sub-arcsecond resolution near-infrared images (e.g., Graham & Liu 1995) have revealed that F10214+4724 consists of an extended, circular arc centered on a compact, weaker source. Gravitational lens models (e.g., Broadhurst & Lehár 1995) offer the best explanation for these structures. In this picture the arc is the lensed IRAS source, which is centered on the weaker intervening lensing galaxy. Recent CO $J = 3 \rightarrow 2$ maps made with $\sim 2''$ resolution (Downes, Solomon & Radford 1995; Scoville et al. 1995) reveal that the molecular gas is also extended. Downes, Solomon & Radford have convolved the NIR arc down to the resolution of their CO image, and find that the result fits the CO data very well (Figure 3). They have also calculated that the CO

https://doi.org/10.1017/S0074180900009645 Published online by Cambridge University Press

emission is magnified 10 times by the lens, has a true radius of 400 pc, and a molecular gas mass of 2×10^{10} $M_\odot$. Accounting for the amplification factor, IRAS F10214+4724 has properties which are similar to the local universe ULIRGS.

5. Summary

From the examples given here it is clear that much has already been learned from studies of molecular gas in the nuclear regions of galaxies. There are often dense concentrations of gas found in the central few hundred parsecs, which in the cases of active and starburst nuclei, have physical and chemical properties which are very different from any molecular regions observed in our Galaxy. In many cases, large scale bars (and even possibly smaller central bars) and/or galaxy interactions influence the nuclear activity by supplying the fuel to the AGN or starburst. These dynamic influences are also likely to be at least partially responsible for the extreme properties which are seen in some circumnuclear molecular clouds. The expanded capabilities of the current millimeter interferometers and the future MMA and LSA interferometers will make subarcsecond resolution observations of the dense circumnuclear gas routinely possible. Such studies will certainly provide exciting new insights into the extreme conditions faced by molecular clouds near active regions.

Acknowledgements

My warmest thanks go to Nathalie Brouillet, Dennis Downes, R. Peng, Seiichi Sakamoto, Eva Schinnerer, and Min Yun for sending me unpublished or in press results, images and/or preprints for this presentation, and allowing me to show them in my talk. I also further thank Eva Schinnerer for her help with the I Zw 1 section of this paper.

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Discussion

Hjalmarson: You mentioned that the HCN brightness in the NGC 1068 (and M 51) nuclei is as high or higher than that of CO, and that this was hard to understand. Could you please elaborate a bit on this?
Tacconi: The reason is that the *chemistry* in the nucleus of NGC 1068 may be unusual. X-ray and UV observations have shown that there is an oxygen depletion in the ionized gas in the narrow line region of NGC 1068. Models by Sternberg et al. and also Shalabiea & Greenberg show that if the same oxygen depletion exists in the *molecular* gas, one could arrive at a high HCN/CO ratio. That is, the high ratio could be due to chemistry, rather than just density arguments.

Pecker: I feel (vaguely) that magnetic fields are essential in understanding galactic evolution. How do you measure them (if at all)? Do you use them in the evolutionary processes of dust and molecules?
Tacconi: Obviously magnetic fields are important. However, it is difficult enough to measure them in the molecular clouds of our own galaxy. It would be impossible to do with current technology at the distances of most of the nuclei presented here.

Van der Tak: Are the clumps seen in NGC 253 in lines of CS and HCN actually the same? Mapping such complex fields can be quite tricky in the case of sparse UV-coverage, depending on whether you use *selfcal*, if zero spacings are available, etc.
Tacconi: Although missing flux can be a problem, particularly for extended structures, these types of structure traced by the CS and HCN lines probably do not suffer much from the effects you mentioned. For example, in the case of NGC 1068, we have compared a CO map made at $3''$ resolution at IRAM with the published map of Helfer & Blitz (1995; also similar resolution and with zero spacing) and we see very little difference in the flux level or source structure for the compact ($< 3''$) sources.

Irvine: In M 82 you reported a rather high HNC/HCN ratio. This would be surprising in warm gas. What are the physical conditions in this case?
Tacconi: These results are from Brouillet, Schilke & Pineau des Forêts. They discuss them completely in their poster at this meeting.