Properties of Dark Matter Haloes

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**Abstract**

An overview is presented of the main properties of dark matter haloes, as we know them from observations, essentially from rotation curves around spiral and dwarf galaxies. Detailed rotation curves are now known for more than a thousand galaxies, revealing that they are not so flat in the outer parts, but rising for late-types, and falling for early-types. A well established result now is that most bright galaxies are not dominated by dark matter inside their optical disks. Only for dwarfs and LSB (Low Surface Brightness galaxies) dark matter plays a dominant role in the visible regions. The 3D-shape of haloes are investigated through several methods, that will be discussed: polar rings, flaring of HI planes, X-ray isophotes. It is not yet possible with rotation curves to know how far haloes extend, but tentatives have been made. It will be shown that the dark matter appears to be coupled to the gas in spirals and dwarfs, suggesting that dark baryons could play the major role in rotation curves. Theories proposing to replace the non-baryonic dark matter by a different dynamical or gravity law, such as MOND, have to take into account the dark baryons, especially since their spatial distribution is likely to be quite different from the visible matter.

**Key words:** dark matter, galaxies, rotation curves, flaring, flattening

**1 Rotation Curves**

At galactic scales, the best tools to probe the dark matter content of the universe are combined HI and Hα or CO rotation curves of spiral galaxies (see the review by Sofue & Rubin 2001). The optical rotation curves provide high spatial resolution in the visible disk, and in particular in the center, to trace central mass concentrations, while only the HI gas extend far enough in radius to trace the outer parts, where dark matter is dominating. A lot of progress has been made recently in our knowledge of dark matter content of galaxies, because of large samples observed in 2D Fabry-Perot Hα spectroscopy, and also I-band or near-infrared photometry (Mathewson et al 1992, Schommer et al 1993, Eskridge et al 2000). B-band images of galaxies suffer from extinction, in
Fig. 1. Examples of Hα rotation curves (dots) and their fits with I-band images (full lines); the corresponding M/L ratios is indicated above each panel, from Buchhorn (1993).

particular in the center of galaxies, leading to underestimating the stellar disk contribution to the mass, and magnifying the contribution of an hypothetic dark component. Also the mass-to-light ratios are varying more strongly with stellar populations in the blue. This is illustrated by the larger scatter of the Tully-Fischer relation in the blue (e.g. Verheijen 2001).

1.1 Rotation curves of normal spirals

The new feature resulting from these recent surveys is that for most spiral galaxies, the dark matter is not dominant within the optical disk. Indeed, the 500 rotation curves observed by Mathewson et al. (1992) have been reproduced remarkably well by Buchhorn with mass-to-light ratios constant with radius (e.g. Freeman 1993, and fig 1) and with values compatible with what is known from stellar populations. The fact that the baryonic matter is actually dominant is reflected by the very good fit of all oscillations or "wiggles" in the observed rotation curves, corresponding to spiral arms in the disk. A non-baryonic component would not follow the spiral instabilities in the disk, and would have diluted these oscillations in the rotation curves.

This point is related to the maximum disk hypothesis: the latter tries to fit rotation curves in attributing the maximum mass to the disk, compatible to the central part of the curve. Then, keeping the M/L ratio constant with radius, the rotation curve happens to be reproduced quite well over the optical disk, without dark matter. Of course, it is still possible to reduce M/L of the stellar component, and also fit the rotation curve with the addition of a dark matter component. But the peculiar streaming motions features are then less well reproduced (Sackett 1997, Palunas & Williams 2000).

Also, the fact that most galaxy disks possess bars, and these bars are rotating rapidly (their cororation is located through resonances in the middle of the disk), pleades in favor of a disk dominated by the visible matter, with a neg-
Fig. 2. (a) The universal rotation curve of spiral disks at different luminosities ($M_I$); radii are normalised to $R_{200}$, the mean radius containing a mean halo overdensity of 200. (b) The slope of the rotation curve in the region (0.6-1) $R_{opt}$ versus the rotation velocity $V_{opt}$ at $R_{opt}$. From Persic et al. 1996).

ligible contribution of spherical dark matter; dynamical friction against the dark matter component would slow down the bars in a few dynamical times (Debattista & Sellwood 1998).

The bottom line is therefore that dark matter is only needed at large radii, in the HI-21cm extensions. The fact that the rotation curve is flat in the outer parts, while it is no longer attributable to the stellar disk or bulge, has been called the conspiracy. Why does the velocity due to the spherical non-baryonic dark matter coincide exactly to that of the stellar component?

In fact, rotation curves are not all flat, depending on their morphological types (Casertano & van Gorkom 1991): early-type galaxies have rotation curves that begin to fall down, while late-type and dwarfs have not yet reached their maximum velocity at the last observed radius.

When compiling 1100 rotation curves, and normalising them to their exponential radial scales, Persic et al. (1996) found that spiral discs (once the contribution of the bulge is removed in galaxies), may have an universal rotation curve, only determined from their total luminosity (cf fig 2). At high luminosities, there is no or only a slight discrepancy between the observed rotation curve and that contributed by the luminous matter, while a larger dark matter component is required at low luminosities: the dark-to-luminous mass ratio scales inversely with luminosity (fig 2). The halo core radius is comparable to the optical radius, but shrinks for low luminosities.

However, to draw these conclusions, Persic et al. (1996) assumed that there is a constant ratio between the end-radius of the visible disk ($R_{23.5}$), and the exponential characterictic radius, or in other words, that all disks have the
same shape. This is not quite true, as emphasized by Palunas & Williams (2000). The latter authors have carried out a detailed study of 74 galaxies, where 2D Fabry-Perot Hα spectroscopy exist (Schommer et al. 1993) and I-band photometry. Very good fits of the rotation curves are obtained without dark matter, out to R_{23.5}, with a constant M/L. They conclude that mass traces light, in particular since the surface brightness profiles of the various galaxies present pronounced differences. The small number of galaxies with a poor fit have strong non-axisymmetric structures (bars and strong spiral arms). The resulting I-band M/L = 2.4 ± 0.9 h_{75}, is compatible with normal stellar populations. This indicates that the dark matter is not dominant within optical disks, or is perfectly coupled to the visible matter.

Already this fact is contradictory to expectations from CDM scenarios. CDM halo profiles are centrally concentrated, and numerical simulations predict that the dark matter dominates inside spiral disks. For example in a galaxy of the mass of the Milky Way, ΛCDM simulations predict three times more dark matter than is observed (Steinmetz & Navarro 2000). On the contrary, this fact is in agreement with MOND hypothesis.

### 1.2 Rotation curves of dwarfs and LSB

The relative importance of dark matter is increasing towards late types and dwarf irregular galaxies are completely dominated by dark matter. They are ideal tools to probe theories of dark matter, since the uncertainties on the stellar mass-to-light ratio has negligible influence on the derived radial matter profile. For the prototype of these dwarfs, DD0154, the rotation curve is well determined until 15 optical scale lengths; the HI gas component is more massive than the stellar disk (Carignan & Beaulieu 1989).

The derived radial profile of dark matter in dwarfs is not peaked towards the center, since the rotation curves are slowly rising. This is one of the main problems for the ΛCDM theories: the radial distribution is predicted by simulations to be highly peaked, with a cusp, or density following a power-law of slope -α = -1.5 (Navarro, Frenk & White 1997, Fukushige & Makino 97). Observed rotation curves points towards no cusp, but cores (Moore 1994, Dalcanton & Bernstein 2000). According to Burkert & Silk (1997), this problem could only be solved by the introduction of baryonic dark matter inside the optical disk, with a mass several times the visible mass, and with a similar radial distribution.

However, there are still uncertainties in the mass-to-light ratios, and the rotation curves are not fully sampled in all dwarf galaxies available, so that it might be still difficult to conclude for all of them (Swaters 1999, van den Bosch

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New models of dark matter have been proposed to solve precisely this problem, self-interacting dark matter with a non-zero cross-section (Spergel & Steinhardt 2000), but many new problems then appear. Other mechanisms have been proposed, such as stellar feedback, to reduce central densities of CDM (Navarro et al 1996, Binney et al 2001); but this mechanism has very low efficiency, as soon as the galaxy is more massive than \(10^7\, M_\odot\) (Mc Low & Ferrara 1999).

Low Surface Brightness galaxies (LSB) are also dominated by dark matter; they can be dwarfs, but also massive galaxies, with a large amount of HI gas. Their rotation curves are also good constraints for dark matter models. Again, they are incompatible with the cuspy profiles predicted for ΛCDM, but can be fitted with models where matter follows light, although with too large mass-to-light ratios (de Blok et al 2001).

2 3D-shape of Haloes

For the sake of simplicity, many models choose a spherical shape for the dark matter component, but this particular shape is very unlikely. All current scenarios predict in fact flattened shapes, more or less flattened according to dark matter candidates.

2.1 Axis ratio in the galactic plane

CDM simulations end up with triaxial shapes for collapsed structures, so that the haloes are not axisymmetric even in the plane of the baryonic galactic disk. This can be checked through the orbits of the baryons, and in particular the HI gas, with low velocity dispersion. Of course, inclination effects have to be taken into account, as well as flaring, warps or other distortions, due to the spiral, bars or ring features in the galaxy disks.

The result of these investigations is that galaxies are actually axisymmetric in their planes, with a very low upper limit for the eccentricity: below 0.1 with the isophote shape versus HI velocity widths method (Merrifield 2002), or even less than 0.045, when using near-infrared data to avoid extinction (Rix & Zaritsky 1995). On special cases, the limit can be better, eccentricity of the order of 0.012 in potential in the very regular early-type galaxy IC2006 with an HI ring (Franx et al 1994).

This axisymmetric shape of galactic haloes is confirmed by the low scatter observed for the Tully-Fisher relation.
2.2 Axis ratio perpendicular to the plane

The flattening in the direction perpendicular to the galactic plane is more difficult to establish. Predictions are slightly different according to the nature of dark matter. Non-baryonic pure CDM haloes are predicted already quite flattened in numerical simulations; they are half oblate and half prolate, with axis ratios of the order of $c/a = 0.5, b/a = 0.7$. It is interesting to note that the dark haloes are predicted more flattened than observed elliptical galaxies; the distribution peaks at E5 (while elliptical galaxies peak at E2 ($c/a = 0.8$)! cf Dubinski & Carlberg (1991).

However, these predictions of pure dark matter simulations were already incompatible with the observed axisymmetry of galaxy disks described above. The dissipative infall of gas in non-baryonic dark haloes should be taken into account. This concentrates even more the haloes, through adiabatic contraction, and also forces them to an oblate shape, and the prediction now become in average: $c/a = 0.5, b/a > 0.7$ (Katz & Gunn 1991; Dubinski 1994).

As for the self-interacting dark matter model (SIDM), the predicted shape is almost spherical. Bullock (2002) reconsider ΛCDM simulations and found rounder haloes; the warm dark matter models predict even more spherical haloes.

If the dominant dark matter around spiral galaxies is baryonic, and in the form of cold gas, it will be dissipative, and is predicted more flattened (Pfenniger & Combes 1994). Account must be taken however of the strong flaring of disks in the outer parts, that makes the potential rounder. The very frequent warps of galaxy planes in the outer parts, related to gas accretion and long relaxation time there, also accentuate the roundness of the potential.

2.3 Polar rings

Polar ring galaxies are peculiar objects composed of two systems with almost perpendicular angular momenta: a host galaxy, early-type in general (a lenticular more frequently), is surrounded by a perpendicular ring of gas and stars following nearly polar orbits. These systems are thought to be formed during an accretion or merger event. They are quite precious tools to probe the 3D shape of dark matter haloes, since HI gas is orbiting perpendicular to the main plane of the host galaxy.

Many problems however have prevented a clear picture to emerge:

- the early-type host system has a stellar component with large velocity dis-
Fig. 3. Histogram of halo flattening, according to the three methods used in the literature: flaring gas-layer, polar-rings and X-ray isophotes.

- gas cannot coexist at the same radius in perpendicular planes, since collisions will dissipate its energy quickly, and it will infall to the center. Therefore, it is impossible to compare equatorial and polar velocities at a given radius (and indirect comparisons at different radii are model dependent.)
- due to an obvious selection effect, observed polar rings are massive, and therefore the polar matter cannot be considered as test particles to probe the host galaxy potential, but the polar mass perturbs the potential, and the polar ring might even be self-gravitating.

The estimation of the potential flattening around one of the best known polar ring galaxy NGC4650A has given rise to very different results: either spherical, or flattened along the host galaxy plane, or flattened along the polar ring itself (Sackett et al. 1994, Combes & Arnaboldi 1996). The latter geometry could be explained in the case of a non perturbative merger, where a massive galaxy settles with its flattened dark halo, perpendicular to the host lenticular system (Bekki, 1998), or in case of gas accretion, if gas is representing a significant part of the dark matter around galaxies (Bournaud & Combes 2002). The fact that polar ring galaxies have a wider HI velocity width with respect to corresponding galaxies in the Tully-Fisher relation (Iodice et al 2002) supports this hypothesis.
In the outer parts of galaxies, if the gas is in hydrostatic equilibrium, its scale height is a function of the density of dark matter in the plane (which provides the restoring force towards the plane), and of the gas velocity dispersion. The HI gas dispersion is observed to be almost constant with radius in face-on galaxies: $\sigma_z$ (HI) = 10 km/s (Dickey et al 1990, Kamphuis, 1992), and since the surface density of dark matter is falling with radius (to provide the flat rotation curve), the restoring force is declining, and therefore the gas is flaring with radius. The amount of flaring is an indicator of the surface density of dark matter in the plane, with respect to a spherical distribution which produces only radial forces. The method was applied to the galaxy NGC 4244 by Olling (1995, 1996), and to NGC 891 by Becquaert & Combes (1997), and both haloes were found quite flattened, with an axis ratio of $q= c/a= 0.2$. But here too, some free parameters have to be chosen, that can moderate these results. First, the flaring of the HI plane is well measured for edge-on galaxies, but then the velocity dispersion perpendicular to the plane is not well known, and must be extrapolated from other galaxies, or derived from a model. More important, the deduced degree of flattening depends on the assumed truncation radius of the dark matter halo. Indeed, contrary to a spherical distribution, the forces inside a certain radius is strongly dependent on the mass outside, if the halo is flattened. And since for a flat rotation curve, the mass is increasing linearly with radius, the inside force is very quickly dominated by the mass outside, which is completely unknown.

If the halo is truncated at the last HI measured radius, it can be highly flattened. Paradoxically, for the same rotation curve, the dark potential of the “maximal halo/minimal disk” solution is rounder than for the “maximal disk/minimal halo” solution, since there is then more mass in the outer parts. Introducing a truncation in the dark halo outside of the last observed HI point makes it much more flattened for a given HI thickness: for example the flattening derived for NGC 4013 is $q=0.1$, for M31, $q=0.2$ (Becquaert, 1997).

Another method has been used to obtain the shape of dark haloes around elliptical galaxies possessing diffuse X-ray emission (Buote et al. 2002): haloes are triaxial, with significant flattening. A compilation of all published results has been recently made by Merrifield (2002), and an updated version is reproduced in fig 3).

Weak lensing by galaxies (or galaxy-galaxy lensing) is a new method that can bring information on the galaxy potential at large scale, both the 3D shape and the radial extent (see Hoekstra’s talk at this workshop). The first results point to flattened haloes (Hoekstra et al 2002).
As for the MOND hypothesis, Milgrom (2001) has demonstrated that it is equivalent to assume two dark matter components, with respect to the $z$-behaviour: a disk and a round halo. In the flaring region, the fake massive disk dominates the true one, and therefore the $z$-force is larger than the Newtonian one: the halo should appear quite flattened, through the flaring method. At larger radii (and larger $z$), the fake round halo dominates.

3 How Far do Haloes Extend?

We know rotation curves in the outer parts of spiral galaxies only through the HI gas kinematics. But the HI disc is typically observable up to $R_{25}$, after which the neutral gaseous disc is sharply truncated, and we have no more information.

The HI cut-off is probably due to an ionisation of the HI by the extragalactic UV field radiation. Maloney (1993) describes such a process in the case of NGC 3198 and gives a profile of the HI decrease with a cut-off radius around the column density of $10^{19}$ cm$^{-2}$, at several times the stellar disc radius. Bland-Hawthorn al. (1997) suggest another mechanism: the photoionization of the HI might be caused by hot and young inner stars. To understand the sharp edge in the atomic hydrogen disc, Bland-Hawthorn al. (1997) have searched and detected ionised hydrogen, beyond the edge of the HI disc of NGC 253. More essential, the authors used the H$\alpha$ velocity to extend the rotation curve of this galaxy and conclude the rotation curve may fall near the HI cut-off. They even find a hint for the expected increase-before-drop signature in the rotation curve of a truncated disk (cf Casertano 1983). This suggests that the edge of the dark matter component is not far from the HI truncature. This result is only tentative, and it is of first importance to confirm it and repeat in other galaxies, to determine the nature and distribution of dark matter. Evidence for the Keplerian falloff (and possibly the truncation signature) would help to know the total mass of spiral galaxies and to test models of 3D dark matter structures, their flattening and radial extension.

Moreover, a truncation signature, and a fall-off at large radius would bring strong constraints to the MOND hypothesis.

4 Tidal Tails

The length, thinness and general morphology of tidal tails in interacting galaxies, such as the Antennae, are quite sensitive to the halo mass distributions in
Fig. 4. Rotational velocity (in km/s), versus radius, normalised to the outer one, for dwarf galaxies, from Hoekstra et al (2001). The HI observed rotation curve is represented by dots with error bars, and the fit is the solid curve. The contribution of the stellar component is the dotted curve, and the scaled HI component is the dashed curve (curve obtained when the HI surface density is multiplied by a factor constant in radius). The scale factors, to obtain the fits in each galaxy, are all gathered around 10, with a small scatter.

Since these arguments encountered some controversies, mainly that the tidal tails do not constrain the total dark matter content, but only its radial distribution, Dubinski et al (1999) subsequently explored many different distributions and shapes. They conclude that tidal tails formation is inhibited in a galaxy with a rising or flat rotation curve dominated by the halo, unless the halo is abruptly cut off just beyond the disk edge. On the contrary, tidal tails such those currently observed are easy to form in galaxies with declining rotation curves, resulting either from compact, low-mass halos or from massive disk components in low-concentration dark halos. The galaxy models that appear to fit most of the observational constraints are those that have disk-dominated rotation curves and low-concentration halos.

These findings appear to put CDM predictions in difficulty. It would be interesting to make simulations of galaxy interactions and tidal tails formation within the MOND hypothesis.
5 Local Dark Matter?

Since the pioneering study by Oort (1960) who found some dark matter in the Milky Way disk near the Sun, many studies were carried out before Hipparcos with contradictory results: Bahcall (1984) finds that half of the local mass is dark, while the conclusions of Bienaymé et al (1987) and Kuijken & Gilmore (1989) were compatible with no dark mass in the disk. Bahcall et al (1992) quantified that locally there is 53% more dark matter than visible stars. Crézé et al (1998) from Hipparcos data concluded to no disk dark matter. However this result relies on the simplifying assumptions of axisymmetry and stationarity, both not satisfied due to the presence of a contrasted spiral structure and expected strong evolution in a barred galaxy. The derived stellar stellar density locally is 0.04 M\(_\odot\)/pc\(^3\), while the total density 0.08 M\(_\odot\)/pc\(^3\). The difference is assumed to be the gas density, which is not well known.

Recently, Ibata et al. (2001) identified a stellar stream assumed to be coming from the disruption of the Sagittarius dwarf, through cool carbon giant stars in the Galactic halo. They argue that the orbits of these stars in the dark matter halo of the Milky Way and the morphology of the stream put constraints on the flattening of the halo, which they found quasi spherical.

6 Tully-Fisher Relation

The Tully-Fisher relation, which has relatively small scatter when near infrared photometry is used, tells us that galaxy disks obey a scaling law (mass-to-size relation) in addition to the virial theorem, and to an almost constant mass-to-light ratio, over a large luminosity range. Since the relation involves the global velocity width of the galaxy, it is strongly weighted to the central parts, where all the velocity gradient is observed in general (with exception for dwarfs, with still rising rotation curves). The relation therefore does not tell us about the dark matter, which is not dominant in the central parts for bright spirals. However, it becomes a precious tool to detect galaxies that are dominated by dark matter in their central parts, where the M/L ratio becomes high.

Precisely the relation breaks down towards low luminosity galaxies, and extreme late-type spirals (Matthews et al. 1998). Then the gas mass which becomes significant, has to be taken into account in the "luminosity" of the galaxy. The gas mass fraction can be very large, and for LSB dwarfs reach the highest levels of any known galaxy type (fg=95%) (Schombert et al. 2001). The gas mass fraction is strongly correlated with luminosity and surface brightness (McGaugh & de Blok, 1997). Adding the gas "luminosity" to the optical
luminosity is known as *baryonic correction* (Milgrom & Braun 1988). With this correction, gas-dominated dwarf galaxies follow the same TF relation as for bright spiral galaxies. McGaugh et al. (2000) call this the “baryonic TF relation”. The relation is plotted in terms of mass versus velocity, assuming a constant M/L ratio for the stellar component. Then, to compensate for the faint galaxies break, i.e. for $V_{rot} \leq 90 \text{ km s}^{-1}$, the gas mass is added to the stellar mass, to compute the total visible baryonic mass $M_d = M_* + M_{gas}$. With this total mass, the TF relation is satisfied over the entire mass range, confirming that the relation only involves baryonic matter, which is in accordance with the MOND hypothesis.

7 Baryonic Dark Matter

If we want to test any proposed theory of gravity, such as MOND that replaces the non-baryonic dark matter, we still have to take into account the baryonic dark matter, which dominates the visible matter, and can change considerably.
Fig. 6. Radial distributions of various surface densities in a typical spiral galaxy NGC 6946: H$_2$(CO) and HI column densities, Blue, Radio-continuum and Hα surface densities (adapted from Tacconi & Young, 1986).

The quantity of baryons in the Universe (and more precisely the fraction of the critical density in baryons $\Omega_b$) is constrained by the primordial nucleosynthesis to be $\Omega_b = 0.015 \, h^{-2}$, with $h = H_0/(100 \, \text{km/s/Mpc})$ is the reduced Hubble constant. With $h = 0.4$, $\Omega_b$ is 0.09, and more generally $\Omega_b$ is between 0.01 and 0.09 (Walker et al. 1991, Smith et al. 1993), while the visible matter corresponds to $\Omega_\ast \sim 0.003 \, (M/L/5) \, h^{-1}$ ($+0.006 \, h^{-1.5}$ for hot gas). Therefore, most of the baryons (90%) are dark. This is supported by the recent measurements of the CMB anisotropies (BOOMERANG, MAXIMA, cf Jaffe et al 2000).

7.1 Nature of the baryonic dark matter

Since about a decade, the microlensing experiments have accumulated lensing events by compact objects in the Milky Way halo (Lasserre et al 2000, Alcock et al. 2001), and brown dwarfs are now ruled out as candidate for the baryonic dark matter. There could be a small contribution in white dwarfs, but the bulk
of the mass has to be contributed by other candidates. These can only be gas now, either hot ionised gas around filaments in the intergalactic space (of which only a fraction $\sim 10^{-4}$ is detected through the neutral fraction in Lyα absorption lines), or cold neutral molecular gas associated with galaxies.

One model proposes to extrapolate the visible gaseous disk towards large radii, with thickening and flaring, following the HI disk. The cold and dark H$_2$ component is supported by rotation, exists only outside the optical disk, where it is required by rotation curves (Pfenniger et al 1994, Pfenniger & Combes 1994). The gas is stabilised through a constantly evolving fractal structure, experiencing Jeans instabilities at all scales, in thermal equilibrium with the cosmic background radiation at $T = 2.7 (1+z)$ K.

Other models distribute the dark molecular gas in a spherical or flattened halo, with no hole within the optical disk. The molecular gas is not so cold, and is associated with clusters of brown dwarfs or MACHOS (de Paolis et al. 1995, Gerhard & Silk 1996, Kalberla et al. 1999).

7.2 Coupling between HI gas and dark matter

In the first model, the HI gas can be considered as a tracer of the dark baryons, the interface between the molecular clumps and the extra-galactic radiation field. Beyond the HI disk, there could be an ionization front, and the interface might become ionized hydrogen. In this context, there should exist a distribution correlation between the dark matter and the HI gas. This is indeed the case, as already remarked by Bosma (1981), Broeils (1992) or Freeman (1993): there is a constant ratio between the surface density of dark matter, as deduced from the rotation curves, and the HI surface density, $\Sigma_{DM}/\Sigma_{HI} = 7-10$ (cf figure 4, extracted from Hoekstra et al. 2001). This ratio is constant with radius in a given galaxy, and varies slightly from galaxy to galaxy, being larger in early-types (figure 5). However, the dark matter does not dominate the mass in the latter, and therefore the estimate of its contribution is more uncertain. The correlation is the most striking in dwarf galaxies, which are dominated by dark matter (figure 4).

7.3 H$_2$/HI ratio and its radial variation

The differences between HI and H$_2$ (traced by CO line emission) radial distributions in galaxies is striking (cf figure 6). While all components related to star formation, the blue luminosity from stars, the Hα (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 ex-
In fact, the true H$_2$ radial distribution is not known, since the CO emission is not a good tracer, especially because it depends on metallicity (may be in a non-linear way); it is well known that the metallicity decreases exponentially with radius in typical spirals. The CO-emission exponential fall off has therefore to be corrected to deduce the true H$_2$ distribution. Given that the H$_2$/HI surface density ratio is larger than 10 in the center, it is not impossible that cold H$_2$ exists in such proportions in the outer parts as to account for rotation curves in spiral galaxies.

7.4 Warm H$_2$ as a tracer?

H$_2$ is a symmetric molecule, and does not radiate at low temperature (the first accessible level with quadrupole transitions is at 500K above the fundamental).
Fig. 8. Radial distribution of the hot gas fraction $f_g$ in clusters of galaxies: the abscissa $\delta$ is the average density inside the radius $r$, normalised to the critical density. The filled circles, empty triangle and crosses are the data, while the squares connected by a dashed line are the theoretical predictions (cosmological simulations from several groups), with an assumed baryon fraction of $f_b = \Omega_b/\Omega_m = 0.16$; other model variants (with or without stellar feedback, supernovae winds) are shown with $f_b = \Omega_b/\Omega_m = 0.20$ (small squares), from Sadat & Blanchard (2001).

Among the various methods to try to detect it indirectly (e.g. Combes & Pfenniger 1997), one of the most favorable is to observe the fundamental pure rotational lines $S(0)$ at 28 $\mu$m and $S(1)$ at 17 $\mu$m. Gas must be warm ($\sim 100$K) to have some significant emission, but some warm gas is always expected to be present in a turbulent fractal medium, where small clumps enter in collisions frequently. Slow shocks can then heat some small fraction of the gas, such that emission in the first rotational lines is detectable.

Already ISO observations of these lowest pure rotational lines of H$_2$ in NGC 891 have brought clues for the existence of large quantities of H$_2$ in galaxies (Valentijn & van der Werf 1999). The H$_2$ emission is not decreasing steeply with radius, as is the CO integrated emission (see fig 7). The warm H$_2$ gas is well mixed with the CO gas, according to its kinematics. The linewidths
suggest that the more fundamental line $S(0)$ is more extended than $S(1)$. Although the observations stop at the end of the optical disk, it seems possible to detect the emission in the outer parts.

These observations should be pursued in external galaxies, at much further radius than was possible with ISO. If the presence of large dark gas is confirmed in galaxies, it will change drastically the MOND predictions, since this dark baryons have not the same radial distribution than the visible matter.

### 7.5 Distribution of baryonic matter in galaxy clusters

In galaxy clusters, the hot gas detected in X-rays dominate the visible mass. Depending on the cluster, most or all of the baryons have become luminous, since the visible baryonic mass fraction is representative of the whole universe $f_b = \Omega_b/\Omega_m \sim 0.15$. A striking feature is the radial distribution of visible and dark masses, which is now reversed at those scales. Indeed, if the dark matter fraction is increasing with radius in galaxies, it is decreasing with radius in clusters (cf fig 8). This result was already emphasized by David et al (1995), and has been confirmed and precised since then (Ettori & Fabian 1999, Sadat & Blanchard 2001). The gas mass fraction ranges from 10 to 25%, and varies from cluster to cluster. These variations may be explained if the dark matter has a significant baryonic component. In those clusters where no significant amount of baryonic dark matter remain, it is quite difficult to maintain a MOND interpretation of the non-baryonic dark matter, which is more concentrated than the visible matter. Already Milgrom (1998) acknowledged that the MOND hypothesis was not able to account for clusters cores, except in the presence of a dominant baryonic dark component in the center.

### 8 Conclusions

Dark haloes at galactic scales are now constrained by more precise rotation curves. Bright spiral galaxies are not dominated by dark matter in their optical disks. The dark-matter/visible mass ratio is a function of luminosity and surface brightness. Dwarf and LSB galaxies are the best laboratories for dark matter studies since they are dominated by unseen matter down to their central regions. The derived radial profile of dark matter is not centrally concentrated and presents no cusp as predicted in the CDM scenario.

The 3D shape of haloes is still badly constrained. Polar rings are often self-gravitating and there are some clues that their potential is flattened along the polar plane. The HI plane flaring method depends strongly on the assumed
truncation radius of the dark matter component.

Observations have shown however that haloes are oblate and galaxy potential axisymmetric in their planes.

Statistical galaxy-galaxy lensing might bring some progress in the determination of shape and radial extension of dark matter haloes.

The formation of tidal tails in galaxy interactions is a good test of the shape of their potential. Simulations have shown that only galaxies dominated by their visible matter, or with their halo truncated outside their optical disk, were able to form tails corresponding to observations. Such simulations should be explored within the MOND hypothesis.

Most baryons are dark, according to primordial nucleosynthesis and CMB anisotropies. These baryons could be present in the form of cold molecular clouds in the outer parts of galaxies, with a H$_2$/HI surface density ratio of about 10, as suggested by rotation curves. This reservoir of gas in the outer parts account for galaxy evolution, that requires fresh replenishment of gas for star formation, and explains the evolution of morphological types along the Hubble sequence: late-types have a much larger proportion of dark matter than early-types, while secular evolution (through bars and spirals), and interactions/mergers tend to progressively transform late-type galaxies in early-type ones.

In galaxy clusters, the baryonic matter is almost all visible in the form of hot X-ray gas. The distribution of the dark with respect to visible matter, which increases with radius at galactic scales, and then decreases with radius at cluster scale, might raise strong constraints in all modified gravity/dynamics theories. For all these scenarios, the spatial distribution of baryonic dark matter is a fundamental element to consider.

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