Collisional baryonic dark matter haloes

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Accepted 1999 April 12. Received 1999 April 7; in original form 1998 July 30

ABSTRACT
If dark haloes are composed of dense gas clouds, as has recently been inferred, then collisions between clouds lead to galaxy evolution. Collisions introduce a core in an initially singular dark matter distribution, and can thus help to reconcile scale-free initial conditions — such as are found in simulations — with observed haloes, which have cores. A pseudo-Tully–Fisher relation, between halo circular speed and visible mass (not luminosity), emerges naturally from the model: $M_{\text{vis}}/V^7 = 2$.

Published data conform astonishingly well to this theoretical prediction. For our sample of galaxies, the mass–velocity relationship has much less scatter than the Tully–Fisher relation, and holds as well for dwarf galaxies (where diffuse gas makes a sizeable contribution to the total visible mass) as it does for giants. It seems very likely that this visible-mass/velocity relationship is the underlying physical basis for the Tully–Fisher relation, and this discovery in turn suggests that the dark matter is both baryonic and collisional.

Key words: galaxies: evolution – galaxies: haloes – dark matter.

1 INTRODUCTION
A great variety of dark matter candidates exist, motivated by diverse pieces of evidence, typically indirect (see, for example, the review by Trimble 1987). One such piece of evidence comes from the ‘Extreme Scattering Events’ (ESEs: Fiedler et al. 1987); these are radio-wave lensing events caused by dense blobs of plasma crossing the line of sight. Walker & Wardle (1998a) presented a model in which these events are caused by ionized material associated with planetary-mass, molecular gas clouds in the Galactic halo. This model is good at explaining the ESE phenomenon, but carries with it the implication that most of the mass of the Galaxy is in this cold, dense form. If the Galactic dark matter is really in cold gas clouds — as, in fact, has been proposed previously by a number of authors (Pfenniger, Combes & Martinet 1994; de Paolis et al. 1995; Gerhard & Silk 1996) — then consistency with a variety of data requires that these clouds satisfy several constraints (Gerhard & Silk 1996). Foremost amongst these is the requirement that collisions between clouds should not entirely deplete the halo of its dark content. If the Galactic dark matter is really in cold gas clouds — as, in fact, has been proposed previously by a number of authors (Pfenniger, Combes & Martinet 1994; de Paolis et al. 1995; Gerhard & Silk 1996) — then consistency with a variety of data requires that these clouds satisfy several constraints (Gerhard & Silk 1996). Foremost amongst these is the requirement that collisions between clouds should not entirely deplete the halo of its dark content. If the Galactic dark matter is really in cold gas clouds — as, in fact, has been proposed previously by a number of authors (Pfenniger, Combes & Martinet 1994; de Paolis et al. 1995; Gerhard & Silk 1996) — then consistency with a variety of data requires that these clouds satisfy several constraints (Gerhard & Silk 1996). Foremost amongst these is the requirement that collisions between clouds should not entirely deplete the halo of its dark content. If the Galactic dark matter is really in cold gas clouds — as, in fact, has been proposed previously by a number of authors (Pfenniger, Combes & Martinet 1994; de Paolis et al. 1995; Gerhard & Silk 1996) — then consistency with a variety of data requires that these clouds satisfy several constraints (Gerhard & Silk 1996). Foremost amongst these is the requirement that collisions between clouds should not entirely deplete the halo of its dark content.

2 ISOTHERMAL HALOES
In a halo with one-dimensional velocity dispersion $\sigma$ the typical relative speed of a pair of clouds is $\sqrt{6}\sigma$. Essentially all collisions are highly supersonic and even glancing impacts — i.e. those with impact parameter roughly equal to twice the cloud radius — are expected to unbind the clouds, with the result that the collision products become visible as diffuse gas (which may subsequently be transformed into stars). In this circumstance the cross-section for disruptive collisions between clouds is just four times the geometric cross-section of a single cloud. Recognizing that each collision disrupts two clouds, we see that the collision rate can be written as

$$\frac{d\log \rho}{dr} = \frac{8\sqrt{6} \rho \sigma}{\Sigma},$$

where $\rho$ is the halo density, and $\Sigma$ is the mean surface density of the individual clouds. A more rigorous treatment, in which one integrates the collision rate over the velocity distribution of the clouds, yields a numerical factor $(32/\sqrt{\pi})$ which differs by less than 10 per cent from that in equation (1).

Collisions occur preferentially between pairs of clouds having antiparallel velocities, so that the collision products have a much smaller velocity dispersion than the parent clouds (by a factor of $\sqrt{8}$, and subsequently undergo infall in the gravitational potential. This infall modifies the potential, which in turn leads to evolution of the dark halo density beyond that described by equation (1). (This is ‘halo compression’ —see Blumenthal et al. 1986.) We shall not attempt a self-consistent treatment but, rather, we neglect the evolution of the gravitational potential. This allows us to estimate the dark halo density evolution in a straightforward manner by integrating equation (1);
3 A PHYSICAL BASIS FOR THE TULLY–FISHER RELATION

The Tully–Fisher (TF) relation is an empirical result that connects the width of 21-cm line emission, $\Delta V$, from a spiral galaxy with the expected luminosity of the galaxy, $L$:

$$L \propto \Delta V^{\alpha},$$

where $\alpha = 4$ (Strauss & Willick 1995); the scatter in this result is quite small. Unfortunately there is no sound theoretical basis for the TF relation. Attempts to derive it on the basis of the virial theorem, plus the assumption of fixed surface brightness for all galaxies (‘Freeman’s law’), fail foul of the fact that TF holds also for very low surface-brightness galaxies (Zwaan et al. 1995; McGaugh & de Blok 1998). Put another way, we expect $\Delta V \sim 2V$, so that the kinematics reflect the properties of the dark halo, but $L$ is a manifestation of the stellar component of the galaxy, and no direct coupling between these two is expected a priori. Indeed, as total mass-to-light ratios can vary by more than an order of magnitude among the population of observed galaxies, one tends to think of the visible and dark components as almost independent. However, the collisional process that we described in Section 2 converts dark matter into visible forms, and thus creates a close coupling between the dark halo and the visible galaxy. Such a coupling holds promise for explaining the Tully–Fisher relation; this appealing attribute of baryonic models has been recognized previously (Pfenniger, Combes & Martinet 1994; Gerhard & Silk 1996).

We can compute the total visible mass, $M_{\text{vis}}$, in the form of stars and gas (without actually saying anything about their relative proportions), from

$$M_{\text{vis}}(t) = \int_0^t 4 \pi r^2 \rho(r,0) dr.$$  

With the evolving isothermal halo described by equation (3), this gives

$$M_{\text{vis}} = \frac{\pi \sigma^2}{G} r_c.$$  

Notice that $M_{\text{vis}}$ is perfectly well defined, despite the total mass of the dark halo diverging at large radii. If we adopt the reasonable supposition of a roughly similar stellar mass-to-light ratio for all spirals then, provided that diffuse gas makes a negligible contribution to $M_{\text{vis}}$, we expect $L \propto V^{3.5}$, which is close to equation (7). In the usual form, however, TF is a relation between global 21-cm linewidth, $\Delta V$, and luminosity. Moreover, various exponents $\alpha = 4$ are observed, so it is not immediately obvious that our theory is in agreement with the data.

Spectral-line imaging (notably 21-cm imaging) gives detailed information on the velocity field of a galaxy, allowing accurate determination of the rotation curve (hence $V$), rather than just the global property $\Delta V$ which can be determined with a single dish radio telescope. Broeils (1992, chapter 4, appendix A) has investigated the $L[\Delta V]$ and $L[V]$ relationships for a sample of 21 galaxies with well-determined rotation curves. He finds that blue luminosity is more tightly correlated with $V$ than $\Delta V$; the former displays a scatter of 0.22, and the latter 0.28, in log$_{10} L$. (More precisely, Broeils used the circular speed in the flat part of the rotation curve, which we take to be a good estimator for $V$.)

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Furthermore, the relation he derives is $L \propto V^{3.4}$, which is very similar to the form we predict.

We could go further and compare the normalization of this result with that of our own theory, but in doing so we would be forced to introduce an additional quantity, the value of the stellar mass-to-light ratio, which is a priori unknown. This can be avoided if we compare $M_{\text{vis}}$ directly with mass estimates derived from rotation curve decompositions which, in effect, measure the stellar mass-to-light ratio for each galaxy. Furthermore, by utilizing mass, rather than luminosity, we expect better agreement with our theory because we can include the diffuse gas content. Note that diffuse gas is often a substantial fraction of the total visible mass of dwarf galaxies; in the (extreme) case of DDO154 it amounts to 80 per cent of the visible mass (Carignan & Freeman 1988). While Broeils (1992) did not investigate the possibility of any correlation between $M_{\text{vis}}$ and $V$, he did give maximum disc decompositions of the rotation curves for 15 of the 21 galaxies studied; his results are summarized in Table 1, and plotted in Fig. 1. Also shown in Fig. 1 is the relation given by equation (9), with the cloud surface density ($\Sigma$) treated as a free parameter.

![Figure 1. Data for a sample of 15 galaxies with well-determined rotation curves (see Table 1), showing the total visible mass as a function of galaxy circular speed (i.e. $M_{\text{vis}}$). Contributions to $M_{\text{vis}}$ come from stars – both bulge and disc (determined from ‘maximum disc’ decompositions) – and diffuse gas. The plotted symbol size is arbitrarily chosen. The line shows the prediction of equation (9), with cloud surface density ($\Sigma$) treated as a free parameter.](https://academic.oup.com/mnras/article-abstract/308/2/551/1048629)

The explicit numerical form of our fit is

$$M_{\text{vis}} = 7.0 \times 10^3 V_{100}^{7/2} M_\odot, \quad (10)$$

corresponding to $\Sigma = 140 \, \text{g cm}^{-2}$ (for $t = 10 \, \text{Gyr}$), and $r_c = 1.9 V_{100}^{1/2} \, \text{kpc}. \quad (11)$

We will not attempt to give a figure of merit for the fit quality, as the uncertainties associated with the data involve systematic uncertainties in rotation-curve decomposition, and these are hard to quantify. We can, however, measure the scatter of the data about the theoretical prediction: the root-mean-square deviation is 0.084 in $\log_{10} M_{\text{vis}}$. By comparison the scatter in the Tully–Fisher relation for this sample is almost a factor of 3 larger (0.24 in $\log_{10} L_B$ – slightly bigger than the scatter of 0.22 for the full

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**Table 1.** Galaxies with well-determined rotation curves. Circular speeds are taken from table A.1 (column 9), p. 94 of Broeils (1992), while masses are obtained from ‘maximum-disc’ rotation-curve decompositions – the sum of columns 7 (diffuse gas), 9 (disc stars) and 11 (bulge stars) of table 2, p. 244, in Broeils (1992). Only 15 galaxies are common to both tables.

<table>
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<tr>
<th>Name</th>
<th>$V$</th>
<th>$M_{\text{vis}}$</th>
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<tr>
<td>NGC55</td>
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</tr>
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</table>

**Figure 2.** As Fig. 1 but for the stellar mass only, i.e. excluding the contribution of diffuse gas to the total visible mass; the theoretical line is identical to that in Fig. 1. It is clear that the dwarf galaxies, which have a high mass fraction in diffuse gas, systematically depart from the relationship defined by the giants, if only stellar mass is included in the accounting. Compare this with Fig. 1, where a single relation is valid for the whole sample.
sample of 21 galaxies studied by Broeils). Notice that only a part of this difference can be accounted for by uncertainties in galaxy distances, as the stellar mass inferred from rotation-curve decomposition is proportional to distance, while luminosity and the measured gas mass are both proportional to (distance)^2. We also note that if the mass contributed by diffuse gas is neglected then the dwarf galaxies systematically depart from the relation defined by the giants; this point is graphically illustrated in Fig. 2, where stellar mass is plotted as a function of halo circular speed. These facts oblige us to conclude that the fundamental connection is between total visible mass and halo circular speed, with the Tully–Fisher relation emerging as an approximation which is valid when most of the visible mass is in stellar form.

To add a little more weight to this conclusion, we emphasize that our sample of galaxies is very heterogeneous: it spans the entire size spectrum from dwarfs to giants; it includes low surface-brightness objects; most importantly, perhaps, it includes cases in which the visible galaxy makes a negligible contribution to the rotation curve. This last point is crucial as it requires that the observed \( M_{\mathrm{vis}}[V] \) relation be interpreted as \( M_{\mathrm{vis}} \) being determined by \( V \) and not the other way around. That is, purely from an observational perspective we can assert that the visible mass content of a galaxy is determined by the velocity dispersion of the dark matter halo. Our theory shows why this ought to be so, and it follows that these data support the model of a baryonic dark halo, with clouds of typical surface density \( \Sigma = 140 \, \text{g cm}^{-2} \).

4 DISCUSSION

The evolution implicit in equation (9) could, in principle, be used to further test the theory we have presented, but in practice this would be difficult. In particular the requisite sensitivity and angular resolution, for determining 21-cm rotation curves of normal galaxies at \( z \sim 1 \), are both beyond the reach of current instrumentation. Some studies have already been made of Tully–Fisher-type correlations of galaxies at \( z \sim 1 \), based on optical data alone (e.g. Vogt et al. 1997). These show mild evolution in a sense opposite to that expected in our theory (if a constant mass-to-light ratio is assumed), and we must suppose that this is a result of stellar populations being younger at earlier epochs. Notice that there are serious consequences for galaxy distance estimates based on a local Tully–Fisher relation if the actual TF relation evolves with look-back time.

It is well known that the infrared TF relations show less scatter than their visible counterparts (Aaronson, Huchra & Mould 1979), because infrared photometry is less sensitive to the young, hot stars that tend to dominate the luminosity (but not the total stellar mass) of the galaxy. Extinction corrections are also smaller in the infrared. This argues that rotation-curve decompositions based on infrared photometry ought to be better than those based on visible photometry. In addition, there is no particular reason to suppose that ‘maximum-disc’ rotation-curve decompositions give the best estimates of the stellar mass-to-light ratio. Thus, with a study that is specifically aimed at testing equation (9), it may be possible to reduce the scatter seen in Fig. 1 below its already small value. Ideally one would like to work with a sample of galaxies from a single cluster, thereby reducing the dispersion contributed by distance uncertainties; distance errors probably dominate the currently observed scatter of 0.084 dex in the \( M_{\mathrm{vis}}[V] \) relation.

Any cluster of galaxies that is well approximated by an isothermal distribution of dark matter should fit into the scheme we have outlined, simply by an appropriate choice of velocity dispersion. [We estimate from the evaporation constraints given by Gerhard & Silk (1996) that the clouds can survive for roughly a Hubble time in the environment of a rich cluster of galaxies.] For example, taking \( \sigma = 10^2 \, \text{km s}^{-1} \) equation (10) predicts a visible mass of \( M_{\mathrm{vis}} = 7 \times 10^{13} \, \text{M}_\odot \), broadly consistent with the data (Jones & Forman 1984), and equation (11) gives a dark matter core radius of \( r_c = 100 \, \text{kpc} \). This core radius is rather larger than indicated by analysis of cluster lensing data (Miralda-Escudé 1993; Flores & Primack 1994) but we must bear in mind that lensing measures the total surface density, not just the dark component. For galaxies, the greatest visible contribution typically comes from stars, the presence of which is relatively straightforward to quantify, but for rich clusters it is usually the hot intracluster medium that dominates, and here the inferred mass distribution is much more model dependent. (Notice, again, that the theory we have presented is only partially predictive in that it gives the total visible mass, but does not tell us whether this ought to be in stars or diffuse gas.) In particular we note (i) it is thought that in ‘cooling flow’ clusters a large amount of gas accumulates in some (unknown) form at the centre of the cluster (Fabian 1994), and (ii) there are tentative detections of huge amounts of warm (EUV emitting) gas in some clusters (Mittaz, Lieu & Lockman 1998).

In the foregoing discussion we have given no consideration to the material properties of the cloud-collision products, being content with the notion that this stuff becomes part of the visible pool. A basic analysis of the effects of the shock (Walker & Wardle 1998b) indicates that, for the Galactic halo, the result of a collision will typically be atomic gas, even though the clouds are initially molecular. This suggests a possible connection with the ‘High Velocity Clouds’ (HVCs) (Wakker & van Woerden 1997) which are seen (almost exclusively) in 21-cm emission: some HVCs may simply be material from recent dark cloud collisions. This gas is expected to have such a low column density that it will be stopped by the diffuse interstellar medium, at the first encounter with the Galactic plane, thereby contributing to the assembly of the gaseous disc and, subsequently, the Milky Way.

As well as being relevant to the Tully–Fisher relation, the model we have presented is germane to the ‘Disc-Halo Conspiracy’ (Sancisi & van Albada 1987). The conspiracy is so-called because it seems puzzling that (giant) spiral galaxy rotation curves should be as flat as they are observed to be, given that the acceleration is predominantly because of stars at small galactocentric radii and dark matter at large radii. In the model we have presented, however, the conspiracy is no surprise; rather it is an innate feature, as dark matter is converted to visible forms by cloud–cloud collisions. With the model of Section 2 we cannot sensibly compute rotation curves – because we have neglected evolution of the gravitational potential – so these statements are necessarily qualitative. A useful quantitative treatment would require a self-consistent description of the evolution; more careful consideration of the initial conditions (dark matter density profile) would also be appropriate.

The principal difficulty with our model is that the fit shown in Fig. 1 requires \( \Sigma = 140 \, \text{g cm}^{-2} \) (for \( t = 10 \, \text{Gyr} \)), whereas Kormendy (1990) measures halo core radii that suggest a smaller cloud surface density, \( \Sigma \sim 40 \, \text{g cm}^{-2} \). Both of these values are higher than the original estimate (Walker & Wardle 1998a) based on scintillation data, and incompatible with each other. Kormendy...
Further constraints on the density distribution of the cold clouds are considered by Draine (1998), based on optical refraction by the neutral gas (‘gas lensing’). These constraints are compatible with $\Sigma = 140 \text{ g cm}^{-2}$ provided that the internal density profile of the clouds is not strongly centrally concentrated; convective polytropes, for example, are acceptable.

5 CONCLUSIONS

Modelling galaxy haloes as isothermal spheres composed of collisional, baryonic dark matter leads us to expect non-singular dark halo density distributions with a predictable visible mass content. Both of these expectations are borne out in the data, with the latter result very likely being the fundamental basis for the Tully–Fisher relation. Although simple, the theory is remarkably good at predicting (spiral) galaxy masses across the whole size spectrum from dwarfs to giants. The evident success of this description of galaxy evolution gives strong support to the notion that galaxy haloes are composed of a vast number of cold, dense, planetary-mass gas clouds.

ACKNOWLEDGMENTS

Thanks to Mark Wardle, Jeremy Mould, Bohdan Paczyński, Ken Freeman and James Binney for their helpful comments. The Special Research Centre for Theoretical Astrophysics is funded by the Australian Research Council under its Special Research Centres Program.

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