MODELING OF MOLECULAR EMISSION FROM CENTRES OF GALAXIES

S.AALTO
Steward Observatory
University of Arizona

1. Introduction

Evidence is mounting that the molecular clouds pervading the inner regions of galaxies are rather different from the cold Giant Molecular Clouds (GMCs) dominating the emission in the disk of our Galaxy.

The differences may be especially profound for starburst and interacting galaxies, which have a large fraction of their total ^{12}CO in the inner kpc. Due to the bright central molecular emission, multi-line mm- and submm observations are possible—shedding light on the structure and physical conditions of the molecular clouds.

2. Molecular Line Ratios

The unusual character of molecular clouds in the centres of galaxies is apparent in the measured molecular line ratios for these systems. The ^{12}CO/^{13}CO 1–0 intensity ratio ($=\mathcal{R}_{(1-0)}$) in galaxy centres is usually about a factor of two larger than the mean $\mathcal{R}_{(1-0)} \approx$ 6-7 (Polk et al. 1988) found for the disk of the Milky Way (e.g. Young and Sanders 1986; Aalto et al. 1991, 1995). Aalto et al. (1995) observed ^{12}CO and ^{13}CO 1–0 emission in 31 starburst galaxies; the mean $\mathcal{R}_{(1-0)}$ is 13 $\pm$6 for the centres of these galaxies while a few luminous mergers have $\mathcal{R}_{(1-0)} > 20$. The mean $\mathcal{R}_{(2-1)}$ (for 11 galaxies) was also 13. Out of 9 studied galaxies (NGC 3256, NGC 1808, NGC 5055, Arp299, NGC 660 NGC 2146, NGC 4048/39, NGC 6221 and NGC 7552), Aalto et al. found that $\mathcal{R}_{(1-0)}$ and $\mathcal{R}_{(2-1)}$ vary significantly with position in 6 of them. $\mathcal{R}_{(1-0)}$ is usually highest in the centre of the galaxy. The southern merger NGC 3256, for instance, has a large $\mathcal{R}_{(1-0)} =$ 35 in the centre but 5 kpc north-east of the nucleus $\mathcal{R}_{(1-0)}$ is $\approx$ 10.

In general, the ^{12}CO 2–1/1–0 intensity ratio (=r_{12}) is close to unity in centres of galaxies. Aalto et al. (1995) find a mean r_{12} of 0.93±0.22 for a set of 19 starburst galaxies, in good agreement with Braine et al. (1993) who find a mean of 0.89 for the centres of nearby spirals. The r_{12} for the disk of the Milky Way is 0.5 in the solar neighbourhood increasing to 0.75 4 kpc from the Galactic centre (Hasegawa, this volume). Aalto et al. (1995) find a mean value of 1.3 for the ^{13}CO 2–1/1–0 ratio measured in 11 galaxies, but the uncertainties are large.

In galaxy centres, the emission from CS, HCN, and HCO^+ is bright relative to ^{12}CO, indicating the presence of significant amounts of gas with densities $n > 10^4$ cm^{-3}. Aalto et al. (1995) find a mean ^{12}CO/HCN 1–0 intensity ratio of 16 for 11 starburst galaxies. Helfer and Blitz (1993) find a mean ratio of 20 for the bulges of 19 spirals.

3. Cloud Properties

A simple model consisting of a mixture of dense "cores" ($n > 10^4$ cm^{-3}) surrounded by lower density "envelopes" ($n = 10^2 - 10^3$ cm^{-3}) will, in general, reproduce the above line ratios. Although the lower-density component will have the highest volume filling factor, the bulk of the molecular mass may reside in the cores. In this scenario the ^{12}CO 1–0 emission will often be dominated by emission from the "envelopes" (large filling factor combined with high temperature) and *the optical depth of the ^{12}CO 1–0 line is moderate,* $\tau \approx 1$ rather than optically thick ($\tau >> 1$), as is often assumed for the ^{12}CO 1–0 line. The ^{13}CO 1–0 emission, on the other hand, will be characterised by a mixed contribution from the "envelopes" and cores. The ^{13}CO 1–0 line is optically thin in the "envelope" component, but may be saturated in the core clouds. Although having a smaller filling factor, the contribution from the saturated emission could be significant due to higher brightness. The dense "core-component" will be bright in high-density tracer emission.

Individually, the line ratios discussed above are not usually good indicators of temperature. The ^{12}CO 2–1/1–0 line ratio, for instance, is governed by a combination of density, temperature, and optical depth. The ratios combined into one model, however, are consistent with rather high temperatures, $T_{\rm k}$=50-100 K (e.g. Martin and Ho 1986; Mauersberger et al. 1990), for the molecular gas—at least in the "envelope"component.

The causes of spatial variations remain poorly understood, although some new clues have recently emerged. Aalto et al. (1995) report a tentative correlation between $\mathcal{R}_{(1-0)}$ and gas surface density: $\mathcal{R}_{(1-0)}$=5-10 for disks with $\Sigma = 10 - 10^2$ M$_\odot$pc^{-2}, $\mathcal{R}_{(1-0)}$=10–20 for galactic centres with $\Sigma = 10^2 - 10^4$ M$_\odot$pc^{-2}, and $\mathcal{R}_{(1-0)} > 20$ for galactic centres with $\Sigma \gtrsim 10^4$

$M_{\odot} pc^{-2}$.

4. The Effect of the Environment

The properties of the gas clouds are likely to respond to the surrounding conditions. Clouds in the inner regions of starburst galaxies experience vigorous star-forming activity and feel squeezed by the deep central potential well. Moreover, as indicated above, the gas surface density is considerably higher than that of the Galactic disk.

Using the estimates of gas surface density, one can make a simple estimate of the hydrostatic pressure associated with that gas column. Not surprisingly, this pressure is several orders of magnitude higher than that of the Milky Way disk. Given that the clouds are in equilibrium through $P_c \propto n(\Delta V)^2$, they must either be very dense or have large individual line-widths. Helfer and Blitz (1993) suggest the mean density of molecular gas is large, possibly as a result of a high ambient pressure. However, a large fraction of the ^{12}CO 1–0 emission may originate in gas at a density of only $n \approx 10^3$ cm^{-3}. These structures should have large individual line-widths in a high-pressure environment and may not be self-gravitating clouds. Even if there is a significant column density in these structures, their large line-widths (and high kinetic temperatures) will prevent the ^{12}CO 1–0 optical depths from becoming large. Starburst activity and the dissipation of turbulence are possibly important sources for heating the gas in the inner region of galaxies (e.g. Güsten 1989).

Multitransition observations of ^{12}CO and its isotopomers as well as the high-density tracers will explore the limitations of the above model. It is essential to combine data on both low and high transitions with data from various molecules for a more complete picture of the molecular ISM. Interferometric observations allow further exploration of gas distribution and kinematics and their relation to the physical conditions of the molecular gas.

References

Aalto, S., Black, J.H., Johansson, L.E.B., and Booth, R.S., 1991, A&A 249, 323
Aalto, S., Booth, R.S., Black, J.H., Johansson, L.E.B., 1995, A&A in press
Braine, J., Combes, F., Casoli, F., Dupraz, C., Gerin, M., Klein, U., Wielebinski, R., Brouillet, N., 1993, A&AS 97, 887
Güsten, R., 1989, In: *The Center of the Galaxy*, Morris M., (ed.) (Dordrecht.Kluwer) p. 89
Helfer, T.T., Blitz, L., 1993, ApJ 419, 86
Martin R.N, Ho, P.T.P., 1986, ApJ 308, L7
Mauersberger, R., Henkel, C., and Sage, L.J., 1990, A&A 236, L63
Polk, K.S., Knapp, G.R., Stark, A.A., and Wilson, R.W.,1988, ApJ 332, 432