CO, $^{13}$CO and [CI] in galaxy centers

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Abstract. Measurements of [CI], $J=2\rightarrow1$ $^{13}$CO and $J=4\rightarrow3$ $^{12}$CO emission from quiescent, starburst and active galaxy centers reveal a distinct pattern characterized by relatively strong [CI] emission. The [CI] to $^{13}$CO emission ratio increases with central [CI] luminosity. It is lowest in quiescent and mild starburst centers and highest for strong starburst centers and active nuclei. C$^0$ abundances are close to, or even exceed, CO abundances. The emission is characteristic of warm and dense gas rather than either hot tenuous or cold very dense gas. The relative intensities of CO, [CI], [CII] and far-infrared emission suggest that the dominant excitation mechanism in galaxy centers may be different from that in Photon-Dominated Regions (PDRs).

Keywords: Galaxies – ISM – molecules – carbon lines

1. Introduction

Carbon monoxide (CO), the most common molecule after H$_2$, is routinely detected in external galaxies. When exposed to photons of energy greater than 11.1 eV, CO is readily photodissociated into atomic carbon and oxygen. As the C$^0$ ionization potential is only 11.3 eV, i.e. quite close to the CO dissociation energy, neutral carbon may be quickly ionized. Because carbon monoxide, its isotopes, as well as neutral and ionized carbon respond differently to ambient conditions, observations of the relative emission strengths of $^{12}$CO, $^{13}$CO, C$^0$ and C$^+$ provide significant information on the physical condition of cloud complexes from which the emission arises. Even though far-infrared continuum and [CII] lines are much more efficient coolants overall, CO and [CI] lines are especially important for the temperature balance of cool and dense molecular gas.

2. Relative intensities of CO $^{13}$CO and [CI]

CO may be observed from the ground in many transitions. Emission from C$^+$ has been observed towards numerous galaxies from the KAO and ISO platforms. Emission from C$^0$ can also be measured from the ground but only under excellent atmospheric conditions. To date, the total number of galaxies detected in [CI] is about 30. Most of the extragalactic 492 GHz [CI] measurements are summarized in just two papers,
Figure 1. [CI] (top) and $J=2–1$ $^{13}$CO (bottom) spectra observed towards galaxy centers. The vertical scale is $T_{mb}$ in K; the horizontal scale is velocity $V_{LSR}$ in km s$^{-1}$. Note decreasing ratio [CI]/$^{13}$CO going from left to right.

Almost all galaxies mapped thus far show strong concentrations of both atomic carbon and molecular gas well contained within radii $R \leq 0.5$ kpc. The area-integrated CO and [CI] luminosities of the observed galaxy centers cover a large range. Quiescent centers (NGC 7331, IC 342, Maffei 2, NGC 278, NGC 5713) have modest [CI] luminosities $\approx 1 \leq L_{[CI]} \leq 5$ K km s$^{-1}$ kpc$^2$ (with 1 K km s$^{-1}$ kpc$^2$ corresponding to $2.2 \times 10^{20}$ W). Starburst nuclei (NGC 253, NGC 660, M 82, NGC 3628, NGC 6946) have luminosities $10 \leq L_{[CI]} \leq 40$ K km s$^{-1}$ kpc$^2$, except M 83 which has only $L_{[CI]} = 3.6$ K km s$^{-1}$ kpc$^2$. The highest luminosities, $L_{[CI]} \geq 50$ K km s$^{-1}$ kpc$^2$, are found around the active nuclei of NGC 1068 and NGC 3079.

In previously observed Galactic photon-dominated regions (PDRs), the intensities of $^3P_1–^3P_0$ [CI] and $J=2–1$ $^{13}$CO line emission were generally found to be very similar (cf. Keene et al. 1996; Kaufman et al. 1999). Such ratios of $^3P_1–^3P_0$ [CI] and $J=2–1$ $^{13}$CO close to or less than unity are considered to be characteristic of the effects of enhanced
Figure 2. Left: $\text{[CI]}/(J=4-3\,^{12}\text{CO})$ ratios versus area-integrated luminosity $L_{\text{[CI]}}$. Right: $\text{[CI]}/(J=2-1\,^{13}\text{CO})$ ratios versus $L_{\text{[CI]}}$. The $I_{\text{[CI]}}(J=4-3\,^{12}\text{CO})/I_{\text{[CI]}}(3\,^{13}\text{CO})$ ratio appears to be a well-defined function of log $L_{\text{[CI]}}$; the $I_{\text{[CI]}}(J=2-1\,^{13}\text{CO})/I_{\text{[CI]}}(4-3\,^{12}\text{CO})$ ratio is not. Galactic sources (not shown) would all be crowded together in the lower left corner.

UV radiation on molecular gas in PDRs. However, Fig. 1 shows that galaxy centers may have much stronger $\text{[CI]}$ emission.

In Fig. 2 we present a full comparison of the intensities of the 492 GHz $\text{[CI]}$ line, the 461 GHz $J=4-3\,^{12}\text{CO}$ line and the 220 GHz $J=2-1\,^{13}\text{CO}$ line. The $3\,^3\text{P}_1-3\,^3\text{P}_0\,\text{[CI]}$ line is stronger than $J=2-1\,^{13}\text{CO}$ in all except three galaxies. The highest $\text{[CI]}/^{13}\text{CO}$ ratios of about five belong to the active galaxies NGC 1068 and NGC 3079. Generally, the $3\,^3\text{P}_1-3\,^3\text{P}_0\,\text{[CI]}$ line is weaker than the $J=4-3\,^{12}\text{CO}$ line, but not by much. Thus, galaxy centers have much stronger $\text{[CI]}$ emission than the Galactic PDR results would lead us to expect.

In the galaxy sample independently observed by Gerin & Phillips (2000) more than two thirds also have a ratio $\text{[CI]}/^{13}\text{CO} \geq 2$. Low ratios are expected in high-UV environments, and in environments with high gas (column) densities where virtually all carbon will be locked up in CO. In the Galaxy, high ratios are found in environments with low gas column densities and mild UV radiation fields, such as exemplified by translucent clouds and at cloud edges. There, $^{12}\text{CO}$ and especially $^{13}\text{CO}$ will be mostly dissociated, and gas-phase atomic carbon may remain neutral. In dense clouds, $\text{[CI]}$ may be relatively strong if the dominant heating mechanism is some other than UV photons. The data presented here and in Gerin & Phillips (2000) suggest that most of the emission from galaxy centers does not come from very dense, starforming molecular cloud cores or PDR zones.
Figure 3. Observed line intensity ratios [CI]/\(^{13}\)CO versus [CI]/CO 4–3 compared to LVG radiative-transfer model ratios at selected gas densities, temperatures and velocity gradients assuming an isotopic ratio \([^{12}\text{CO}]/[^{13}\text{CO}] = 40\). Galaxy centers are marked by filled hexagons, PDRs by open hexagons (LMC) or open triangles (Milky Way), and the Milky Way Center by a cross. Line families indicate abundances \(N[\text{CI}]/N(\text{CO}) = 0.1, 0.3, 1\) and 3. Within each family, a dotted line corresponds to a gradient \(N(\text{CO})/dV = 3 \times 10^{16} \text{cm}^{-2}/\text{km s}^{-1}\), solid line to \(N(\text{CO})/dV = 1 \times 10^{17} \text{cm}^{-2}/\text{km s}^{-1}\) and dashed lines to \(N(\text{CO})/dV = 3 \times 10^{17} \text{cm}^{-2}/\text{km s}^{-1}\). On each track, temperatures of 150, 100, 60, 30, 20 and 10 K are marked from left to right by small open circles.

3. Modelling of [CI], CO and \(^{13}\)CO

Very approximate column densities may be calculated assuming optically thin [CI] and \(^{13}\)CO emission in the high-temperature LTE limit, but accurate results are obtained only by more detailed radiative transfer calculations. Curves illustrating the possible physical condition of gas clouds, shown in Fig. 3, were calculated with the Leiden radiative transfer models (see http://www.strw.leidenuniv.nl/~radtrans/). The four panels correspond to molecular gas densities ranging from \(n(\text{H}_2) = 500 \text{cm}^{-3}\) to \(n(\text{H}_2) = 10000 \text{cm}^{-3}\). In each panel, mostly horizontal tracks mark CO gradients \(N(\text{CO})/dV = 0.3, 1.0\) and \(3.0 \times 10^{17} \text{cm}^{-2}/\text{km s}^{-1}\) for [C\(^{\circ}\)]/CO abundances of 0.1, 0.3, 1.0 and 3.0 respectively and kinetic temperatures ranging from 150 K (left) to 10 K (right) are marked. Lines of constant kinetic temperature would be mostly vertical in these panels. The diagrams contain points representing the observed galaxy centers as well as star-forming regions (White & Sandell 1995; Israel & Baas, unpublished; Bolatto et al. 2000) and the Milky Way center (Fixsen, Bennett & Mather 1999).
The star-forming PDRs have relatively low neutral carbon versus CO abundances $(C^\circ/CO) \approx 0.1–0.3)$. Most galaxy centers (especially the active ones) have significantly higher abundances exceeding unity, independent of the assumed gas parameters. The diagonal distribution of galaxy centers roughly follows lines of constant kinetic temperature. The actual temperatures $T_k$ and molecular gas densities $n(H_2)$ cannot be determined independently. For instance, if we assume $n = 500 \text{ cm}^{-3}$, we find $T_{\text{kin}} > 150$, whereas by assuming $n \geq 3000 \text{ cm}^{-3}$ we find more modest values $T_{\text{kin}} = 30 – 60$ K similar to the dust temperatures $33 \leq T_d \leq 52$ K found for these galaxy centers by Smith & Harvey (1996). The only available direct determination, for M 82 by Stutzki et al. (1997), yields $n \geq 10^4 \text{ cm}^{-3}$ and $T_k = 50 – 100$ K, in very good agreement with the above. Where the molecular line emission in most galaxy centers appears to arise from warm, dense gas (as opposed to either hot and tenuous or cold and very dense gas), the centers of NGC 7331, M 51 and NGC 4826 seem to be cooler independent of assumed gas density.

4. [CI], [CII] and FIR intensities

Fig. 4 combines [CI] line intensities with those of [CII] and the far-infrared continuum (for references, see Israel & Baas 2002). The results resemble those obtained by Gerin & Phillips (2000). There is no longer a clear distinction between the various types of objects. The [CII]/FIR ratio increases with [CI]/FIR, but the [CII]/[CI] ratio decreases as [CII]/FIR increases. An upper limit for [CII] places the merger galaxy NGC 660 in the same diagram positions as the ultraluminous mergers Arp 220 and Mrk 231 observed by Gerin & Phillips. The highest [CII]/FIR ratios are reached for PDR model gas densities $n = 10^3 – 10^4 \text{ cm}^{-3}$ (Gerin & Phillips 2000), but fully half of the ratios in Fig. 4 are much higher than predicted by the PDR models. In low-metallicity environments, this may be explained by longer mean free pathlengths of energetic UV photons (Israel et al. 1996). However, this is not a credible explanation for high-metallicity (see Zaritsky, Kennicutt & Huchra 1994) galaxy centers.

Ideally, the observations should be modelled by physical parameters varying as a function of location in a complex geometry. Practically, we may attempt to approach such a reality by assuming the presence of a limited number of distinct gas components. The analysis of multitransition $^{12}$CO, $^{13}$CO and [CI] observations of half a dozen galaxy centers (Israel & Baas 2003 and references therein) suggests that, within the observational errors, good fits to the data can be obtained by modelling
with combinations of dense/cool and tenuous/warm gas components. At the same time, however, the energy requirements of keeping relatively large mass fractions at relatively high temperatures, and the peculiar [CI]/[CII] ratios again suggest that exploration of excitation models other than PDRs might be fruitful.

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