Molecular Gas in Galaxies

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July 14, 2000

Abstract. Knowledge of the molecular component of the ISM is fundamental to understand star formation. The H$_2$ component appears to dominate the gas mass in the inner parts of galaxies, while the HI component dominates in the outer parts. Observation of the CO and other lines in normal and starburst galaxies have questioned the CO-to-H$_2$ conversion factor, and detection of CO in dwarfs have shown how sensitive the conversion factor is to metallicity. Our knowledge has made great progress in recent years, because of sensitivity and spatial resolution improvements. Large-scale CO maps of nearby galaxies are now available, which extend our knowledge on global properties, radial gradients, and spiral structure of the molecular ISM. Millimetric interferometers reveal high velocity gradients in galaxy nuclei, and formation of embedded structures, like bars within bars. Galaxy interactions are very effective to enhance gas concentrations and trigger starbursts. Nuclear disks or rings are frequently observed, that concentrate the star formation activity. Since the density of starbursting galaxies is strongly increasing with redshift, the CO lines and the mm dust emission are a privileged tool to follow evolution of galaxies and observe the ISM dynamics at high redshift: they could give an answer about the debated question of the star-formation history, since many massive remote starbursts could be dust-enshrouded.

Keywords: molecules, dust, galaxies, dynamics, millimeter

1. Introduction

The interstellar medium, according to its density and physical conditions, can be found essentially as atomic hydrogen or molecular hydrogen. The latter plays a fundamental role in star formation. But the bulk of molecular hydrogen is cold (~10K), does not radiate and is thus completely invisible. The H$_2$ component is known in galaxies essentially from the CO tracer, but the way to derive the total amount of molecules is uncertain, and mapping other tracers is of prime importance: UV absorption lines, dust emission, mid-IR rotational lines of warm H$_2$, etc...

This paper reviews all of our indirect knowledge about the H$_2$ component, and compares all the tracers in order to determine how much molecular mass is in galaxies. The relation with the atomic gas HI is described. The molecular content of galaxies is traced as a function of morphological type, of evolution state. Its role is emphasized in dynamics of galaxies (bars and spirals) and in galaxy interactions and mergers. Finally, the H$_2$ content as a function of redshift is briefly
discussed, as a way to trace the evolution of star formation, and to
determine the importance of starbursts versus AGN for instance.

2. CO to H$_2$ conversion ratio

2.1. UV absorption lines

The CO molecule is excited by H$_2$ collisions, and should be a good
tracer of molecular gas; but its main rotational lines are most of the
times optically thick. It is possible to observe its isotopic substitutes
$^{13}$CO or C$^{18}$O, but these are poor tracers since they are selectively
photo-dissociated, and trace only the dense cores.

The H$_2$/CO conversion ratio was first calibrated by comparing the
UV absorption lines of CO and H$_2$ along the same line of sight (Coperni-
cus, e.g. Spitzer & Jenkins 1975; ORFEUS, cf Richter et al., 1999a,b).
This is now becoming possible at much larger-scale, with the FUSE
satellite, and molecular hydrogen bands have been observed toward
several stars lying behind diffuse and translucent clouds (Tumlinson
et al. 1999, Snow 2000). However, only very low column densities are
accessible, in order to see the background source, and therefore these
observations sample only the diffuse gas, which is not representative
of the global molecular component. It is well known now that the
conversion factor might vary by one order of magnitude from diffuse
to dense clouds, since the relation between the virial mass and CO
luminosity is non linear.

2.2. Virial hypothesis

The main justification to use an H$_2$/CO conversion ratio is the Virial
hypothesis: in fact, the CO profiles do not yield the column densities,
but they give the velocity width $\Delta V$ of molecular clouds. Once the
latter are mapped, and their size R known, the virial mass can be
derived, proportional to $\Delta V^2 R$. There exists a good relation between
the CO luminosity and the virial mass; however it is a power-law of
slope different from 1: $M_V \propto L_{CO}^{0.76}$ (cf Solomon et al. 1987).
Therefore the conversion ratio should vary by more than a factor 10 from small to
Giant Molecular Clouds (GMC). At large-scale in our Galaxy, and in
external galaxies, the observations provide an average over the whole
mass spectrum of clouds, and the hypothesis is made that this average
conversion ratio is the same from galaxy to galaxy. If $T_b$ is the bright-
ness temperature of the average cloud, the conversion ratio X should
vary as $n^{1/2}/T_b$, where n is the average density of the cloud. This does
not take into account the influence of the gas metallicity.
2.3. Variation with metallicity: dwarfs and LSBs

At constant H$_2$ column density, the CO luminosity varies with the metallicity Z, sometimes more than linearly. In the Magellanic Clouds, LMC or SMC (Rubio et al. 1993), the conversion ratio X might be 10 times higher than the "standard" ratio. The ratio can be known for local group galaxies, since individual clouds can be resolved, and virial masses computed (Wilson 1995).

The strong dependency of the H$_2$/CO conversion ratio on metallicity Z is also the main problem in the observations of dwarf and Low Surface Brightness (LSB) galaxies. Both have low metallicity. Not only, the low abundance of C and O lowers the abundance of CO, but also the dust is less abundant, and therefore the UV light is less absorbed, and spread all over the galaxy, photo-dissociating the CO molecules. When the dust is depleted by a factor 20, there should be only 10% less H$_2$, but 95% less CO (Maloney & Black 1988).

CO emission is in general very low in dwarf galaxies, and it is difficult to know their H$_2$ content. If the HI/H$_2$ ratio is assumed constant from galaxy to galaxy, then X varies with $Z^{-2.2}$ (Arnault et al 1988). Recent results by Gondhalekar et al (1998), Taylor et al (1998) and Barone et al (2000), confirm this strong dependency on metallicity, increasing sharply below 1/10th of solar metallicity.

Low-surface-brightness galaxies have large characteristic radii, large gas fraction and are in general dark matter dominated; they are quite un-evolved objects. Their total gas content is similar to that of normal galaxies (McGaugh & de Blok 1997). But CO is not detected in LSB (de Blok & van der Hulst 1998, Braine et al. 2000a).Due to their low surface density, below the threshold for star formation, these galaxies have a very low efficiency of star formation (Van Zee et al 1997). The cause could be the absence of companions, since LSB live in poor environments (Bothun et al. 1993). It is well known that galaxy interactions, by driving in a high amount of gas, trigger star formation.

3. Other promising tracers

3.1. Dust as a tracer

At millimetric wavelengths, in the Rayleigh-Jeans domain, dust emission depends linearly on temperature, and its great advantage is its optical thinness. In some galaxies, CO and dust emission fall similarly with radius, like in NGC 891 (Guélin et al. 1993). In other, such as NGC 4565 (Neininger et al. 1996), the dust emission falls more slowly than CO, although more rapidly than HI emission. This can be interpreted by the exponential decrease of metallicity with radius. The dust/HI ratio follows this dependency, while CO/HI is decreasing more rapidly.
Figure 1. Scale-length ratio between the mm dust emission and the CO(1-0) emission versus the $L_{\text{IR}}/L_B$ ratio, for NGC 891 (Guélin et al. 1993), M82 (Thuma et al. 2000), NGC 4565 (Neininger et al. 1996), M51 (Guélin et al. 1995), NGC 5907 (Dumke et al. 1997), NGC 6946 (Bianchi et al. 2000) and NGC 7331 (Bianchi et al. 1998). The scales have been compared, when the intensity has been divided by $e$ with respect to the center.

(either due to metallicity, or excitation problems). In M82, due to the intense starburst and related cosmic ray heating, the CO is much more extended than the dust 1.2mm emission (Thuma et al. 2000). Figure 1 compares the CO and mm dust emission scale lengths in a few spiral galaxies, as a function of star-formation activity (traced by far-infrared to blue luminosity ratio): in galaxies with active star formation, the CO emission is enhanced (the derived $M(\text{H}_2)/M(\text{HI})$ is larger), and the dust closely follows the CO radial distribution. On the contrary, in less active galaxies, the HI mass dominates, and the dust emission follows the HI in the outer parts of the galaxy disk, beyond the end of the CO disk. ISO 200$\mu$m images have shown that the dust radial distribution is more extended than stellar disks (Alton et al. 1998), and that the ratio of cold to warm dust is increasing with radius.

3.2. Rotational mid-IR lines

A very small fraction of the molecular gas can be excited to very high temperatures through shocks and then be observed directly, through the ro-vibration lines. Starbursts and mergers reveal strong 2.2 $\mu$m emission, like in NGC 6240 (DePoy et al. 1986). The source of excitation
has long been debated (X-ray heating, UV fluorescence, shocks...) and it was recently concluded that global shocks were responsible (van der Werf et al. 1993, Sugai et al. 1997). Pure rotational lines have been observed with ISO. In Arp220, as much as 10% of the ISM could be in the warm phase, i.e. $3 \times 10^9 \, M_\odot$ (Sturm et al. 1996) while CO observations conclude to a total $M(H_2) = 3.5 \times 10^{10} \, M_\odot$ (Scoville et al. 1991). In normal galaxies, the warm $H_2$ could be less abundant (Valentijn et al. 1996).

The ISO satellite also allowed to explore the pure $H_2$ rotational lines, the first $S(0) \,(J= 2 \rightarrow 0)$ of the para-hydrogen having its upper level at $\sim 500 \, K$ above ground ($28 \, \mu m$ in wavelength). Valentijn & van der Werf (1999) derived the radial distribution of the two first lines in the edge-on galaxy NGC 891. Surprisingly, the $S(0)$ emission has a rather flat distribution, while the CO emission falls down exponentially. The different line-widths for the two first lines (the $S(1)$ being much narrower) tend to support an interpretation in terms of a two-component medium, where a cool $H_2$ gas dominates the $S(0)$ emission. The temperature is then below 90K, and the derived column density of $H_2$ is $10^{23} \, cm^{-2}$, ten times larger than the HI column density. This is based on the assumption that the ortho-para ratio is about 1. The mass derived is then sufficient to explain the flat rotation curve. Other choices of the parameters could reduce the derived gas mass, however. How is this $H_2$ gas heated? The ionising and photo-dissociating radiation from stars are not sufficient in the outer parts of the galaxy disk. It is possible that the usual turbulence of molecular clouds, maintained by gravitational instabilities, is producing mild shocks, sufficient to heat a fraction of the molecular gas, at relatively low temperatures. This fraction of warm $H_2$ might then be a good tracer of the bulk of cold $H_2$ in the absence of CO molecules.

4. Comparison with the HI component

4.1. Radial distribution

The differences between HI and $H_2$ (or CO) radial distributions in galaxies is striking: while the $N(H_2)/N(HI)$ in the center can reach 10 or 20, it falls below 1 and even 0.1 in the outer parts. While all components related to star formation, the blue luminosity from stars, the $H\alpha$ (gas ionised by young stars), the radio-continuum (synchrotron related to supernovae), and even the CO distribution, follow an exponential distribution, the HI gas alone is extending much beyond the “optical” disk, sometimes in average by a factor 2 to 4 ($R_{HI} = 2-4 \, R_{opt}$). The HI
gas has very often a small deficiency in the center. Would this mean that the atomic gas is transformed in molecular phase in the denser central parts? This is possible in some galaxies, where the HI and CO distribution appear complementary, but it is not the general case, all possibilities have been observed, including a central gaseous depletion, both in CO and HI (like in M31 or NGC 7331).

Smith et al. (2000) have recently proposed a new probe of H$_2$ in galaxies. Considering that the HI gas is coming from dissociated molecular gas in PDRs, the volumic density of local H$_2$ can be deduced from measurements of the HI column density together with the far-ultraviolet (FUV) photon flux. They apply this idea to M101, and find that, after correction for the metallicity gradient and for the extinction of the FUV emission, the H$_2$ density is about constant over radius up to 26 kpc from the center, i.e. close to R$_{25}$.

4.2. Vertical structure

In our own Galaxy, and in external galaxies seen edge-on, the galaxy disks appear much narrower in CO emission than in HI. This suggests that the molecular gas is more confined to the plane, due to a much lower vertical velocity dispersion. Surprisingly, this is not the case: in face-on galaxies both CO (Combes & Becquaert 1997) and HI (Kamphuis 1992) velocity dispersions are observed of similar values ($\sigma_v \sim 6$ km/s), and remarkably constant with radius. A possible interpretation is that both gas are the same dynamical component, which changes phase along its vertical oscillations. It is possible that the H$_2$ gas follows the HI, but the CO is photo-dissociated at high altitudes, or not excited. Or even the H$_2$ could disappear, since the chemistry time-scale ($\sim 10^5$ yr) is much smaller than the dynamical z-time-scale ($\sim 10^8$ yr).

5. CO and H$_2$ content as a function of type

From the Amherst CO survey of more than 300 galaxies, Young & Knezek (1989) and Young & Scoville (1991) have concluded that the average molecular content was comparable to the atomic content: $M(H_2)/M(HI) \sim 1$. However, some of these galaxies were selected from their IRAS flux, and this could introduce a bias. A recent survey by Casoli et al (1998) near the Coma cluster has shown an average $M(H_2)/M(HI) \sim 0.2$.

It is well established that the HI component is proportionally more abundant relative to the total mass in late-type galaxies. The opposite trend is observed for the H$_2$, at least as traced by the CO emission. $M(H_2)/M(HI)$ is therefore smaller for late-types, by a factor $\sim 10$. 
However, this could be entirely a metallicity effect. Since the metallicity is increasing with the mass of the galaxy, a test is to select the most massive galaxies of late-type. For these high-mass galaxies, there is no trend of decreasing H$_2$ fraction with type (Casoli et al. 1998).

6. Role in Dynamics

6.1. Bars, nuclear bars

The dissipative character of the gas is fundamental for the formation of bars within bars, and for the transfer of angular momentum to the outer parts, to allow the radial inflows. The atomic gas is most of the time depleted in galaxy centers, and the molecular component is the best tool to trace the gas behaviour there. The millimeter interferometers provide now a sufficient spatial resolution for the CO maps. In general, barred galaxies show characteristic features corresponding to the offset dust lanes seen in optical. When these two features are seen only to start from the nucleus, they are called twin-peaks (Kenney et al. 1992) and correspond to the presence of an inner Lindblad resonance, implying orbits perpendicular to the bar in the center. The gas is often concentrated in resonance rings (nuclear rings, cf Sakamoto et al 1999, Thornley et al. 1999), or in nuclear spirals. It is often difficult to discriminate between several possibilities to account for the non-circular motions observed: nuclear bars or warps, as in the Seyfert galaxies NGC 1068 and NGC 3227 (Schinnerer et al. 2000).

6.2. Gas in shells

Molecular gas can sometimes be detected far from the galaxy centers, outside the optical image of the galaxy. This is the case for the shells in Centaurus A (Charmandaris, Combes & van der Hulst 2000). Shells are formed by stars of disrupted companions, by a phase-wrapping process (Quinn 1984). A large fraction of elliptical galaxies possess shells (Schweizer & Seitzer 1992), and this is believed to support the hierarchical merging scenario for their formation. In a merging event, gas is expected to dissipate and fall to the center (Weil & Hernquist 1993). However, atomic gas has been observed associated with shells (Schiminovich et al 1994). In the phase-wrapping process, this is only possible if there exists a gas component condensed in small clouds, with a large mean free path. This component has only very small dissipation, and behaves more like ballistic particles, like stars. The ensemble of molecular clouds has such properties. If the disrupted companion possessed dense molecular clouds, they could have followed the stars in
the shell formation, and through photo-dissociation and evaporation, reform some atomic gas in shells. The detection of CO emission in shells support this scenario (Charmandaris et al. 2000). The surprise if the derived large amount of molecular gas in shells: 50% of gas in shells is molecular, and more than 10% of all the gas in Centaurus A is away from the inner parts. Moreover, the H$_2$/HI ratio is the same in the nuclear disk and in the shells. How has the gas been enriched in metals, so far from the nucleus? The solution might lie in the recent star formation triggered in the shell gas by the impact of the radio jet (Graham 1998, 99). The shells detected in CO are precisely aligned with the radio jet, and the recently formed stars could have enriched the observed gas in metals and account for the CO detection.

6.3. Tidal dwarfs

Tidal dwarfs are small systems becoming gravitationally bound within tidal tails dragged by the interaction between two massive gas-rich galaxies. The collapse of the gas in these systems trigger new star formation (e.g. Duc & Mirabel 1998).

Braine et al (2000) report the discovery of CO emission in two tidal dwarf galaxies, in the Arp105 and Arp245 systems. In both cases, they derive that the molecular gas peaks at the same location as the HI gas, and infer from this that the molecular gas formed from the atomic hydrogen, rather than being torn in molecular form from the interacting galaxies. In fact, this could also be a consequence of the CO being visible in these dwarfs, only because of the metallicity enrichment due to the new stars formed there (see previous section).

7. CO at high redshift

The recent years have seen the rapid development of sub-mm surveys in blank areas, searching for high-redshift continuum sources. Since the spectral energy distribution (SED) of starbursting galaxies have a characteristic peak around 60-100 µm due to dust heated by newly born stars, the millimeter domain becomes a privileged range to detect these objects at $z$ up to 10. The slope of the SED (in $\nu^4$) is such that the K-correction is even negative, i.e. it is more easy to detect objects at higher redshift than $z = 1$, at a given frequency, and sky surveys could be dominated by remote objects (see e.g. Blain & Longair 1993, 1996). The density of sources detected up to now account for a significant fraction of the CIBR (Hughes et al. 1998). Identification of the sources (redshifts) and of the nature of the emission is difficult. At least 20% of
the sources reveal an AGN activity, and most of them are at relatively low redshift $1 < z < 3$ (Barger et al. 1999).

The detection of large amounts of molecular gas could help to identify starbursts versus AGNs. However, the detection of the CO lines are much more difficult, since the K-correction is not negative (Combes et al 1999). Today, a dozen of sources have been detected in CO at redshifts between 2 and 5, and most of them are amplified by gravitational lensing. With the new millimeter instruments planned over the world (the Green-Bank-100m of NRAO, the LMT-50m of UMass-NAOE, the ALMA (Europe/USA) and the LMSA (Japan) interferometers) the sensitivity will be enhanced such as to detect most of the sources identified in the continuum. This will bring fundamental information about the cold gas component in high-z objects and therefore about the physical conditions of the formation of galaxies and the first generations of stars. At high enough redshifts, most of the galaxy mass could be molecular. The starburst occurring in these objects could enrich quickly the ISM to solar values (Elbaz et al. 1992).

8. Conclusion

Our knowledge of the molecular component of galaxies is improving fast, and it is now realized how much the $\text{H}_2$/CO conversion ratio is varying with type and star forming activity. Other tracers will be highly valuable in the near future: mm dust emission and pure $\text{H}_2$ rotational lines. The CO tracer is complementary to the HI line to trace the gas dynamics in galaxies, since their radial distribution are quite different and anti-correlated. With improved sensitivity, it is now possible to detect CO lines even outside the optical galaxies. The first studies of $\text{H}_2$ gas at high redshifts have been done, thanks to the gravitational telescopes. With the future mm instruments, it will be possible to study the history of star formation, directly with measuring the amount of gas available, and deriving the star formation efficiency.

References

Alton, P. B., Trewella, M., Davies, J. I. et al.: 1998, A&A 335, 807
Alton P.B., Davies J.I., Bianchi S., 1999: A&A 343, 51
Arnault P., Kunth D., Casoli F., Combes F. 1988 A&A 205, 41
Barger, A.J., Cowie, L.L., Sanders, D.B.: 1999, ApJ 518, L5
Barone L.T., Heithausen A., Huettemeister S., Fritz T., Klein U.: 2000, MNRAS in press (astro-ph/0005311)
Bianchi, S., Alton P.B., Davies, J. I., Trewella M.: 1998, MNRAS 298, L49
Bianchi, S., Davies, J. I., Alton, P. B., Gerin, M., Casoli, F.: 2000, A&A 353, L13
Blain A.W., Longair M.S.: 1993, MNRAS 264, 509
Blain A.W., Longair M.S.: 1996, MNRAS 279, 847
Bothun, G., Schombert, J., Impey, C. et al.: 1993, AJ 106, 530
Braine, J., Herpin, F., Radford, S. J. E.: 2000a, A&A 358, 494
Braine, J., Liskenfeld, U., Duc, P.-A., Leon, S.: 2000b, Nature 403, 867
Casoli F., Sauty S., Gerin M. et al. 1998, A&A 331, 451
Charmandaris V., Combes F. & van der Hulst J.M.: 2000, A&A 356, L1
Combes F., Becquaert J.-F.: 1997, A&A 326, 554
Combes F., Maoli R., Omont A.: 1999, A&A 345, 369
de Blok W.J.G., van der Hulst J.M. 1998, A&A 336, 49
Depoy, D. L., Becklin, E. E., Wyom-Williams, C. G.: 1986, ApJ 307, 116
Duc, P.-A., Mirabel, I. F.: 1998, A&A 333, 813
Dumke, M., Braine, J., Krause, M. et al.: 1997, A&A 325, 124
Elbaz D., Arnaud M., Casse M., et al.: 1992, A&A 265, L29
Gondhalekar P.M., Johansson L.E.B., Brosch N. et al.: 1998 A&A 335, 152
Graham, J.A., 1998, ApJ 502, 245
Graham J.A., 1999, BAAS 194,7303
Guélin M., Zylka R., Mezger P.G. et al. 1993, A&A 279, L37
Guélin M., Zylka R., Mezger P.G. et al. 1995, A&A 298, L29
Hughes D.H., Serjeant S., Dunlop J. et al.: 1998, Nature 394, 241
Kamphuis J.: 1992, PhD thesis, Groningen
Kenney, J. D. P., Wilson, C. D., Scoville, N. Z. et al.: 1992, ApJ 395, L79
Maloney P., Black J.H. 1988, ApJ 325, 389
McGaugh S., de Blok W.J.G 1997 ApJ 481, 689
Nealinger N., Guélin M., Garcia-Burillo S. et al. 1996, A&A 310, 725
Quinn P.J.: 1984, ApJ 279, 596
Richter, P., de Boer, K. S., Bomans, D. J. et al.: 1999a, A&A 351, 323
Richter, P., de Boer, K. S., Widmann, H. et al.: 1999b, Nature, 402, 386
Rubio M., Lequeux J., Boulanger F. 1993, A&A 271, 9
Sakamoto K., Okumura, S.K., Ishizuki, S., Scoville, N. Z.: 1999, ApJS 124, 403
Schiminovich D., van Gorkom, J., van der Hulst, J., Kasow S.: 1994, ApJ 432, L101
Schinnerer, E., Eckart, A., Tacconi, L. J. et al.: 2000, ApJ 533, 826 & 850
Schweizer F., Seitzer P.: 1992 AJ 104, 1039
Scoville N.Z., Sargent, A. I., Sanders, D. B., Soifer, B. T.: 1991, ApJ 366, L5
Smith D.A., Allen R.J., Bohlin R.C. et al.: 2000, ApJ in press (astro-ph/0003394)
Snow, T.: 2000 in "First Results from the FUSE Mission", 24th meeting of the IAU, Joint Discussion 11, August 2000, Manchester, England.
Solomon P.M., Rivolo A.R., Barrett J.W., Yahil A.: 1987, ApJ 319, 730
Spitzer L., Jenkins E.B.: 1975, ARAA 13, 133
Sturme, E., Lutz, D., Genzel, R., et al.: 1996, A&A 315, L133
Sugai, H., Malkan, M. A., Ward, M. J. et al.: 1997, ApJ 481, 186
Taylor C.L., Kobulnicky H.A., Skillman E.D. 1998, AJ 116, 2746
Thorley, M., Regan, M., Helfer, T. et al.: 1999 Ap&SS 269, 391
Thuma, G., Neininger, N., Klein, U., Wielebinski, R.: 2000, A&A 358, 65
Tumlinson, J., Shull, J. M., Rachford, B. et al.: 1999, BAAS 195, 0608
Valentijn E., van der Werf, P., de Graauw T., de Jong T.: 1996, A&A 315, L145
Valentijn E. A., van der Werf, P.: 1999, ApJ 522, L29
van der Werf P., Genzel, R., Krbabe, A. et al.: 1993, ApJ 405, 522
van Zee L., Haynes M.P., Salzer J.J. 1997 AJ 114, 2497
Weil & Hernquist 1993]weil Weil M.L., Hernquist L., 1993, ApJ 405, 142
Wilson C.D. 1995, ApJ 448, L97
Young, J., Knezek, M. 1989, ApJ, 347, L55
Young, J., Scoville N.Z. 1991, A.R.A.A. 29, 581