VERY COLD GAS AND DARK MATTER

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Abstract. We have recently proposed a new candidate for baryonic dark matter: very cold molecular gas, in near-isothermal equilibrium with the cosmic background radiation at 2.73 K. The cold gas, of quasi-primordial abundances, is condensed in a fractal structure, resembling the hierarchical structure of the detected interstellar medium.

We present some perspectives of detecting this very cold gas, either directly or indirectly. The H$_2$ molecule has an “ultrafine” structure, due to the interaction between the rotation-induced magnetic moment and the nuclear spins. But the lines fall in the km domain, and are very weak. The best opportunity might be the UV absorption of H$_2$ in front of quasars. The unexpected cold dust component, revealed by the COBE/FIRAS submillimetric results, could also be due to this very cold H$_2$ gas, through collision-induced radiation, or solid H$_2$ grains or snowflakes. The γ-ray distribution, much more radially extended than the supernovae at the origin of cosmic rays acceleration, also points towards and extended gas distribution.

1. Introduction

The possibility that most of the mass of the Universe could be under the form of gas around or in between galaxies has been widely discussed in the 1960's (e.g. the review by Peebles, 1971). At that time gas was assumed to be distributed in a smooth homogeneous fashion. This was not justified by observations of the interstellar gas already then. The intergalactic material
was supposed to be hydrogen exclusively (with some helium), either atomic, molecular, ionized, or even in a condensed snow. Self-gravity was ignored. Several tests were proposed, such as emission or absorption of HI at the 21 cm line, the Gunn-Peterson test in the Ly\(\alpha\) line of HI or the Lyman band in molecular hydrogen; the existence of an intergalactic plasma would have been detected through free-free emission or absorption, recombination lines, chromatic phase lag, or Thomson scattering.

All the tests were negative, constraining the density of any intergalactic gas several orders of magnitude below the closure density. However, the homogeneity hypothesis is drastic, especially when comparing to the now much better known ISM, and including gravity as a major force. The Gunn-Peterson test is of course invalidated in case of a clumpy medium.

Even until recently, the hypothesis of cold gas as dark matter was eliminated quickly, without critical reflection, through stability arguments (e.g. Hegyi & Olive 1986): for an homogeneous galactic gaseous halo, the virial temperature is of the order of \(10^6\) K; the gas cannot remain hot, it would have been seen in X-ray; in any case, at this temperature, cooling processes are violent, the gas collapses and forms stars. Hydrogen snowballs, massive enough not to collide with each other (\(m > 1\) g) quickly evaporate, unless gravitationally bound (but then they join the problem of brown dwarfs).

All the above objections disappear when a realistic hierarchical structure of cold and dense clouds is considered, closely resembling the familiar fractal structure of the detected ISM (Pfenniger et al. 1994). A model was then built to account for the baryonic dark matter around galaxies, composed of basic “clumpuscules” of molecular hydrogen, of a Jupiter mass \((10^{-3} M_\odot)\), but with a much smaller density than brown dwarfs, with \(10^9-10^3\ cm^{-3}\) and radius of \(\approx 20\) AU (Pfenniger & Combes 1994). For these basic units clumpuscule are self-gravitating, statistically in equilibrium with pressure forces, at the limit of the adiabatic regime, since then the radiation transfer time equals the dynamical time. They compose the smallest scale of a hierarchical structure, that ranges over six orders of magnitude, up to giant molecular clouds of 100 pc; above this scale, bigger gaseous complexes are torn apart by galactic shear. The ensemble of clumpuscules is in quasi isothermal equilibrium with the bath of photons of the cosmic background radiation at \(T = 2.73\) K\((1 + z)\). Due to the fractal structure (of dimension \(D < 2\)), the clumpuscules collide together frequently, with, for such fractal dimension, a rate of the order of the cooling-heating and dynamical times.

But all the fractal structure is far from local thermodynamical equilibrium as explained in another paper in this volume, the equilibrium including gravity is only statistical. The large fluctuations prevent most of the clumpuscules to cool down and collapse further (were they distributed homogeneously they would not). Through these collision induced fluctuations,
the gas maintains exchanges with the background, coalescing in giving back energy, or fragmenting and evaporating in absorbing energy. The condensed structure resembles closely the well-studied ISM gas, already known as a $D < 2$ fractal-like structure over several orders of magnitude in scale (Larson 1981; Scalo 1985; Falgarone et al. 1992). The main difference is that star-formation in the visible disk has metal-enriched the medium that can then cool down much faster, and the heating sources have partly destroyed the condensed fractal and formed a diffuse intercloud medium.

In galaxy outskirts, the condensed H$_2$ phase is almost only in contact with the intergalactic radiation field, which photodissociates a small fraction of it into HI gas, because at the envisaged column densities ($\sim 10^{25}$ cm$^{-2}$) H$_2$ can self-shield easily. An even smaller fraction could be ionized. Since the average surface density of the gas is falling as $R^{-1}$, HI must disappear into ionised gas at a critical radius; this corresponds to the sudden fall off of HI measurements, resembling an ionisation front (e.g. the case of NGC 3198, van Gorkom et al. 1987, unpublished). From this point of view, the atomic gas in the outer parts serves as a tracer of dark matter.

There is indeed some evidence that the gas and dark matter are intimately related. From the flat rotation curves, the surface density of dark matter $\sigma_{DM}$ varies asymptotically as $R^{-1}$, and as well the HI surface density $\sigma_{HI}$ (cf. Fig. 1). Bosma (1981) was the first to notice a constant ratio of $\sigma_{DM}/\sigma_{HI}$ as a function of radius in spirals, which has been confirmed by many authors (Sancisi & van Albada 1987; Puche et al. 1990), and varies between 10 and 20 according to the morphological type (Broeils 1992; Carignan, this volume).

The presence of large gaseous extensions around galaxies can explain the widespread detection of absorption lines in front of quasars. The Ly$\alpha$
forest, and the large frequency of absorptions on a single line of sight (up to 100) remain unexplained. If these absorptions come from gas around galaxies, the derived cross-section of a galaxy corresponds to a radius of 480 kpc at \( z = 2.5 \) (Sargent 1988). The gas corresponding to these atomic absorptions remains a small fraction of the critical density. But already the total contribution of the gas in damped Ly\( \alpha \) systems amounts to about the luminous matter density in present galaxies (e.g. Lanzetta et al. 1991).

The model of cold gas as dark matter sheds also some light on puzzles such as the presence of huge amounts of hot gas in clusters (the hot gas represents 8 to 10 times the mass in galaxies in some rich clusters, Edge & Stewart 1991), the overabundance of gas in interacting galaxies (Braine & Combes 1993), the necessity of gas infall for maintaining star-formation and the spiral structure, and the evolution of galaxies along the Hubble sequence (e.g. Pfenniger et al. 1994).

Recent models have also been proposed, taking up the hypothesis that H\( _2 \) gas could contribute significantly to the dark matter, based mainly in massive proto globular cluster clouds possibly mixed with brown dwarfs (de Paolis et al. 1995; Gerhard & Silk 1995). In this case, the cold H\( _2 \) is not very cold, but has a temperature between 5 and 20 K, which makes it easier to detect in emission. To us is unclear, however, how cold gas coexisting with a brown dwarf cluster could be maintained in the mutual gravity at this low temperature, since the brown dwarfs must be subject to a significant dynamical friction, and the cluster must undergo core collapses that inevitably relax and virialize also the gas to a higher temperature.

2. Local dark matter and gravitational stability

2.1. FIT OF THE ROTATION CURVE

The rotation curve of our own Galaxy is well-known from several tracers, including the HI, H\( _2 \) gas or ionised gas, and is typical for a SBbc galaxy: massive bulge traced by a central peak of rotational velocity, flat rotation in the outskirts, although uncertainties become large outside of the solar circle, due to the lack of precise distance indicators (e.g. Fich & Tremaine 1991). Given all the observed parameters of the bulge, stellar and gaseous disks, is it possible to constrain the model of dark matter confined in the disk, in particular in solar neighbourhood?

We have retained a simple axisymmetric model of the Galaxy, composed with a bulge (Plummer component), an exponential stellar disk, with or without truncation, and two gaseous disks. The first represents the observable molecular ring, and is modelled by a difference between two Toomre disks of index \( n = 2 \) (Toomre 1963). The second represents the observed HI component, and is modelled by an empirical ring like distribution, de-
Figure 2. Fit of the Milky Way rotation curve, with the parameters of Table 1. Data points are from the compilation of Fich & Tremaine (1991). The dark matter is assumed to follow the HI distribution: a) without dark matter; b) with dark matter, with a distribution following that of HI, and $\sigma_{DM}/\sigma_{HI} = 15$; c) same with $\sigma_{DM}/\sigma_{HI}=20$

Sufficient in the center, and falling as $R^{-1}$ at large radii. The mass of this component has been multiplied by an adjustable ratio $\sigma_{DM}/\sigma_{HI}$ to model the gaseous dark matter. The disks are modelled with a finite thickness, and the rotation curves are calculated following the integral formulation from Casertano (1983). The final fit is displayed in Fig. 2, together with the observed points. All the adopted parameters are listed in Table 1.

First, we see that it is possible to account for the rotation curve without any dark matter until $R = 10$ kpc. Afterwards dark matter is actually necessary to avoid a fall off of the circular speed (Fig. 2a). But adding the dark matter in the disk, with the bulk of it outside the solar radius reduces the rotation speed inside $R = 10$ kpc. The modelisation is therefore not unique, it depends on several free parameters of total mass and concentrations, much more than in the hypothesis of a spherical DM halo. For instance the rotational velocity at the extreme galactic radii depends on how the HI-DM disk is truncated. Fig. 2b and c display reasonable good fits, with $\sigma_{DM}/\sigma_{HI}=15$ and 20 respectively. We can estimate the dark matter frac-

| Component | Mass $[10^{10} M_\odot]$ | Scale-lengths [kpc] | Type |
|-----------|-----------------|-----------------|------|
| Bulge     | $M_b = 1$       | $a_b = 0.25$    | Plummer |
| Disk      | $M_d = 6$       | $a_d = 2.7$     | Exponential |
| H$_2$     | $M_{H_2} = 0.2$ | $R_1 = 6.0$ $R_2 = 6.8$ | diff $n = 2$ Toomre disks |
| HI        | $M_{HI} = 0.4$  | $R_0 = 8. \ (1)$ $\mu \propto R^{-1}$ |

(1) Start of the $R^{-1}$ behaviour
tion in the disk at the solar radius at about 50% of the total mass. This is compatible with the recent claim from Bahcall et al (1992), but not from the Kuijken & Gilmore studies (1989), but the question of the existence of local dark matter is still open.

2.2. HI SCALE-HEIGHT

The gaseous plane of the Milky Way is flaring linearly with radius, outside the solar circle, i.e. the HI scale-height $h_z \approx 0.045R$ (Merrifield 1992). If the gas is considered in gravitational equilibrium in the direction perpendicular to the plane, with a constant velocity dispersion $\sigma \approx 10\,\text{km/s}$ as in face-on galaxies (e.g. Dickey et al 1990), then different scale-heights are predicted by the different models for the dark matter. In the case of a spherical halo, the equilibrium requires $GM(R)R^{-3}h_z^2 \approx \sigma^2$, and since $M(R) \propto R$, we predict $h_z = 0.09R$, which is larger than observed. A flattened dark halo is needed. In the case of a self-gravitating disk, where the dark matter follows the HI flaring, the equilibrium requires $2\pi G\mu h_z \approx \sigma^2$, with the surface density $\mu \propto R^{-1}$; a height $h_z = 0.03R$ is predicted with the rotation curve model of the previous section. This is quite compatible with the observations, given the uncertainty in $\sigma$, and the probable overestimation of the observed height by the Milky Way warp.

2.3. OUTER DISK STABILITY

For Gerhard & Silk (1995), the main problem raised by the existence of a self-gravitating gaseous disk in the outskirts is its global stability. For a flat rotation curve, the surface density $\Sigma$ falls off as $R^{-1}$ as well as the epicyclic frequency $\kappa$, so that the critical velocity for axisymmetric stability $c_v \propto \Sigma/\kappa$ is constant. This critical velocity dispersion is of order $60-70\,\text{km}\,\text{s}^{-1}$ in the Galaxy, while the observed velocity dispersion perpendicular to the plane is of the order of $7-10\,\text{km}\,\text{s}^{-1}$ (e.g. Dickey et al. 1990).

We have already discussed how this can be approached (e.g. Pfenniger et al. 1994). First, gaseous disks are not razor thin: they flare with radius (Merrifield 1992), which reduces self-gravity and the critical velocity. Second, real gaseous disks are manifestly unstable, as witnessed by the spiral waves, asymmetries and large scale inhomogeneities of outer HI disks in every spiral. Third, the dispersion, averaged over the gravitational scales up to $\sim 1\,\text{kpc}$ and over a few rotation periods, is indeed close to the critical velocity. Finally, the clumpy gaseous dark matter component may still retain, as stars, a substantial dispersion anisotropy, contrary to a classical smooth gas; so the velocity dispersion, well measured perpendicular to the plane, is not necessarily a good indicator of the effective horizontal dispersion (see also Elmegreen, this volume).
3. Perspectives of detection

The above model is not only a plausible and conservative hypothesis on the nature of dark matter, but it is a falsifiable one, since a series of observations can be carried out to confirm or refute our propositions. We review below possible observational tests and try to select the most promising ones.

3.1. THE HYPERFINE STRUCTURE OF ORTHO-H$_2$

The hydrogen molecule can be found in two species, para-H$_2$, in which the nuclear spins of the two protons are anti-aligned, and the resulting spin $I = 0$, and ortho-H$_2$ for which the total nuclear spin is $I = 1$, with the spins of the two protons parallel. The rotation quantum number $J$ is even for para-H$_2$ and odd for ortho-H$_2$. In the para ground state $J = 0$, there is no hyperfine splitting, but for the ortho $J = 1$, three levels can be identified, corresponding to $F = 0, 1$ and 2. This splitting comes from the interaction of the nuclear spin magnetic dipole, with the magnetic field created from the motion of charges due to rotation. To this interaction, must be added the spin-spin magnetic interaction for the two nuclei, and the interaction of any nuclear electrical quadrupole moment with the variation of the molecular electric field in the vicinity of the nucleus (Kellog et al. 1939, 1940; Ramsey 1952). Magnetic dipole transitions are possible for $\Delta F = 1$, i.e. there are two transitions, $F = 2 - 1$, and $F = 1 - 0$. The wavelength of these two transitions have been measured in the laboratory at 0.55 and 5.5 km, or more precisely at frequencies of 546.390 kHz and 54.850 KHz respectively for $F = 1 - 0$ and $F = 2 - 1$.

In fact this structure could be called ultrafine structure, since it is several orders of magnitude below hyperfine structure (cf. Field et al. 1966). Since the interaction involves two nuclear momenta, the splitting is proportional to $\mu_n^2$, the nuclear magneton, while the hyperfine structure involves the product of $\mu_n$, with the Bohr magneton $\mu_o = eh/(4\pi mc)$, where $m$ is the electron mass. The ultrafine to hyperfine structure ratio is therefore $\mu_n/\mu_o = m/m_p$, where $m_p$ is the proton mass.

3.2. THE ORTHO-PARA RATIO

Only the ortho-H$_2$ is concerned by the ultrafine structure. Normal molecular hydrogen gas contains a mixture of the two varieties, with an ortho-to-para ratio of 3, when the temperature is high with respect to the energy difference of the two fundamental states (171 K). At lower temperatures, the ortho-to-para ratio must be lower, if the thermodynamical equilibrium can be reached, until all the hydrogen is in para state at $T = 0$. However, due to the rarefied density of the ISM, the ortho-to-para ratio is frozen to the H$_2$-
formation value. Considerable densities are required for the ortho-to-para conversion, which occurs in solid $\text{H}_2$ for instance.

But the fractal gas must be seen as a dynamical structure far out of thermodynamical equilibrium, not only with large density contrasts, but also large temperature contrasts. The HI is then the warm interface, and $\text{H}_2$ the coldest component, in a mass ratio of about 1 to 10. By continuity, $\text{H}_2$ forms from HI and vice versa with a rate given by the clump collision time-scale at the scale corresponding to the virial temperature of the transition. This is in any case relatively short: for 3000 K, $D \sim 1.7$, we estimate a duty-cycle of transformation HI to $\text{H}_2$ of the order of $10^6-7$ yr.

Now the key role in ortho to para conversion in interstellar clouds is the proton exchange reaction ($\text{H}^+ + \text{H}_2(j = 1) \rightarrow \text{H}^+ + \text{H}_2(j = 0)$, cf. Dalgarno et al. 1973; Gerlich 1990). This reaction can transform the ortho in a time-scale $5 \cdot 10^{13} n(\text{H}_2)^{-1/2}$ s, if the $\text{H}^+$ ions in dense clouds are essentially due to cosmic ray impacts, with the ionising flux $\xi = 10^{-17}$ s$^{-1}$ characteristic of the solar neighbourhood. The corresponding time-scale for a clumpuscule near the sun is 10 yr, and the ortho fraction is negligible, but at large distances in the Galaxy outskirts, where the cosmic-ray flux falls to zero, we can expect a significant part of ortho-$\text{H}_2$ in the cold gas.

3.3. DETECTABILITY OF THE $\text{H}_2$ ULTRAFINE LINES

On Earth, the ionosphere is reflecting the long radio wavelengths, which is useful for long distance communications. The ionospheric plasma is filtering all frequencies below the plasma frequency $\nu = e(4\pi n/m)^{1/2} \approx 100$ MHz. It is therefore necessary to observe from space. Even from space, the long wavelength radiations are somewhat hindered by interplanetary or interstellar scintillations (e.g. Cordes et al. 1986).

3.3.1. Interstellar plasma

In the ISM the plasma frequency can be estimated by $\nu_p = 9n_e^{1/2}$ kHz, where $n_e$ is the electron density. Since the latter is in average of the order of $10^{-3}$ cm$^{-3}$, the plasma frequency $\nu_p \approx 250$ Hz. Radiation of frequencies below that value does not propagate in the medium. More exactly, since the ISM is far from homogeneous, low-frequency radiation propagates in rarefied regions, and is reflected and absorbed by denser condensations. For kilometric wavelengths, there is no problem of propagation, but the waves are scattered due to fluctuations in electron density. The electric vector undergoes phase fluctuations, since the index of refraction is $(1 - \nu_p^2/\nu^2)^{1/2}$, where $\nu$ is the radiation frequency. If the ISM is modeled by a gaussian spatial distribution of turbulent clumps of size $a$, the scattering angle can be expressed by $\theta_{\text{scat}} \approx 10^8 (L/a)^{1/2} (\Delta n_e^2)^{1/2}/\nu^2$ radian, where $L$ is the
total path crossed by the radiation (e.g. Lang 1980). At a typical distance of \( L = 3 \) kpc, and for the frequencies considered (\( \approx 200 \) kHz), \( \theta_{\text{scat}} \) is of the order of \( 1^\circ \). This means that higher angular resolution should be inaccessible below 0.1 MHz. The scintillation problem is therefore severe, and hinders the resolution of point sources, but still the galactic disk can be mapped.

The interplanetary medium produces somewhat less scattering, and the total order of magnitude remains unchanged.

### 3.3.2. Intensity of the \( \text{H}_2 \) ultrafine lines

The radiation has a dipole matrix element proportional to \( \mu_\text{n}^2 \); the line intensity is therefore much weaker than for usual hyperfine transitions (magnetic dipole in \( \mu_\text{m}^2 \)). Since the spontaneous emission coefficient \( A \) is proportional to \( \nu^3 \), the life-time of a hydrogen molecule in the upper ultrafine states is much larger than a Hubble time: \( A \approx 10^{-32} \) sec\(^{-1} \). It is then likely that the desexcitation is mostly collisional. Even at the 3K temperature, the upper levels are populated in the statistical weights ratio. A weak radiation is therefore expected, but the velocity-integrated emission \( (\int T_a \, dv) \) is ten orders of magnitude less than for the HI line, for the same column density of hydrogen. The prospects to detect the lines are scarce in the near future, since it would need an instrument of about 6 orders of magnitude increase in surface with respect to nowadays ground-base telescopes! A solution could be to dispose a grid of cables spaced by \( \lambda/4 \approx 125 \) m on a significant surface of the Moon, e.g. an area of \((300 \text{ km})^2\). This requirement could be released, however, if there exists strong coherent continuum sources at km wavelengths. The \( \text{H}_2 \) ultrafine line could then be detected much more easily in absorption, with presently planned km instruments.

### 3.4. THE HD AND LIH TRANSITIONS AND DETECTABILITY

HD has a weak electric dipole moment; it has been measured in the ground vibrational state from the intensity of the pure rotational spectrum to be \( 5.85 \pm 0.17 \cdot 10^{-4} \) Debye (Trefler & Gush 1968). The first rotational level is at \( \approx 130 \) K above the ground level, the corresponding wavelength is 112 \( \mu \). This line could be only observed in emission from heated regions, and given the very low abundance ratio HD/\( \text{H}_2 \) \( \approx 10^{-5} \) and weak dipole, does not appear as a good tracer of the cold gas.

The LiH molecule has a much larger dipole moment, \( \mu = 5.9 \) Debye (Lawrence et al. 1963), and the first rotational level is only at \( \approx 21 \) K above the ground level. The corresponding wavelength is 0.67 mm (Pearson & Gordy 1969; Rothstein 1969). The line frequencies in the submillimeter and far-infrared domain have been recently determined with high precision in the laboratory (Plummer et al. 1984; Bellini et al. 1994), and the great
astrophysical interest of the LiH molecule has been emphasized (e.g. Puy et al. 1993). A tentative has even been carried out to detect LiH at very high redshifts (de Bernardis et al. 1993). This line is unfortunately not accessible from the ground at \( z = 0 \) due to \( \mathrm{H}_2\mathrm{O} \) atmospheric absorption. This has to wait the launching of a submillimeter satellite, in which case it is a good candidate. The abundance of LiH/\( \mathrm{H}_2 \) is at most \( \approx 10^{-10} \), in the absence of photodissociation, and the optical depth should reach 1 for a column density of \( 10^{12} \, \text{cm}^{-2} \), or \( N(\mathrm{H}_2) = 10^{22} \, \text{cm}^{-2} \), in channels of 1 km s\(^{-1}\).

3.5. THE \( \mathrm{H}_2^+ \) HYPERFINE TRANSITIONS

The abundance of the \( \mathrm{H}_2^+ \) ion is predicted to be less than \( 10^{-11} \) to \( 10^{-10} \) in chemical models (e.g. Viala 1986). But the \( \mathrm{H}_2^+ \) ion possesses an hyperfine structure in its ground state, unfortunately in the first rotational level \( N = 1 \). The electron spin is \( \frac{1}{2} \), and the nuclear spin \( I = 1 \), which couple in \( F_2 = I + S = \frac{5}{2} \) and \( \frac{3}{2} \); then \( F = F_2 + N = \frac{7}{2} \), \( \frac{5}{2} \) and \( \frac{3}{2} \). Five transitions are therefore expected, of which the strongest is \( F, F_2 = \frac{7}{2}, \frac{5}{2} \rightarrow \frac{3}{2}, \frac{1}{2} \), at 1343 MHz (Sommerville 1965; Field et al. 1966). At the interface between the cold molecular gas and the interstellar/intergalactic radiation field, one can hope to encounter a sufficient column density of \( \mathrm{H}_2^+ \). The excitation to the \( E_u = 110 \, \text{K} \) level is problematic however.

3.6. C AND O POLLUTION OF THE QUASI-PRIMORDIAL COLD GAS

As soon as there exist some metal enrichment from stellar nucleosynthesis, cold gas could be traced by CO molecules, provided a sufficient column density can be shielded from photodissociation. The abundance [O/H] decreases exponentially with radius in spiral galaxies, with a gradient between 0.05 and 0.1 dex/kpc (e.g. Pagel & Edmunds 1981), and the \( N(\mathrm{H}_2)/I(\mathrm{CO}) \) conversion ratio is consequently increasing exponentially with radius (Sakamoto 1996). There could be even more dramatic effects such as a sharp threshold in extinction (at 0.25 mag) before CO is detectable (Blitz et al. 1990), due to photo-dissociation. We can then estimate until which radius the dense clouds are likely to contain CO molecules, if we assume that the opacity gradient follows the metallicity gradient. Assuming the proportionality relation \( N(\mathrm{H}) \approx 2 \cdot 10^{21} \, A_V \, \text{atoms cm}^{-2} \, \text{mag}^{-1} \) between the gas column density and opacity in the solar neighbourhood (Savage et al. 1977), and a column density of \( 10^{25} \, \text{cm}^{-2} \) for the densest fragments, their opacity \( A_V \) falls to 0.25 at \( R \approx 60 \, \text{kpc} \), but of course the CO disappears at larger scales before.

The lack of heating sources is another effect hindering the detection of molecular tracers in emission, far from star-formation regions. It is impos-
sible to detect emission from a cloud at a temperature close to the background temperature. Only absorption is possible, although improbable for a surface filling factor of less than 1%. Absorption is biased towards diffuse clouds (intercloud medium) with a large filling factor and a low density (and therefore a low excitation temperature). This is beautifully demonstrated in the molecular absorption survey of Lucas & Liszt (1994) in our Galaxy. But this diffuse medium is preferentially depleted in CO at low metallicity.

Galaxy clusters is a privileged environment where the cold gas might be metal-enriched. Galaxy-galaxy interactions progressively heat the cold gas coming from individual galaxies; the virialised hot medium (10^6−7 K) experiences a strong mixing, and is enriched by the galaxy ejecta, to the observed intra-cluster abundance of ≈ 0.3 Z⊙. In the cluster center, where the density of hot gas is high enough, a cooling flow is started, and the gas temperature runs away down to the background temperature again, in a fragmented structure (Pfenniger & Combes 1994). The cluster medium is therefore multiphase, with a dense phase completely screened from the X-ray flux (Ferland et al. 1994). This accounts for the apparent complete disappearance of gas in cooling flows, and may explain the high concentration of dark matter in clusters deduced from X-ray data and gravitational arcs (Durret et al. 1994; Wu & Hammer 1993). Many authors have tried to detect this gas in emission or absorption, either in HI (e.g. Dwarakanath et al. 1995) or in the CO molecule (e.g. Braine & Dupraz 1994). Maybe the best evidence of the presence of the cooling gas is the extended soft X-ray absorption (White et al. 1991). The gas has a high surface filling factor (≈ 1), and a column density of the order of N_H ≈ 10^{21} cm^{-2}. The total mass derived is of the order of 10^{11} M⊙ over a 100 kpc region. This diffuse phase corresponds to the interface between the very cold molecular gas and the hot medium. Part of the interface is atomic, part is ionised (as observed Hα filaments suggest). Although the HI is not detected in emission with upper limits of the order of 10^9 − 10^{10} M⊙, it is sometimes detected in absorption, when there is a strong continuum source in the central galaxy. The corresponding column densities are > 10^{20} cm^{-2}.

If the molecular clouds are cold (T ≈ 3 K) and condensed (filling factor < 1%), it is extremely difficult to detect them, either in emission or in absorption, even at solar metallicity. The best upper limits reported in the literature (N(H_2) < 10^{20} cm^{-2}, average over 10 kpc wide regions, but assuming T ≈ 20 K and solar metallicity, i.e. the standard N(H_2)/I(CO) conversion ratio, are perfectly compatible with the existence of a huge cold H_2 mass (the conversion factor tends to infinity when the temperature tends to the background temperature).
3.7. UV H$_2$ ABSORPTION IN FRONT OF QUASARS

For the bulk of the gas at $T = T_{bg}$, only absorption could be detected. Absorption in the vibration-rotation part of the spectrum (in infrared) is not the best method, since the transitions are quadrupolar and very weak. An H$_2$ absorption in Orion has been detected only recently (Lacy et al. 1994) and the apparent optical depth is only about 1%. This needs exceptionally strong continuum sources, which are rare. Electronic lines in the UV should be more easy to see in absorption.

Molecular hydrogen has been found in absorption in front of the PKS-0528-250 quasar by Foltz et al. (1988), at a redshift $z = 2.8$ where there is already a damped Ly$\alpha$ system; the column density is not very high, $10^{18}$ cm$^{-2}$, with an estimated width of 5 km s$^{-1}$ and a temperature of 100 K. Recognizing H$_2$ absorption is not easy in the Ly$\alpha$ forest, and many tentative have remained inconclusive. A careful cross-correlation analysis of the spectrum is needed in order to extract the H$_2$ lines from the confusion. Already Levshakov & Varshalovich (1985) had made a tentative detection, towards PKS0528-250, with some 13 coincident lines among the Lyman and Werner H$_2$ bands. High velocity resolution to reduce confusion would be helpful in the future to detect more systems. Again absorption is biased towards diffuse gas in galaxies, but in less than $f = 1\%$ of cases, a damped H$_2$ system should be detected. A molecular clumpuscule on the line of sight of a quasar should produce a very wide saturated absorption, since the line would be in the square-root section of the curve of growth, and nearby lines should overlap (most of the UV continuum could be absorbed). If the clumpuscule is in our own galaxy, temporal variations are expected over a few months interval. It might be the most promising way to detect the cold H$_2$ gas in the outer parts of galaxies.

3.8. SUBMILLIMETER CONTINUUM

The far-infrared and submillimeter continuum spectrum from 100 $\mu$m to 2 mm has been derived from COBE/FIRAS observations by Reach et al. (1995). They show that in addition to the predominant warm dust emission, fitted by a temperature of $T \approx 20$ K, there is evidence for a very cold component ($T = 4 - 7$ K), ubiquitous in the Galaxy, and somewhat spatially correlated with the warm component (see also Mather, this volume). The opacity of the cold component, if interpreted by the same dust model, is about 7 times that of the warm component. It could correspond to those dense clumps of gas, shielded from the interstellar radiation field, that have been polluted by dust and heavy elements.

Schaefer (1996, and this volume) proposes that the cold dust component detected by COBE/FIRAS might be due in fact to molecular hydrogen.
emission, as collision-induced dipole transitions: in small aggregates at very high density (a fraction of Amagat = $4 \cdot 10^{18}$ cm$^{-3}$), the H$_2$ gas can emit a continuum radiation, corresponding to free-bound or free-free transitions of weakly bound H$_2$ dimers, containing a large fraction of ortho-H$_2$. The para-para complexes do not produce the radiation, by symmetry. Schaefer finds a good fit for the COBE spectra if the dense H$_2$ clouds follow the HI distribution in the outer parts of the Galaxy.

The weak-dipole radiation due to H$_2$ collisional complexes is an interesting possibility to detect the presence of cold molecular hydrogen. Only exceptionally dense regions could explain the signal detected by COBE, since the emission is proportional to the square of the density (Schaefer 1994). The required density then imposes the temperature ($T > 11$ K), to avoid the transition to solid molecular hydrogen. Already we had remarked that at the present cosmic background temperature of $T_{bg0} = 2.726 \pm 0.01$ K, the average pressure in the H$_2$ clumpuscules was about 100 times the pressure of saturated vapour, and that probably a fraction of the molecular mass might be in solid form (Pfenniger & Combes 1994). Already traces of H$_2$ snow flakes can improve the coupling with the CBR, but the large latent heat of 110 K per H$_2$ molecule and the lack of nucleation sites prevent a large mass fraction to freeze out. The condition of dimerization is then largely satisfied in the conditions of the clumpuscules ($T \approx 3$ K, $n \approx 10^{10}$ cm$^{-3}$). We expect continuum radiation to be emitted and absorbed by the H$_2$ collisional complexes, through collision-induced dipole moment. The absorption coefficient peaks around $\lambda = 0.5$ mm. The optical depth of each clumpuscule is however quite low $\tau \approx 10^{-9}$ which makes such signature hardly detectable.

4. Gamma-ray distribution

Gamma rays (\(\gamma\)) of high energy come mainly from the interaction of cosmic rays (CR) with the nucleons of the ISM (e.g. Bloemen 1989). Many attempts have been made in the recent years to derive the radial distribution of CR’s from observation of \(\gamma\)’s, assuming that the gas distribution is well known, derived from HI and CO measurements. Two main problems arose from these derivations: the CR distribution obtained has a very much smoother and extended radial dependence (scale-length 16 kpc) than the assumed CR sources (supernovae and stellar distribution, scale-length 4 kpc); and the H$_2$ mass derived from CO emission and a constant H$_2$/CO conversion ratio in the Galactic Center, appears too high by a factor at least 3 with respect to the \(\gamma\) rays detected there (Osborne et al. 1987).

The fact that the \(\gamma\)-ray distribution is much more extended radially than the CR sources has been interpreted in terms of CR diffusion (Bloemen 1989). However the amount of diffusion is not well known. CR particles
are closely following the magnetic field lines, due to their small gyration radius, and the field intensity is a function of gas volumic density, so that it is intrinsically hard to disentangle the CR and gas distributions. The possibility of convection in the halo, that can redistribute the CR’s in a flatter radial profiles, has been debated. Large halos are excluded however, from the study of primaries, secondaries, and radioactive secondaries as a function of energy (e.g. Weber et al. 1992). Also the thickness of the radio synchrotron halo has been derived around 3.6 kpc (e.g. Beuermann et al. 1985), giving the scale-height of CR electrons.

We have tried to fit the observed EGRET $\gamma$-ray distribution assuming different axisymmetric models for CR and total gas distribution. Some of the models are displayed in Fig. 3. Due to the low CR density in the outer parts of the Galaxy, the existence of large amounts of cold gas there is compatible with the data. A more detailed model, releasing the axisymmetry hypothesis, and taking into account the actual $l-b-v$ diagrams of the HI and CO emissions will be reported in a future work.

5. Conclusions

The main argument for the existence of baryonic dark matter comes from the constraints of the Big Bang nucleosynthesis, compared with the observed abundances of primordial elements. The most recent estimates find that the baryon density relative to the critical closure density must lie in the range $\Omega_B = 0.01 - 0.09$ (Smith et al. 1993). The visible baryons account for a much lower density, around $\Omega = 0.002$ (Persic & Salucci 1992). But the galactic dark matter could still be entirely baryonic (e.g. Carr 1995). The recent micro-lensing experiments conducted towards the Magellanic...
Clouds have revealed that Machos can account for about 20% of these dark baryons (Aubourg et al. 1993; Alcock et al. 1995), although the constraint is loose.

Molecular hydrogen is one of the least exotic candidate (Pfenniger et al. 1994). Present observations are not incompatible with this hypothesis. The main difficulty to detect very cold gas in emission is its temperature close to the one of the cosmic background. However, we must search for observational tests to falsify the proposition. The detection of the “ultrafine” structure of the ortho-H$_2$ molecules at km wavelengths raises considerable difficulties for the near future, but could be a means to fix the $N$(H$_2$)/I(CO) conversion ratio in our Galaxy. The LiH rotational lines will be easily detectable by submillimeter satellites.

Absorption lines detection might be the best way if the gas is indeed very cold. Since the surface filling factor of the molecular clumps is low ($f < 1\%$), large statistics are required, but the perspectives are far from hopeless. H$_2$ absorption in the Lyman and Werner bands has already been identified in a damped Ly$\alpha$ system, at $z = 2.8$. For a clumpscule in our own galaxy falling just on the line of sight of a quasar, we expect a strongly damped and transient absorption over a few months.

Finally, it is not excluded that the cold dust component detected by COBE/FIRAS is tracing the cold H$_2$ component, limited to galactic radii where the cold gas is still mixed with some dust. Gamma ray data could also be interpreted with the help of radially extended gas distributions.

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