Extragalactic H₂ and its variable relation to CO
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We derive and discuss the strong dependence on metallicity of the CO to H₂ conversion factor
X = N(H₂)/I_{CO} = 12.2 - 2.5 \log [O]/[H] appropriate to extragalactic objects, as well as the weaker dependence found for such objects from interferometer measurements.

1. Introduction
The difficulty of directly observing molecular hydrogen (H₂), the major constituent of the interstellar medium in galaxies, and ways of doing so indirectly are reviewed elsewhere in this volume (Combes 2000). Usually, H₂ cloud properties are derived by extrapolation from more easily conducted CO observations. For instance, observed CO cloud sizes and velocity widths yield total molecular gas masses under the assumption of virial equilibrium. However, in extragalactic systems especially, this method is beset by pitfalls (see Israel, 1997, hereafter Is97) and requires high linear resolutions (i.e. use of interferometer arrays). More seriously, the fundamental assumption of virialization appears to be false. As individual components ('clumps') have velocities of only a few km s⁻¹ and CO complex sizes are 50–100 pc, crossing times are comparable to CO complex lifetimes of only a few times 10⁷ years or less (Leisawitz et al. 1989; Fukui et al. 2000; see also Elmegreen 2000). As equilibrium cannot be reached in a single crossing time or less, the virial theorem is not applicable to such complexes. Indeed, the elongated and interconnected filamentary appearance of many large CO cloud complexes do not suggest virialized systems (see also Maloney 1990).

The observed CO intensity is the weighted product of CO brightness temperature and emitting surface area; actual CO column densities are completely hidden by high optical depths. However, in large beams CO cloud ensembles may be assumed to be statistically identical so that CO intensities scale with CO mass within the beam, i.e. beam-averaged CO column density. If we can determine the proportionality, the H₂-to-CO conversion factor X, subsequent CO measurements can be used to find the appropriate H₂ column density and mass. In the Milky Way, the calibration of X is controversial by a factor of about two (cf. Combes 2000), and frequently based on application of the virial theorem (but see preceding paragraph ...).

In other extragalactic environments, the assumption of statistical CO cloud ensemble similarity becomes questionable. Very clumpy, even fractal molecular clouds are very sensitive to e.g. variations in radiation field intensity and metallicity. As H₂ and CO, supposedly tracing H₂, react differently to such variations, X is also very sensitive to them (Maloney & Black 1988). The determination of the dependence of X on metallicity and radiation field intensity, needed to correctly estimate amounts of H₂ in environments (dwarf galaxies, galaxy centers) different from the Solar Neighbourhood thus requires H₂ mass determinations independent of CO.

2. H₂ determinations from dust continuum emission
Fortunately, H₂ and HI column densities are traced by optically thin continuum emission from associated dust particles. Unfortunately, dust emissivities depend strongly on
temperature, dust particle properties are not accurately known and dust-to-gas ratios are frequently uncertain. The effect of these uncertainties are minimized if we can avoid the need for determining absolute values of the dust column density and the dust-to-gas ratio. Far-infrared/submillimeter continuum fluxes and HI intensities from spatially nearby positions, preferably in dwarf galaxies that lack strong temperature or metallicity gradients, can be used to obtain reasonably accurate \( \text{H}_2 \) column densities (Is97). The ratio of dust continuum emission to HI column density at locations lacking substantial molecular gas provides a measure for the dust-to-gas column density ratio. Without requiring its absolute value, we can apply this measure to a nearby location rich in molecular gas to find the total hydrogen column density and, after subtraction of HI, the \( \text{H}_2 \) column density. Division by the CO intensity yields the local value of \( X \) in absolute units with an accuracy better than a factor of two (Is97).

Individual molecular cloud complexes in the nearby Magellanic Clouds were used by Is97 to determine the effects of radiation field intensity (as sampled by far-infrared surface brightness) on \( X \). Over a large range of intensities, \( X \) is linearly proportional to the radiative energy available per nucleon (\( \sigma \)). Quiescent regions in the LMC yield \( X \) values close to those of the Solar Neighbourhood, whereas a value 40 times higher is obtained for the radiation-saturated 30 Doradus region. The more metal-poor SMC exhibits higher \( X \) values, but again linearly proportional to \( \sigma \).

3. Dependence of \( X \) on metallicity

To further study the relation between \( X \) and metallicity, we have added several recent results to the database given by Is97. These include data for NGC 7331 (3 points; Israel & Baas 1999), the Milky Way center and centers of NGC 253 (both from Dahmen et al. 1998), NGC 891 (Guélin et al. 1993; Israel et al. 1999), NGC 3079 (Braine et al. 1997; Israel et al. 1998a) as well as IC 10 (Madden et al. 1997) and D 478 in M 31 (Israel et al. 1998b). Although they were obtained somewhat differently from those in Is97, they are quite comparable (Figs. 1 and 2).

In Fig. 1, radiation-corrected values \( X' = X/\sigma \) are plotted against metallicity \([\text{O}]/[\text{H}]\). In Fig. 2, values of \( X \) are plotted in its usual form. Figs. 1 and 2 yield the relations:

\[
\log X' = \log X/\sigma = -4 \log ([\text{O}]/[\text{H}]) + 33.9
\]

and

\[
\log X = -2.5 \log ([\text{O}]/[\text{H}]) + 12.2
\]

With a larger sample size, these results differ only slightly from those published by Is97. The points representing high-metallicity regions in NGC 7331 extend rather well along the relation defined by the low-metallicity dwarfs, as do those representing the galaxy centers with a larger scatter. Both correlations are highly significant. Thus, eqn. (3.2) should in general be used to convert CO intensities observed in large beams to obtain \( \text{H}_2 \) column densities within a factor of about two. Note that the result may greatly differ from that obtained by applying ‘standard’ Milky Way conversion factors (i.e. lower by a factor of 4–10 for high-metallicity galaxy centers and higher by a factor of 10–100 for low-metallicity irregular dwarf galaxies).

In Fig. 2, we have also included \( X \) values derived by virial theorem application to CO clouds mapped with interferometer arrays taken from Wilson (1995 – replacing her M 31 and M 33 metallicities by those from Garnett et al. 1999), Taylor & Wilson (1998) and Taylor et al. (1999). These points define a different dependence of \( X \) on metallicity, with a much shallower slope of only -1.0. Generally, these \( X \) values are much lower than those in Is97.
4. Discussion

A steep dependence of $X$ on metallicity can be understood within the context of photon-dominated regions (PDRs). In weak radiation fields and at high metallicities, neither H$_2$ or CO suffers much from photo-dissociation, and the CO volume will fill practically the whole H$_2$ volume. However, when radiation fields become intense, CO photo-dissociates more rapidly than H$_2$ because it is less strongly self-shielding. Thus, the projected CO emitting projected area will shrink and no longer fill that of H$_2$. The observed CO intensity, proportional to the shrinking emitting area, then requires use of a higher $X$ factor to obtain the correct, essentially unchanged H$_2$ mass. We have found that at constant metallicity, $X$ must be increased linearly with radiation field intensity.

We may somewhat quantitatively estimate the effects of metallicity on CO (self)shielding and thereby on $X$. From Garnett et al. (1999) we find that over the range covered by Figs. 1 and 2, log [C]/[H] $\propto$ 1.7 log [O]/[H]. Thus, CO abundances drop significantly more rapidly than metallicity [O]/[H], as do dust abundances given by $M_{\text{dust}}/M_{\text{gas}}$ $\propto$ 2 log [O]/[H] (Lisenfeld & Ferrara 1998). Thus, a ten times lower metallicity (cf. Figs 1 and 2) implies a [CO]/[H$_2$] ratio lower by a factor of 50, and less CO shielding by a factor of 5000! The precise effect on $X$ depends on the nature of the cloud ensemble, but at lower metallicities PDR effects very quickly increase in magnitude. In a standard H$_2$ column, there is less CO to begin with, and this smaller amount is even less capable of resisting further erosion by photodissociation. With decreasing metallicity, CO is losing both its selfshielding and its dustshielding, so that even modestly strong radiation fields completely dissociate extended but relatively low-density diffuse CO gas, leaving only embedded smaller higher-density CO clumps intact. As CO intensities primarily sample
emitting surface area, the loss of extended diffuse CO strongly reduces them, even when actual CO mass loss is still modest. Further metallicity decreases cause further erosion and molecular clumps of ever higher column density lose their CO gas. CO is thus occupying an ever-smaller fraction of the $H_2$ cloud which still fills most of the PDR. Its destruction releases a large amount of atomic carbon which is ionized and forms a large and bright cloud of CII filling the entire PDR. This and the expected anticorrelation between CO and CII intensities is indeed observed in the Magellanic Clouds and in IC 10 (Is97; Israel et al. 1996; Madden et al. 1997; Bolatto et al. 2000). As the strongly selfshielding $H_2$ is still filling most of the PDR (cf. Maloney & Black 1988), the appropriate value of $X$ becomes ever higher. In the extreme case of total CO dissociation, any amount of $H_2$ left defines an infinitely large value of $X$!

In contrast, use of e.g. interferometer maps to find resolved CO clouds for the determination of $X$ introduces a strong bias in low-metallicity environments. In the PDR, only those subregions are selected which have most succesfully resisted CO erosion, with CO still filling a relatively large fraction of the local $H_2$ volume. The relatively low $X$ values thus derived, although appropriate for the selected PDR subregions, are not at all valid for the remaining PDR volume where CO has been much weakened or has disappeared; the PDR has a much higher overall $X$ value than the selected subregion. It is because of this bias that the array-derived points in Fig. 2 are much lower than the large-beam points and exhibit a much weaker dependence on metallicity. Incidentally, it also explains the suggested dependence of $X$ on observing beamsize (Rubio et al. 1993).

REFERENCES

Combes, F. 2000 These Proceedings , ***-***