DENSE MOLECULAR GAS IN EXTRAGALACTIC NUCLEI

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Introduction

Until recently, molecular spectroscopy of extragalactic sources was based on the observation of a few molecules, only. From 1971 to 1980, nine molecular species have been detected, most of these with telescopes operating at cm-wavelengths (see the review of Morris and Rickard, 1982). With the exception of the widely distributed CO, only very little data had been obtained. CO is a tracer of low density molecular gas. To detect gas at higher densities ($n(H_2) \geq 10^4\,cm^{-3}$), to trace its distribution and kinematics, to determine temperatures and to study chemical properties, we set up a project with two main lines of research: (1) We attempted to enlarge the number of detected molecular species and (2) we tried to study some of these in more detail, in order to obtain astrophysically relevant results.

New molecules

The first part of the project is highly successful. During the last five years we observed CS (Henkel and Bally, 1985), CH_3OH (Henkel et al., 1987), CN, HNC, C_2H, and HC_3N (Henkel et al., 1988; Mauersberger et al., 1990), N_2H^+ (Mauersberger and Henkel, 1989a), CH_3CCH (Mauersberger et al., 1989b), and SiO (Mauersberger and Henkel, 1990a). C_3H_2 (Seaquist and Bell, 1986), SO (L. Johansson, private communication) and, tentatively, HNCO (Nguyen-Q-Rieu et al., 1989) were also detected. Except C_3H_2, all new species were first observed at mm-wavelengths, most of them with the IRAM 30-m telescope. More discoveries are expected.

The nature of the sources

The detection of SO in the LMC demonstrates, that "rare" molecules can be observed in an extremely metal poor environment. Already investigated in more detail are the nuclei of some nearby spirals, with $10^{10} L_\odot \leq L_{IR} \leq 5\, 10^{10} L_\odot$ about 10–100 times more luminous at infrared wavelengths than the Galactic center. Extremely luminous IRAS sources, like Arp 220 and Mrk 231 ($L_{IR} \sim 10^{12} L_\odot$) may also be suitable sources

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(see the contribution by S. Radford). In the following, we will confine ourselves to quasithermal lines from the nuclear regions of nearby spirals, since most data have been obtained from these sources and since masers are discussed elsewhere (see the articles of V.V. Burdyazha and J.-M. Martin).

Which of the extragalactic sources are the most interesting? The most prolific molecular line sources observable from the northern hemisphere are, in this order, NGC 253, M 82, and IC 342. It is not yet clear whether Maffei 2 is a similarly outstanding source. The by far most prominent southern (Dec $< -30°$) source is NGC 4945. At least three of these main sources exhibit nuclear bars (NGC 253, Maffei 2, and IC 342; see Canzian et al., 1988; Ishiguro et al., 1989; Ishizuki et al., 1990), which are believed to be caused by gravitational perturbations, leading eventually to inflow of gas. At least one source, M 82, appears to show a molecular ring (e.g. Baan et al., 1990). The angular size of the molecular emission regions is typically 10–30″, i.e. they are just resolved with large single dish telescopes. The spatial confinement to a few 100 pc is explained in terms of higher excitation and/or higher densities than in the surrounding medium, which may be caused by the nuclear starburst and by tidal forces, respectively.

Estimates of density and temperature

Five years ago, no multilevel study of extragalactic molecular clouds had yet been made. The first such study with the goal to estimate gas densities, based on methanol, yielded $n(H_2) < 10^6\,cm^{-3}$ for IC 342 (Henkel et al., 1987). Meanwhile multilevel studies in CS, H_2CO, and HC_3N have been made for NGC 253, IC 342, and M 82 (Mauersberger and Henkel, 1989b; Baan et al., 1990; Mauersberger et al., 1990) and main results are summarized below.

The nuclear region of NGC 253 can be modeled, in both CS and HC_3N(for some of the HC_3N spectra, see Fig. 1), by two components with densities $\sim 10^4\,cm^{-3}$ and $> 10^5\,cm^{-3}$, respectively. For the CS J=2–1 emission, a beam filling factor of ~0.2 is obtained within a region of size 11″. Toward IC342, $n(H_2) \leq 10^5\,cm^{-3}$. In M 82, there are two hotspots, ~15″ NE and SW off the nucleus, believed to form a molecular ring around the center of the galaxy. In addition to a $\sim 10^4\,cm^{-3}$ component, $\sim 10^5 cm^{-3}$ is derived for the NE source. Toward the dominating SW source, 2 cm H_2CO emission indicates even higher densities.

The first multilevel study to obtain T_{kin} is that of Martin and Ho (1986). They find 70 K toward the nucleus of IC 342. The HC_3N study of NGC 253 provides some contraints. For the higher density gas, $T_{kin} \geq 60$ K. A comparison of the HC_3N data with those from the center of our Galaxy (Walmsley et al., 1986) shows that the dense component in NGC 253 contributes more to the total HC_3N emission and appears to be hotter and denser. For M 82, a multilevel study in CH_3CCH is under way.

Source	I_{CO}/I_{HCN}	I_{CO}/I_{HCO^+}	I_{CO}/I_{CS}	I_{CO}/I_{CH_3OH}	I_{CO}/I_{CN}
NGC 253	15	17	8	32	7
Maffei 2	–	–	16	–	–
IC 342	–	–	45	54	14
M 82	35	17	40	>160	38
NGC 4945	19	21	64	51	29

Table 1. *Integrated* HCN *(1–0),* HCO^+ *(1–0),* CS *(2–1),* CH_3OH *(2–1), and* CN *(1–0) versus integrated* CO *(1–0) intensities* (I_{CO}) *(see Nguyen-Q-Rieu et al., 1989; Mauersberger et al., 1989; Henkel et al., 1990)*

Abundances

With the small size, complex density structure, and high kinetic temperature of the regions investigated here, H_2 column densities obtained from standard $I_{CO}/N(H_2)$ conversion factors are highly uncertain. Within the limits of accuracy (we estimate $\pm$ one order of magnitude), relative abundances appear to be consistent with those found in the Galaxy. More sensitive results are obtained, when directly comparing integrated line intensities. As can be inferred from Table 1, there are several striking differences among the galaxies studied so far. This is perhaps most obvious when analysing CS and CH_3OH emission in M 82 and NGC 4945. While toward M 82 it is easy to map the J=2–1 CS line (Baan et al., 1990) and while even the rare isotope $C^{34}S$ has been observed in two transitions (Mauersberger and Henkel, 1989b), we did not detect CH_3OH in several of its most prominent transitions. In NGC 4945, however, the CS J=2–1 line intensity is comparable or slightly weaker than the quadruplet of J=2–1 CH_3OH transitions at 97 GHz. Since there is strong evidence that the CS and CH_3OH lines are optically thin, the results are readily explained by a difference in relative abundances exceeding a factor 4. Another example is the remarkable strength of ammonia lines in IC 342 (Martin and Ho, 1986), while the nucleus of the richest molecular source, NGC 253, seems to be devoid of this molecule. Such large scale (>100 pc) abundance variations are remarkable. The implication is that there exist some basic differences between the nuclear regions which influence the chemistry on linear scales of up to now unprecedented lengths.

Another interesting aspect are possible abundance variations within a single nuclear region. In M 82, CO, ^{13}CO, CS, and CN are strongest in the ring ~15″ NE and SW of the nucleus. N_2H^+ J=1–0 emission, however, appears to be centrally peaked (Mauersberger and Henkel, 1990b). Also relevant within this context are the lineshapes of different molecules obtained toward NGC 4945 (compare e.g. the HCN and HNC spectra; Henkel et al., 1990), which may indicate the presence of two main molecular emission regions with different excitation and molecular abundances.

Surveys

To date, about a dozen of extragalactic nuclei have been detected in CS (see Mauersberger et al., 1989a, and Sage et al., 1990, for the bulk of these observations). CS,

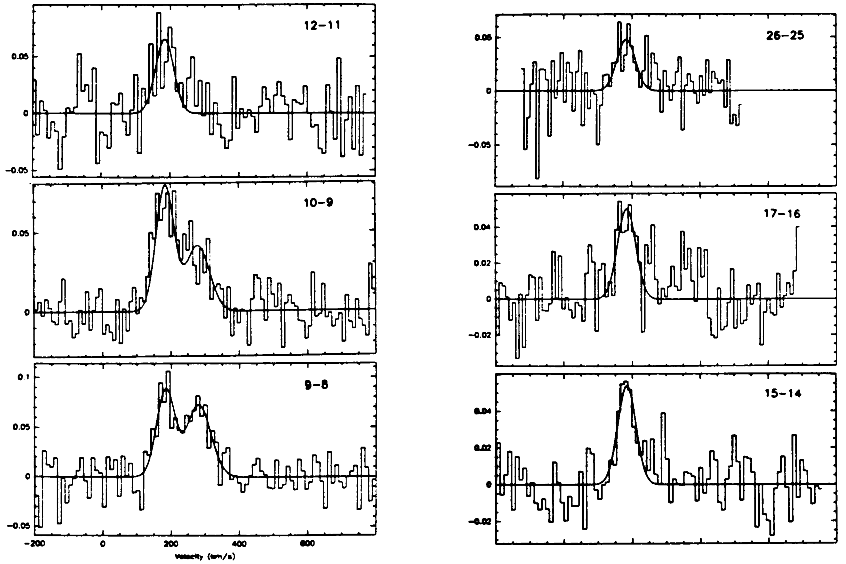

Fig. 1. HC_3N *profiles obtained with the IRAM 30-m antenna toward the nucleus of NGC 253. Since the beam size decreases with higher frequency and rotational quantum number J, two velocity components are seen in the J=9–8 and 10–9 lines but not in the higher transitions.*

CO, CII ($\lambda\,158\,\mu$m), and $S_{100\mu m}$ fluxes are correlated, indicating that CS (as CO) is tracing material in star forming regions. A weak trend for an increasing I_{CS}/I_{CO} integrated line intensity ratio with increasing infrared luminosity has to be confirmed. Such a correlation would indicate that the amount of dense relative to less dense gas ($< 10^4\,cm^{-3}$), mainly traced by CO, is increasing with increasing star forming rate. No correlation is found between I_{CS}/I_{CO} and IRAS color temperatures.

Future prospects

The results obtained so far are not more than an encouraging start. Observationally, more multilevel studies aimed to determine spatial densities and kinetic temperatures of the gas involved in the starburst are highly desirable. More detailed investigations of the LMC, SMC, and of distant but luminous IRAS galaxies would be worthwhile. The discovery of chemical differences and the interpretation of such variations may improve our knowledge of gas phase chemistry. Systematic studies of HCN and HCO^+ (the lines are stronger than those of CS; see the contribution of Nguyen-Q-Rieu) in many sources will reveal more statistical properties of the dense molecular gas.

There are additional important topics not yet addressed. The determination of isotope ratios only involving optically thin species will provide first estimates of the degree of nuclear processing within optically opaque active extragalactic nuclei. Detailed surveys for molecular lines in selected sources will tell us how much of the mm- and submm-continuum is contaminated by a superposition of a large number of weak but broad molecular features. Finally, such studies will have an important impact on our knowledge of the Milky Way. Paradoxically, it seems to be easier to obtain overall abundances of molecular species toward external galaxies than toward our own Galactic center region. Systematic surveys of molecular species other than CO and CS toward the central parts of the Galaxy will elucidate differences between the Galactic center region and the nuclei of more active extragalactic systems.

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