Mem. S.A.It. Vol. 79, 1136

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Physical conditions of molecular gas in spiral galaxy centers

F.P. Israel

Sterrewacht Leiden, Leiden University Postbus 9513, 2300 RA Leiden, The Netherlands
e-mail: israel@strw.leidenuniv.nl

Abstract. The physical condition of molecular gas in galaxies is traced by multitransition ^{12}CO and ^{13}CO intensities. We report on a large survey of spiral galaxy centers. In most of these galaxies, significant concentrations of molecular gas occur within a kiloparsec from their nucleus. This gas consists of at least two components: one is hot and relatively tenuous, the other is dense and relatively cool. Much of the gas mass is in the hot component. As the CO-to-H_2 conversion factor X is much lower in galaxy centers than in the Milky Way disk, total molecular hydrogen masses are typically an order of magnitude lower than estimated by using the standard value of X.

Key words. Galaxies: nuclei – Galaxies: molecules

1. Hydrogen gas in spiral galaxies

Hydrogen makes up the bulk of the interstellar medium (ISM) mass in galaxies. It mostly occurs in the form of neutral atomic (HI) or molecular (H_2) gas which have very different spatial distributions. Overall, most of the mass is in atomic hydrogen, and the HI distribution usually extends far beyond the radius of optical light. However, in the inner regions of galaxies, molecular hydrogen is the component that dominates the ISM mass. Shocked, strongly irradiated, and heated molecular hydrogen has directly observable emission lines in the near- and mid-infrared. The bulk of the molecular hydrogen gas is much cooler and does not betray itself so easily. It can only be seen in absorption against sufficiently bright background stars. The often large amounts of low-excitation molecular hydrogen are therefore usually studied by using less abundant but more easily observed molecules (in particular CO), or radiating dust as a proxy. This introduces new problems having to do, for instance, with varying abundances and excitation conditions. A shortcut, commonly found in the literature, is to assume a fixed relation between ground state carbon monoxide (J=1-0 ^{12}CO) intensities and molecular hydrogen column densities (sometimes expressed as hydrogen mass per observing beam). This relation is calibrated assuming virialized clouds, or by assuming the Solar Neighborhood to be representative. Either assumption is highly questionable, especially when applied to very different environments such as low-metallicity dwarf galaxies or high-metallicity, (dynamically) active environments characterizing spiral galaxy centers.

Alternatively, an independent estimate of total hydrogen column densities can be based

Send offprint requests to: F.P. Israel

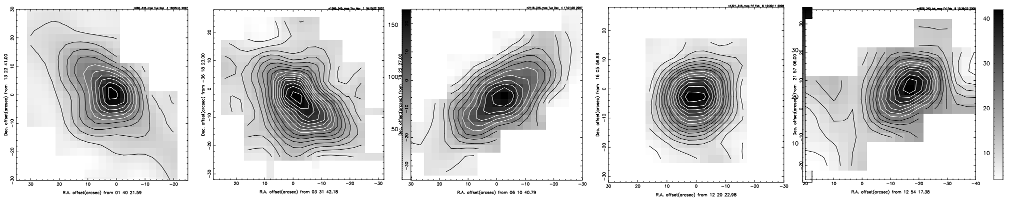

Fig. 1. Central $1' \times 1'$ J=3-2 ^{12}CO maps of (left to right) NGC 660, NGC 1365, NGC 2146, NGC 4321, and NGC 4826. Barely resolved at a resolution of $15''$, the circumnuclear CO concentration is very distinct from the extended disk CO emission

on the continuum emission from dust particles radiating at far-infrared and submillimeter wavelengths (10 μm to 1 mm). Unfortunately, the spectral energy distribution (SED) may represent dust emitting at a range of temperatures. Intensities are a strong function of dust temperature, and also depend on poorly known wavelength-dependent dust particle emissivities and dust-to-gas ratios. As the dust does traces the total (atomic and molecular) hydrogen gas, the molecular component may be estimated by subtracting the observed HI columns from the derived total H columns.

High-resolution (aperture synthesis) HI maps of spiral galaxies show that neutral hydrogen (column) densities increase towards the nucleus. At radii of a few kiloparsecs, there is usually a somewhat abrupt limit to these increases. and the central regions tend to be very poor in neutral atomic hydrogen. However, the molecular gas, concentrated in the spiral arms, takes over where the atomic gas has left off and roughly fills the HI hole by having a very distinct concentration in the inner kiloparsec. Thus, we find that H_2 seeks galaxy centers, and HI avoids them. The central kiloparsec is usually completely dominated by H_2. This dominance decreases when going outward, and the outermost parts of spiral galaxies contain atomic gas almost exclusively.

2. Survey of circumnuclear molecular gas

In the past decade, we have used large millimeter single-dish telescopes such as the 15m SEST, the 15m JCMT and the 30m IRAM telescopes to survey molecular gas in the centers of about 100 galaxies. For two thirds of this sample, we have obtained measurements in matching beams of the lower three rotational transitions of both the ^{12}CO and the ^{13}CO isotopes. In about half of those galaxies, we also mapped the central $1' \times 1'$ in both the J=2–1 and J=3–2 ^{12}CO transitions, and often in the J=4–3 ^{12}CO and $^3P_1$–$^3P_0$ [CI] transitions as well. The galaxies were mostly selected on the basis of their strong infrared (IRAS) emission.

Usually, the CO line emission is highly concentrated towards the center of the galaxy, and these concentrations stand out in very high contrast to the surrounding disk CO emission. A few starburst galaxies lack central CO concentrations, such as the almost face-on NGC 278 and the edge-on NGC 4631 but these are relatively rare. In those galaxies where we do see a clear central concentration, our resolutions of $12'' - 25''$ correspond to linear scales of half a kiloparsec to several kiloparsecs. Consequently, we do not see much spatial detail, but central line profiles frequently show a double-peaked structure and major-axis-velocity maps betray reveal structural details. A typical position-velocity map shows peak emission well away from the nucleus, and in fact a relative minimum in the center. Inferometer array maps confirm that in many galaxies the nuclear region ($R \leq 50$ pc) is indeed devoid of CO emission, but not necessarily free of molecular gas, as sometimes emission from the high-density tracer molecules HCN or HCO^+ implies the presence of a very dense and very compact ($R \leq 10$ pc) molecular source at the nucleus itself, possibly the accretion disk of the central SMBH.

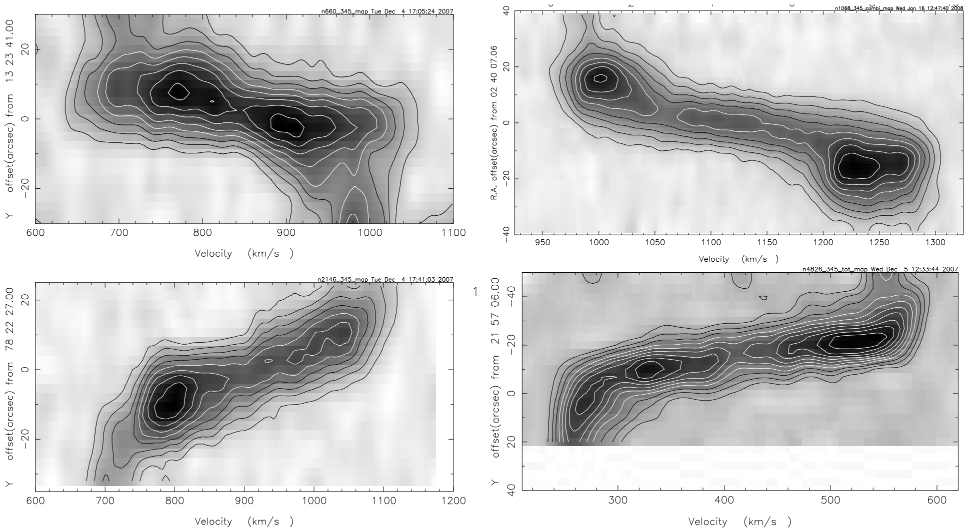

Fig. 2. Major axis position-velocity J=3-2 ^{12}CO maps of NGC 660 (top left), NGC 1068 (top right), NGC 2146 (bottom left), and NGC 4826 (bottom right) illustrate the very steep-gradient solid-body rotation of circumnuclear CO concentrations. Again, high contrast with surroundings is obvious. Although CO intensities clearly drop towards the nucleus, the limited resolution of these maps does not yet allow to determine whether or not compact nuclear molecular clouds are present

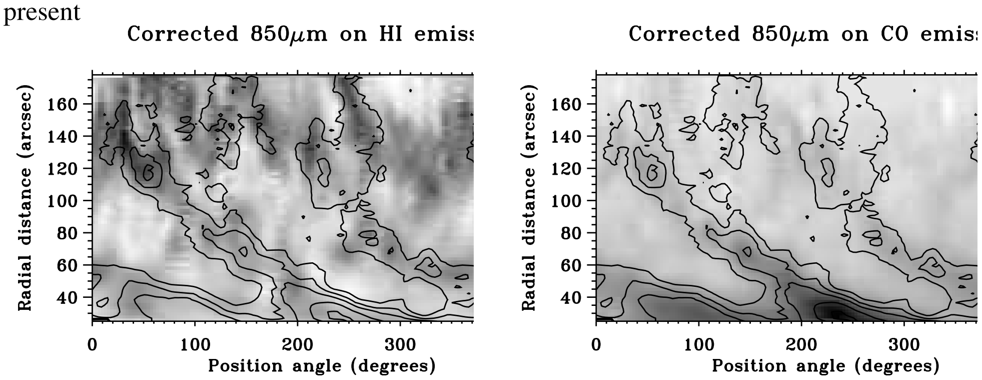

Fig. 3. The complementary nature of HI and H_2 and the smooth distribution of dust is illustrated by these diagrams in polar coordinates showing contours of 850μm continuum mission from dust superposed on grey-scales representing the HI (left) and the J=3–2 CO emission (right) from M 51.

Wherever the morphology of the inner galaxy molecular gas can be distinguished, it is almost always that of (sometimes tightly wound) spiral arms emitting intensely in CO. There is no observational justification for the assumption of disk, ring or torus geometries.

The details differ from galaxy to galaxy. For instance, the CO emission in the merger galaxy NGC 4826 (M 64) is very sharply contained within a radius R = 600 pc. This corresponds precisely to to the radius where the HI rotation curve of the galaxy reverses sign. The outer counterrotating HI gas was probably acquired from the merger. It seems likely that during the merger process, the original (molecular) disk gas lost angular momentum and moved inwards where it is now the dominating presence. In most other galaxies, the bright central CO concentration is superposed on a more diffuse, and much more extended disk CO population.

3. Physical conditions in circumnuclear gas

The physics of the dense ISM can be determined by analysis of molecular line emission, but this requires measurement of several lines and the application of proper chemical and radiative transfer models. It becomes rapidly impossible to model actual data with gas of a single temperature and density. However, we can make a simple but not unreasonable approximation of the more complex reality by assuming the presence of two distinct molecular gas components and determining their characteristics. To this end we require the measurement of at least the lower three transitions of CO in the two main isotopes. No reliable estimates can be obtained from the observation of a few lines only, especially since LTE conditions do not apply. Our sample galaxies exhibit a great variety of line ratios, reflecting conditions differing from one galaxy to another. Nevertheless, in most cases acceptable model fits are easily obtained for the simultaneous presence of lukewarm (T_{kin} = 30 – 50 K), dense ($n_{\rm H2}$ = $10^3 - 10^5$) $\rm cm^{-3}$ and hot (T_{kin} = 100 – 150 K), tenuous ($n_{\rm H2}$ = $10^2 - 10^3$) $\rm cm^{-3}$ gas in the beam. Although there are no *unique* solutions, as tradeoffs between e.g. molecular gas density and temperature are always possible, the model fits constrain possible solutions to a *limited* parameter space. Comparison of line ratios in different beams strongly suggests that the tenuous hot gas is more spread out than the cooler gas, and represents a significant fraction (up to two thirds or more) of the total molecular mass in the center.

By comparing observations made with different beam sizes, we may sometimes unravel important details. For instance, the compact circumnuclear cloud $R < 200$ pc in the nearby Seyfert galaxy NGC 1068 (M 77) consists of very dense, but also rather warm gas that appears to be excited by X-rays from the nucleus, in contrast to the more distant ($R > 1$ kpc) molecular gas that is less dense, modestly warm, and appears to be excited by the UV emission from an ambient starburst. Both the nucleus and the bar are bright in the CO dissociation product C°. Yet, in NGC 3079, an edge-on galaxy with both an AGN and a circumnuclear starburst, the C° avoids the central few hundred parsecs. The radiative transfer models used yield the physical condition (temperature and density) but not the amount of molecular gas. Nevertheless, this can be estimated if the [C]/[H] elemental abundance is known. Fortunately, this is the case for many spiral galaxies. Molecular gas mass determinations reveal a number of interesting conclusions. As already noted, the molecular gas provides most (in fact > 90%) of the total mass of the gas within the central kiloparsec. This molecular mass is often dominated by a hot, tenuous component which provides typically between a third and two thirds of the total molecular mass. Equally important is the finding that there is much less molecular hydrogen than one would expect by applying the 'standard' Solar Neighborhood conversion factor X_{MW} to the observed CO luminosities. This finding is confirmed by other authors who used dust emission to estimate molecular gas mass and reached similar conclusions for a number of individual galaxies. We find a very significant difference, with a conversion range X = $0.05 - 0.30\,X_{MW}$), implying central molecular gas mass to be an order of magnitude lower than found by naively applying X_{MW}. Although molecular gas completely dominates the ISM in the central kiloparsec, its mass is much less than that of the stars. The molecular gas mass is typically of the order of 0.3% to 3% of the dynamical mass in the same central region.

The survey data referred to here, and a more detailed discussion of the results will be presented in a forthcoming paper.