Hunt for Molecules
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HUNT FOR COLD H_2 MOLECULES

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Abstract. The bulk of the molecular component in galaxies is made of cold H_2, which is not observed directly, but which abundance is derived from indirect tracers such as CO emission. The CO to H_2 conversion ratio remains uncertain, and may vary by large factors in special environments with different excitation or metallicity. Recent cold gas discoveries (through γ-rays or cold dust emission) are reviewed and the most promising tracers in the future are discussed, such as the primordial molecules HD and LiH, or the pure rotational lines of excited H_2^*.

1 Introduction

The H_2 molecule has no electric dipole because of its symmetry, and therefore cannot emit line radiation in the radio domain, the only ones that could be excited at the low temperature of the interstellar medium (10-15K). The first rotational line comes from the $J = 2$ level, through quadrupole radiation, and is 512K above the ground state, S(0) at 28μm in wavelength. The second rotational line of the para H_2 is S(2) at 12μm, and the two first lines of the ortho H_2 are S(1) and S(3) at 17μm and 9μm respectively. ISO observations of PDR have revealed a large number of H_2 pure rotational lines (Timmermann et al 1996), and higher resolution observations have confirmed an unexpectedly large amounts of warm H_2 gas in PDR (Allers et al 2005).

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The only other way to detect cold H_2 directly is through the UV lines in absorption, unfortunately this concerns only the untypical very diffuse regions, since higher H_2 column densities are associated to high extinction, that prevent to detect the background sources. This was confirmed by the FUSE survey towards galactic sources (Shull et al 2004). The average molecular fraction of the diffuse ISM is of the order of 10%, and the temperature is warm ($\sim$ 100K). Even in "translucent line of sights", there is only evidence of diffuse clouds (Rachford et al 2002).

We first review our current knowledge of the CO to H_2 conversion ratio, which is still the main method to trace cold H_2 molecules in galaxies. After presenting possible new tracers, we then describe recent discoveries of cold gas, locally in our Galaxy, and in external galaxies or clusters. We conclude with future experiments, which could bring new insights.

2 CO and other tracers

2.1 Uncertainties in the CO to H_2 conversion ratio

Although the determination of this factor has been the goal of multiple studies, it remains largely uncertain; it can vary by a factor 10 or more with metallicity, and also with excitation and local density. When studied for individual clouds, from virial mass arguments, the conversion factor varies by a factor 10 across the mass spectrum of observed clouds. For extreme starbursts, it is usual to adopt a conversion ratio 5 times lower than the average, and the value to adopt for high-z or primordial galaxies is unknown.

Since the factor could be large in the outer parts of galaxies, at low metallicity, it is tempting to wonder how much the dark H_2 gas could account for the galaxy dark matter, in particular the dark baryons (i.e. 90% of them). It is indeed known from microlensing experiments that most of them cannot be in compact objects, and must be in gas, either hot or cold.

The rotation curves here serve as an upper limit on the conversion ratio. In spiral and dwarf galaxies, rotation curves are remarkably fit through HI-scaling by a factor 7-10 (Hoekstra et al 2001). So inside the HI disk, i.e. inside the last point of directly measured rotation curve, it is possible to have only 10-20% of the dark baryons in galaxies. The remaining part must reside in cosmic filaments.

2.2 Other possible tracers

To reveal cold H_2 molecules, we could think of their hyperfine structure (or ultrafine), coming from the interaction between nuclear spin, and the magnetic field generated by rotation. The ground state has 3 levels ($F = I+J=$ 0, 1 and 2) and the corresponding lines are in the kilometric range: F=1-0 at 546.4 kHz (λ =0.5km) and F=2-1 at 54.8 kHz (λ= 5.5km). The line intensities are extremely weak (cf Combes & Pfenniger 1997), the radiation is stopped by the atmosphere, and their detection would require to cover by a loose grid several kilometers on the Moon! This also assumes that there is a significant amount of molecules in the ortho state, even at low temperatures, i.e. the molecules have no time to reach complete equilibrium after their formation.

At 3K, the pressure of H_2 clumps is 100 times the saturated vapor pressure (Combes & Pfenniger 1997). However, since the latent heat is 110K/H_2, there is no time to form much snow in a Hubble time. But the conditions for dimerisation might be reached in some very dense clumps, and continuum emission is expected from dimers, through the dipole induced by collisions (Schaefer 1994, 1999). It is difficult to estimate the amount of H_2 at such high densities, and the amount of dimers formed.

The HD molecule has a weak dipole moment μ= 5.8 10^{-4} Debye (Trefler & Gush 1968). The first rotational level is 130 K above ground state, and the first $J = 1 - 0$ line is at $\lambda = 112\mu$m (Wright et al 1999, Polehampton et al 2002). The emission could come only from excited regions, and is quite weak, given that HD/H_2 is of the order 10^{-5}. HD is therefore not a powerful tracer. The LiH molecule could be a better tracer, since its dipole moment is much stronger μ= 5.9 Debye (Lawrence et al 1963), and the first transition $J = 1 - 0$ is only 21 K above ground state, at $\lambda = 0.67\mu$m (450GHz). This line cannot be detected from the ground, because of H_2O absorption. Assuming an abundance of LiH/H_2 $\sim 10^{-10}$, the line becomes optically thick $\tau \sim 1$ for N(LiH) = 10^{12} cm^{-2} or N(H_2) = 10^{22} cm^{-2}.

The ion H_2^+ (searched for by Encrenaz & Falgarone, as soon as 1971!) has an expected abundance of 10^{-11}-10^{-10}. It has an hyperfine structure, but not in the N=0 state, only N=1, I=1, S=1/2. The energy of the upper level is 110K, among the 5 lines expected, the strongest is at 1343 MHz. If H_2^+ forms through cosmic ray ionization of H_2, it disappears through reaction with H_2 to form the molecular ion H_3^+, which has a key role in ion-molecule interstellar chemistry (e.g. Geballe 2000). The H_3^+ ion has now been detected in the interstellar medium (Geballe & Oka 1996, McCall et al 1999), through absorption lines in the infra-red, via a vibrationnally excited line (since only the asymmetric vibration ν_2 can induce a dipole moment, in this ion which has no permanent dipole). The deuterated ions are more favorable tracers, since they have a weak dipole, H_2D^+ (372GHz emission, Stark et al 1999), or D_2H^+ (692GHz emission, Vastel et al 2004).

Given the weakness of all these tracers, it might be interesting to keep tracking the CO molecule, since traces of C and O are still expected in nearly primordial gas. A residual 10^{-3} solar abundance is observed in Lyα forest clouds, due to the first stars. If the H_2 gas remains clumpy enough, and far from photo-dissociating radiation, it is possible to find CO molecules, assuming that some heating sources exist to keep the brightness temperature above the background (e.g. Braine & Herpin 2004). Alternatively, the molecules should be searched in absorption, although with a low surface filling factor of less than 1%.

3 Hints of dark gas

3.1 γ−rays

Another way to trace cold gas in the interstellar medium is the γ-rays resulting from the interaction of cosmic-rays (CR) with all nucleons (through the creation of π^0). The emission of E > 100 Mev γ-rays is the product of total nucleon density and CR density. The CR are re-accelerated by supernovae and are the products of star formation, their density decreases radially in the Galaxy. It is possible to calibrate their density in the solar neighbourhood, through mapping of all ISM components (HI, CO, Hα). Until recently, due to the low spatial resolution, it was possible to attribute part of the γ-rays to point sources (pulsars), but converging observations now, including extinction (B-V) and cold dust emission in the millimeter range, reveals that γ-rays are tracing dark gas in the local interstellar medium (Grenier et al 2005). This interesting discovery shows that the dark gas is distributed like an envelope around the CO-traced molecular gas, cf Figure 1.

3.2 High Velocity Clouds

Some of the HVC falling towards the Galactic plane appear compatible with an intergalactic origin, with low metallicity (Wakker et al 1999) and high

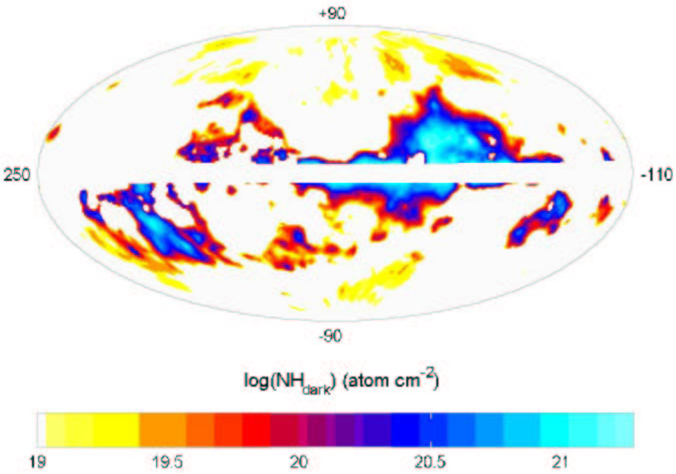

Fig. 1. Map of the local dark gas, in Galactic coordinates centered on l=70°, as traced from γ-ray intensity, reddening E(B-V) and 94 GHz emission, from Grenier et al (2005)

deuterium abundance (Sembach et al 2004). Although H_2 molecules have been detected through UV absorption by FUSE in HVC, up to now no CO emission nor cold dust emission had been detected. For the first time, Miville-Deschênes et al (2005) report dust emission through the comparison of SST (Spitzer Space Telescope) infrared maps with the 21cm HI line emission from the GBT (Green Bank Telescope). The dust is cooler ($\sim$ 10K) than the galactic dust in average, compatible with a large distance from the Galaxy. The column density derived is 5 times that corresponding to the HI, suggesting the existence of dense gas clumps associated to the apparent diffuse HI gas. The clumps would contain dense molecular hydrogen, and would constitute most of the gas accreted by the Galaxy.

3.3 Cooling flows

Cold gas has also recently been discovered in the center of rich galaxy clusters, where it was long searched for, as the end product of cooling flows. It has been realized that the flux of cooling gas is in reality about 10 times lower than expected in the case of spherical inflow without feedback. The cold inflow fuels an AGN in the central cD galaxy, and the radio lobes feedback then moderates the cooling, creating bubbles and shocks (Figure 2). The cold gas has still the dynamics and velocity of the cluster, and is not yet settled in the central galaxy potential well (see Salomé et al 2005, and Salomé, this Proceedings).

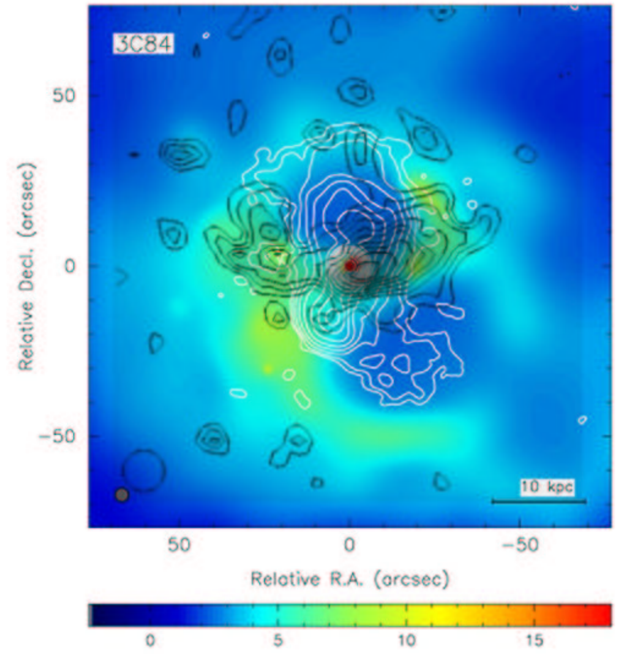

Fig. 2. Map of the center of Perseus cluster: the false color-scale is the X-ray emission from Chandra (Fabian et al 2003), the white contours are the radio emission (Pedlar et al 1990), showing the radio lobes of the central AGN, and the black contours are the CO(2-1) emission, observed with the IRAM-30m (from Salomé et al 2005).

4 Perspectives

The dark H_2 clumps are not compact enough to be gravitational lenses for LMC stars, however they could act as gaseous lenses (Draine 1998) or produce scintillation of optical light, through refraction of the background stellar emission (Moniez 2003). In the strong diffractive regime, it might be possible to distinguish high contrast fluctuations of short time-scales from foreground effects of light propagation through the atmosphere. A project is undertaken to monitor extra-galactic stars every ~ 10 seconds, to discover dark gas of 10^{19} molecules/cm^2 per 10 000 km transverse distance (OSER: Optical Scintillation by Extraterrestrial Refractors, Moniez 2005).

The pure rotational lines of the H_2 molecule might be the best tracer afterall. ISO observations have shown that they are ubiquitous. In outer parts of galaxies they were observed surprisingly high by Valentijn & Van der Werf (1999). In the edge-on galaxy NGC891, the molecular column density was derived to be $N(H_2) = 10^{23}$ cm^{-2}, with an excitation temperature of T = 80-90 K, i.e. 5-15 N(HI), enough to explain the rotation curve.

ISO observations of lines of sights through the Galaxy encountering no star formation regions, but only cold diffuse gas, have shown a rich variety of H_2 rotational lines. The excitation of these lines in the ground vibrational states cannot be due principally to the UV excitation, but has to come from non-thermal excitation (Falgarone et al 2005a). This suggests that within the cold neutral medium, there always exists a few percent of warm gas, due to the intermittent dissipation of MHD turbulence, and this warm gas can be used as a tracer of the cold gas, independent of metallicity. The detection of this warm gas, at large scale in the Galaxy, and in a survey of nearby galaxies, in particular at large distance from the center, is the main goal of the project H_2Ex, a space explorer mission with a dedicated 2m-class telescope, and a high resolution spectro-imager in the mid-IR (Falgarone et al 2005b).

The rotational lines of H_2 are the main coolant of the primordial gas, and its collapse to form the first generation of stars in the universe could be traced by their emission, however orders of magnitude gains in sensitivity are required for future instruments (Mizusawa et al 2005).

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