Modified Newtonian Dynamics in the Milky Way

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ABSTRACT
Both microlensing surveys and radio-frequency observations of gas flow imply that the inner Milky Way is completely dominated by baryons, contrary to the predictions of standard cold dark matter (CDM) cosmology. We investigate the predictions of the Modified Newtonian Dynamics (MOND) formula for the Galaxy given the measured baryon distribution. Satisfactory fits to the observationally determined terminal-velocity curve are obtained for different choices of the MOND’s interpolating function $\mu(x)$. However, with simple analytical forms of $\mu(x)$, the local circular speed $v_c(R_0)$ can be as large as 220 km s$^{-1}$ only for values of the parameter $a_0$ that are excluded by observations of NGC 3198. Only a numerically specified interpolating function can produce $v_c(R_0) = 220$ km s$^{-1}$, which is therefore an upper limit in MOND, while the asymptotic velocity is predicted to be $v_c(\infty) = 170 \pm 5$ km s$^{-1}$. The data are probably not consistent with the functional form of $\mu(x)$ that has been explored as a toy model in the framework of Bekenstein’s covariant theory of gravity.

Key words: gravitation – Galaxy: kinematics and dynamics

1 INTRODUCTION
Recent advances in the modelling of the Milky Way indicate that, contrary to the predictions of cold dark matter (CDM) cosmology (Diemand, Moore & Stadel 2004; and references therein), the inner Galaxy is completely dominated by baryons. We ask whether current Galaxy models are more compatible with the Modified Newtonian Dynamics (MOND).

The evidence for accelerating cosmic expansion can be interpreted either as signalling the presence of a large amount of dark energy (quintessence), or as an indication that Einstein’s minimal theory of gravity must be modified by adding a cosmological constant. Similarly, the evidence for flat galactic rotation curves is conventionally interpreted as evidence for massive halos of cold dark matter (CDM), but twenty years ago Milgrom (1983) suggested that these flat rotation curves might signal the need to modify Newtonian dynamics in regions where the acceleration is smaller than a critical value $a_0$. This proposal, dubbed MOND, was then refined by the introduction of a non-relativistic field equation for the modified gravitational potential $\mu(\rho)$. There is now a significant body of evidence that, for whatever reason, there is a characteristic acceleration $a_0 \approx cH_0$ associated with galaxies (Sanders & McGaugh 2002). Furthermore, MOND has a remarkable ability to account for features in the phenomenology of galaxies that were unknown when Milgrom introduced the theory.

Recent developments in the theory of gravity have added plausibility to the case for modification of gravity rather than addition of exotic matter. First, Bekenstein (2004) has presented a Lorentz-covariant theory of gravity that has a MONDian behaviour in the appropriate limit. Second, it has become recognized (e.g. Grinstein 2004) that spontaneous symmetry breaking in an effective field theory of gravity might well lead to loss of Lorentz invariance of the type required by Bekenstein. A great deal of work needs to be done to determine whether a theory such as that of Bekenstein is compatible with observations of the cosmic microwave background and large-scale structure (e.g. Skordis et al. 2005). But knowledge that it is possible to embed MOND within a physically acceptable dynamical framework, and that this framework is not unattractive from the point of view of mathematical physics, must make us take more seriously the phenomenological successes of MOND.

On the other hand, there is growing evidence that the dark halos of galaxies do not conform to CDM simulations: they are cuspy in neither low-surface-brightness (e.g. Bosma 2004) nor high-surface-brightness galaxies, the centers of which are completely baryon-dominated (Gerhard et al. 2001, Gentile et al. 2004, Cappellari et al. 2005). Moreover the shapes of the rotation curves are intimately connected to the underlying stellar-light profile, just as modified gravity predicts. In this paper, we study the particular case of our own Milky Way galaxy, which is the best example of a baryon-dominated high-surface-brightness galaxy.

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In Section 2 we review the evidence that the inner Galaxy is dominated by baryons. In Section 3 we investigate the predictions of MOND for the Galactic circular-speed curve and the vertical equilibrium of the Solar neighbourhood. Section 4 sums up.

2 THE BASEL MODEL OF THE MILKY WAY

Bissantz & Gerhard (2002) (hereafter BG) present a model of the luminosity density interior to the Sun. Like its predecessor (Binney, Gerhard & Spergel 1997), this model is based on the COBE L-band photometry, but it incorporates constraints from the slight difference in the mean apparent magnitude of red-clump stars on either side of the Galactic centre, and from tracers of spiral arms in the disk. Its bar is thinner than that in the model of Binney et al. (1997).

Bissantz, Englmaier & Gerhard (2003) (hereafter BEG) determine the pattern speeds of the bar and the spiral structure, and upgrade the BG model to a mass model by simulating the flow of gas in potentials obtained by assigning spatially constant mass-to-light ratios to the BG model. Maps of the density of CO and HI in the longitude-velocity plane [(l,v) plane] are derived and compared with the corresponding observational plots. BEG find that they can reproduce the observed (l,v) plots by assigning to the bar a pattern speed that agrees with an independent determination from the kinematics of the solar neighbourhood (Dehnen 2000), while assigning a significantly lower pattern speed to the spiral structure. The spiral structure is four-armed and its amplitude in the mass density is larger by a factor ~1.5 than its amplitude in the near-infrared luminosity density. This standard model explains the entire rotation curve inside a galactocentric radius of ~0.6R\(_0\) where R\(_0\) is the galactocentric radius of the Sun) without any dark matter. However, at the solar radius R\(_0\), the model yields a circular speed that is ~40\,km\,s\(^{-1}\) too low. To make up the balance, an axisymmetric quasi-isothermal dark halo with a large core radius (rc=1.34R\(_0\)) and a small central density is added, and the mass-to-light ratio of the luminous component is lowered by less than 10% compared to the standard model.

The mass model developed by BEG is strongly supported by the results of surveys for microlensing events in fields towards the Galactic centre. Once the mass-to-light ratio of the BG model has been determined, a map of the microlensing optical depth for clump stars can be produced without any further assumptions, and BEG present such a map. In units of 10^-6, the EROS collaboration reported an optical depth of \(\tau_0 = 0.94 \pm 0.3\) at (l,b) = (2.5\(^\circ\),-4\(^\circ\)) (Afonso et al 2003) while BG predicted \(\tau_0 = 1.2\) at this location. The MACHO collaboration reported \(\tau_0 = 2.17^{+0.47}_{-0.38}\) at (l,b) = (1.5\(^\circ\),-2.68\(^\circ\)) (Popowski et al 2002), while BG predicted \(\tau_0 = 2.4\) here. Any transfer of matter from the stellar component to the dark halo would impair this excellent agreement. Still further evidence of the correctness of the Basel model has been provided by an N-body model that self-consistently generates the mass density inferred by BEG (Bissantz, Debattista & Gerhard 2004). This model, which has no free parameters, successfully predicts the proper motions of stars in various bulge fields. When a very plausible model of the mass function of bulge and disk stars is adopted, it also reproduces the distribution determined by the MACHO collaboration of the duration of individual microlensing events. Thus the Basel mass model, and its negligible contribution from CDM to the inner Galaxy, has been very thoroughly validated.

The Basel group is now producing an upgraded version of the Basel model (Englmaier, private communication) and the calculations that follow are based on this new version. The model without dark matter (short-dashed curve of Fig. 4) is 12% heavier than the luminous part of the model with a dark halo (dotted curve of Fig. 4). In the latter, the quasi-isothermal dark halo has a core radius rc = 10.7 kpc and an asymptotic velocity \(v_\infty = 235\,\text{km\,s}^{-1}\). It is assumed that \(R_0 = 8\) kpc and that \(v_\infty(R_0) = 220\,\text{km\,s}^{-1}\). The model with dark matter does not match the bumps in the rotation curve as quite as well as the standard model without dark matter does.

3 THE MILKY WAY IN MOND

The halo introduced by BEG is not cuspy like the halos predicted by CDM cosmology (Diemand et al. 2004, and references therein). A cuspy halo could not have been added: indeed, what drives BEG to assign to baryons essentially all matter within the corotation radius of the bar, and to enhance the amplitude of the spiral structure outside the bar, is the size of the non-circular velocities that are apparent in the observed (l,v) plots: the dark halo is assumed to be axisymmetric, so if much mass is shifted from the baryons to the halo, the non-axisymmetric component of the overall potential is weakened, and the non-circular velocities are predicted to be too small. Given that the structure of the BEG halo is unexpected in the CDM theory, we now ask whether it can be eliminated by assuming that MOND is the correct theory of gravity. A full answer to this question requires extensive numerical work to solve the non-linear field equation (Bekenstein & Milgrom 1984) for the modified potential generated by the Galaxy, including contributions from the bar and spiral structure. However, the non-axisymmetry is important only at \(R \lesssim \frac{1}{2}R_0\), where the effects of MOND are small, which guarantees that the problem arising in the dark matter framework will not arise in MOND. Therefore, as in standard Newtonian theory, the first step is to study the circular-speed curve that follows from the axisymmetric component of the density distribution.

3.1 The rotation curve

In cylindrical or spherical symmetry the gravitational force per unit mass \(K_{MOND}\) predicted by MOND in the Galactic plane is related to the corresponding Newtonian force per unit mass \(K_{Newton}\) as in Milgrom’s formula (Milgrom 1983):

\[
\mu(K_{MOND}/a_0)K_{MOND} = K_{Newton}.
\]

where the interpolating function \(\mu\) runs smoothly from \(\mu(x) = x\) at \(x \ll 1\) to \(\mu(x) = 1\) at \(x \gg 1\). In a flat axisymmetric disk, Milgrom’s formula is only exact if MOND is viewed as a modification of inertia (Milgrom 1994) rather than a modification of gravity. However, using the field equation for the modified gravitational potential (Brada & Milgrom 1994) have shown that
is thus worthwhile to test the ability of this formula to fit the rotation curves of an impressive list of external galaxies (Sanders & McGaugh 2002). It is thus worthwhile to test the ability of this formula to fit the rotation curve of the Milky Way.

Once the values of $a_0$ and of the mass-to-light ratio $\Upsilon$ are known, equation (1) predicts the force field for each choice of interpolating function. From a sample of external galaxies with high quality rotation curves (Begeman et al. 1991) derived $a_0 = 1.2 \pm 0.27 \times 10^{-8} \text{ cm s}^{-2}$ and either standard (short-dashed) or simple (full) interpolating functions.

Table 1. For the Basel model with and without dark matter, and our 4 MONDian models, the columns display respectively the form of the interpolating function $\mu$, the value of $a_0$ in units of $10^{-8} \text{ cm s}^{-2}$, the value of the $L$-band mass-to-light ratio $\Upsilon_L$ in $M_\odot/L_\odot$ ($\Upsilon_L = \xi^2$, where $\xi$ is the scaling constant for the rotation curve in BEG), the circular speed at the solar radius $R_0$ and at infinity in $\text{ km s}^{-1}$, and finally the value $\mu(x_0)$ where $x_0 = v_c^2(R_0)/(R_0 a_0)$.

| $\mu(x)$ | $a_0$ | $\Upsilon_L$ | $v_c(R_0)$ | $v_{\infty}$ | $\mu(x_0)$ |
|-----------|-------|-------------|-------------|-------------|-------------|
| DM        | 1     | 0           | 1.08        | 220         | 0           | 1           |
| no-DM     | 1     | 0           | 1.21        | 180         | 0           | 1           |
| I         | $x/\sqrt{1 + x^2}$ | 1.2 | 1.21  | 200 | 175 | 0.8 |
| II        | $x/\sqrt{1 + x^2}$ | 3.4 | 0.91  | 220 | 210 | 0.4 |
| III       | $x/(1 + x)$ | 1.2 | 0.95  | 208 | 165 | 0.6 |
| IV        | fit   | 1.2         | 1.98        | 220         | 170         | 0.6         |

The short-dashed curve in Fig. 2 shows that when we self-consistently adopt $v_c(R_0) = 200 \text{ km s}^{-1}$ in the Basel model with dark matter, and using the standard interpolating function yields the long-dashed circular-speed curve shown in Fig. 2 (Model I). The circular speed is then $707 \pm 1 \text{ km s}^{-1}$ at $R = 1 / R_0$, exactly as in the Basel model with dark halo, and $200 \text{ km s}^{-1}$ at $R_0$. Thus making gravity MONDian with the standard interpolating function reduces the deficit in $v_c(R_0)$ from $40 \text{ km s}^{-1}$ to $20 \text{ km s}^{-1}$, but does not eliminate it.

However, the value of $v_c(R_0)$ is hard to determine and a lower value than $220 \text{ km s}^{-1}$ is not excluded (e.g. Olling & Merrifield 1998). The primary observable is the terminal velocity $v_t(l)$ at each longitude $l$:

$$v_t(l) = \text{sign}(l) v_c(R_0 \sin l) - v_c(R_0) \sin l.$$  (2)

From $v_t(l)$ it is easy to determine $v_c(R)$ if one knows $R_0$ and $v_c(R_0)$, but neither parameter is known with precision. Given this uncertainty, it is important to understand the predictions of each model for the run of $v_t(l)$ (see Fig. 2). When $v_c(R_0) = 200 \text{ km s}^{-1}$ is assumed, as it was by the Basel group, the baryonic Basel model yields an excellent fit to the data at $|l| \leq 40^\circ$, but the curve is not self-consistent because it does not pass through zero at $|l| = 90^\circ$. The short-dashed curve in Fig. 2 shows that when we self-consistently adopt $v_c(R_0) = 180 \text{ km s}^{-1}$ (see Table 1), in the fourth quadrant the terminal velocities near $l = -20^\circ$ become marginally too negative and from there rise too steeply as $l \to -90^\circ$. However, this self-consistent baryonic Newtonian model is clearly incompatible with the measured terminal velocities.

Our MONDian Model I (long-dashed curve in Fig. 2) reduces the discrepancy with the terminal velocity data, but still fits the data less well than the Basel model with dark matter (dotted curve in Fig. 2) because $v_c(R_0) = 200 \text{ km s}^{-1}$ is low. If we enforce $v_c(R_0) = 220 \text{ km s}^{-1}$ simply by increasing $\Upsilon$, we make $v_t$ too large at $R \approx 1 / R_0$. A better fit can be obtained by adjusting both $a_0$ and $\Upsilon$. To increase $v_c(R_0)$ we increase $a_0$ and thus trigger a MONDian correction at
smaller radii. This in turn obliges us to decrease $\Upsilon$ in order to keep a velocity of 207 km s$^{-1}$ at $R = \frac{1}{4}R_0$, exactly as in the Basel model with dark matter. This decrease in $\Upsilon$ requires a further increase in $a_0$ to retain $v_c(R_0) = 220$ km s$^{-1}$, with the result that by the time we have achieved a satisfactory fit to the rotation curve at $R = \frac{1}{4}R_0$ and $R = R_0$, $a_0$ has increased significantly. The dot-dashed curves in Figs. 1 and 2 show the fits obtained when $a_0 = 3.4 \times 10^{-8}$ cm s$^{-2}$ and $\Upsilon_L = 0.91 M_\odot/L_\odot$ (Model II). This model predicts an asymptotic circular speed of 210 km s$^{-1}$ that is higher than those predicted by the conventional value of $a_0$ (see Table 1).

The asymptotic circular speed of the Galaxy is not well determined (Binney & Dehnen 1997; Wilkinson & Evans 1999). By contrast, in external galaxies with extended HI, the behaviour of $v_c$ at large $R$ is strongly constrained by observations. Extended rotation curves have been obtained for many galaxies with the aim of probing dark halos (e.g. Begeman et al. 1991; Broeils & van Woerden 1994; Gentile et al. 2004). To be specific, we focus here on the case of NGC 3198, which was carefully studied by Begeman et al. (1991); this system is the textbook example of a galaxy with an extended flat rotation curve because it has a large apparent diameter and a velocity field that shows the gas to be confined to a plane and following accurately circular orbits. Fig. 3 shows that when one fits the rotation curve of NGC 3198 with $a_0 = 3.4 \times 10^{-8}$ cm s$^{-2}$, the decrease in $\Upsilon$ that is required to match the measured asymptotic velocity results in $v_c$ being too low at small radii.

Consequently, the data for NGC 3198 rule out the large value of $a_0$ required by Model II. In principle we can make Model II compatible with the standard value of $a_0 = 1.2 \times 10^{-8}$ cm s$^{-2}$ by rescaling it: the rotation curves of the models listed in Table 1 are invariant if we change the value of $R_0$ from 8 kpc and then multiply $\Upsilon$ by $R_0/(8 \text{kpc})$ and $a_0$ by $(8 \text{kpc})/R_0$. However, to obtain $a_0 = 1.2 \times 10^{-8}$ cm s$^{-2}$ by rescaling $R_0$, we would have to set $R_0 \simeq 15$ kpc, which is excluded by a wealth of data on the scale size of the Milky Way.

From this we conclude that, with the standard interpolating function, MOND cannot fit with perfect accuracy the rotation curves of both the Basel model and NGC 3198. This conclusion is consistent with the work of Gentile et al. (2004), who concluded that by varying only $\Upsilon$ it is not possible to obtain entirely satisfactory fits to the rotation curves of five spiral galaxies.

We therefore consider an alternative ‘simple’ interpolating function, namely

$$\mu(x) = \frac{x}{1 + x}. \quad (3)$$

This function provides a less sudden transition from the Newtonian to the MONDian regime than does the standard function. The continuous curve in Fig. 3 shows that the simple interpolating function together with the conventional value $a_0 = 1.2 \times 10^{-8}$ cm s$^{-2}$ yield a extremely good fit to the rotation curve of NGC 3198.

The full curves in Figs. 1 and 2 show the corresponding fits to the Basel model (Model III). We now have $v_c(R_0) = 208$ km s$^{-1}$. Although this value lies very close to the conventional value, we find it is impossible to push $v_c(R_0)$ up to 220 km s$^{-1}$ by increasing $a_0$, because we then have to decrease the mass-to-light ratio radically in order to fit the inner rotation curve $[v_c(0.5 R_0) = 207$ km s$^{-1}]$, making $v_c(R_0)$ too low again. The transition from Newtonian to MONDian physics provided by the simple interpolating function is insufficiently abrupt. Slightly changing the value of $R_0$ does not eliminate the problem. However, Fig. 2 shows that the fit of Model III to the terminal-velocity curve is extremely satisfactory. This simple interpolating function thus fits the data for both NGC 3198 and the Milky Way. However, it does not exactly reproduce the run of $v_c(R)$ of the Basel model; to achieve this, one needs a more complex form of the interpolating function.

3.2 The interpolating function

In low-surface-brightness (LSB) galaxies, $x < 1$ at all radii, with the consequence that the measured acceleration $v_c^2/R$ is approximately equal to $[a_0 YGL(R)/R^2]^{1/2}$. It follows that these galaxies constrain only the product $a_0 \Upsilon$ and leave the interpolating function unconstrained. In high-surface-brightness (HSB) galaxies such as NGC 3198, $x$ ranges from values greater than unity down to small values. Hence with these objects we can break the degeneracy between $a_0$ and $\Upsilon$, but, as Fig. 4 illustrates, the large gradients in rotation curves at small radii, combined with the poor spatial resolution of observations in the 21-cm line, leave considerable degeneracy between $a_0$ and $\Upsilon$, and constrain the interpolating function only weakly. The Basel model is strongly constrained at small radii, and it is pertinent to probe the extent to which it constrains the interpolating function in equation (1).

Imagine an ideal galaxy in which both the asymptoti-
cally flat rotation curve and the luminosity distribution are known with precision. Then with $x = \frac{v_c^2}{(R_0 a_0)}$ we can write

$$\mu(x) = \frac{f(a_0 x)}{a_0 x}, \quad (4)$$

where $f(v_c^2/R)$ is obtained from the Newtonian equation for the force per unit mass with the mass-density $\rho(x)$ replaced by the luminosity-density $j(x)$. From data at large $x$ (corresponding to the central parts of the galaxy), where $\mu(x) \approx 1$ and $f(y) \propto y$, we can read off $\mu$. At large radii (small $x$) we have $\mu(x) \propto x$ and $f(y) \propto y^2$, so we can determine $a_0$. Once $\mu$ and $a_0$ are known, we can completely determine $\mu(x)$ from equation (4).

As an example, we treat the circular-speed curve of the Basel model plus dark halo as a perfect set of data. From the centre we find $\Upsilon_L = 1.08 \, M_\odot/L_\odot$, while the asymptotic velocity $v_\infty = 235 \, \text{km s}^{-1}$ implies $a_0 = 4.47 \times 10^{-8} \, \text{cm s}^{-2}$. This large value of $a_0$ suggests that the model’s asymptotic velocity is too high. If one could show that the Milky Way’s asymptotic circular speed really is this high, MOND would have been falsified.

However, if we combine $\Upsilon_L = 1.08 \, M_\odot/L_\odot$ with the conventional value $a_0 = 1.2 \times 10^{-8} \, \text{cm s}^{-2}$, we infer an asymptotic velocity $170 \, \text{km s}^{-1}$, and can read off the form of the interpolating function that perfectly fits the Basel model at $R \leq R_0$ (Model IV). The dotted curve in Fig. 4 shows this function, which transitions smoothly from $x/(1 + x)$ at $x \leq 1$ to $x/\sqrt{1 + x^2}$ at $x \geq 10$.

Any successful underlying theory for MOND must predict an interpolating function that lies between the curves labelled I and III in Fig. 4. Bekenstein (2004) introduced the TeVeS theory of gravitation, in which the physical metric depends on both the Newtonian acceleration and the gradient of the scalar field. For accelerations that are not large compared to $a_0$, the MONDian and Newtonian accelerations are then related by Eq. (1) with the interpolating function

$$\mu(x) = \frac{\sqrt{1 + 4x} - 1}{\sqrt{1 + 4x} + 1}, \quad (5)$$

which is shown as the dashed curve in Fig. 4. Since this curve lies far below the dotted curve at all values of $x$, the correction to Newtonian gravity to which this function gives rise is much too big to be compatible with the dynamics of the Milky Way (see Table 1). Of course, since the Galaxy is not spherical, the interpolating function (5) does not apply to it, and even the concept of an interpolating function cannot be used for the Galaxy in TeVeS. However, it is not obvious that when non-spherical geometry is taken into account, Bekenstein’s toy $F$ will yield a sufficiently rapid transition from the MONDian to the Newtonian regime. Hence, groups that are endeavouring to determine the implications of TeVeS for large-scale structure should be cautious about conclusions obtained using Bekenstein’s toy $F$, and especially not disregard this gravitational theory if predictions happen to disagree with observations when using this particular $F$.

3.3 The vertical equilibrium

We now examine the consistency of MOND with the vertical dynamics of the solar neighbourhood. This is in principle a complex problem, because out of the plane it is not a priori clear that the Newtonian and modified-gravity accelerations will be parallel, as Milgrom’s formula (1) implies. However, equation (1) is known to hold outside Kuzmin and exponential disks, as well as in cylindrical symmetry, so it may be expected to provide a good first approximation in the Milky Way.

At $R_0$ (assumed here to be 8 kpc), the surface density of baryons is $\Sigma_0 = 53 \, M_\odot \, \text{pc}^{-2}$ [Holmberg & Flynn 2004]. An infinite sheet with this surface density generates a Newtonian vertical acceleration $K_{z, \text{Newton}} \approx \pi G \Sigma_0 \approx 0.25 a_0$, for $a_0 = 1.2 \times 10^{-8} \, \text{cm s}^{-2}$. The radial acceleration is $v_c^2/R_0 \approx 6.5 \times K_{z, \text{Newton}}$, which implies that the modification of the vertical force is dominated by the external field effect. Thus $K_{z, \text{MOND}} \approx K_{z, \text{Newton}}/\mu(v_c^2/R_0 a_0)$. Observations show that 1.1 kpc above the plane, the vertical force is larger than that arising from the baryons in Newtonian theory by a factor $\approx 7/5$ [Kuijken & Gilmore 1991; Holmberg & Flynn 2004]. It follows that MOND requires that

$$\mu(v_c^2/R_0 a_0) \approx 5/7 \approx 0.71. \quad (6)$$

The extreme right column of Table 1 shows that, given the significant uncertainties, this constraint is satisfied by the standard, simple and fitted interpolating functions when $a_0 = 1.2 \times 10^{-8} \, \text{cm s}^{-2}$. The choice $a_0 = 3.4 \times 10^{-8} \, \text{cm s}^{-2}$ used in Model II places the solar neighbourhood so deeply into the MOND regime that the predicted large correction to the vertical force is excluded by the observations.
4 DISCUSSION

By combining near-infrared photometry and simulations of gas flow in the plane, and without invoking dark matter in the inner 5 kpc, the Basel group has developed an extremely successful model of the Milky Way that accounts for the structure of \((l,v)\) plots for CO and HI, for the proper motions of bulge stars, for the microlensing optical depth towards bulge fields, and for the observed distribution of the durations of microlensing events. Given the number of these checks, there can be little doubt that we now really do know the distribution of baryons inside the solar radius. For no other galaxy do we have information of comparable quality.

It is far from clear that the Basel model is compatible with the predictions of CDM. In the light of early indications that baryons dominate the inner Galaxy, an attempt was made to build models that minimize the dark halo consistent with constraints from simulations of clustering CDM (Klypin, Zhao & Somerville 2002). In all these models, however, CDM contributes significantly to the density at \(\sim 3\) kpc from the Galactic centre where the Basel model requires the density to be almost entirely invested in stars. To investigate this matter further, we need a CDM-inspired model that includes a stellar bar and reproduces the photometry of the Galaxy. It would be of great interest to calculate the predictions of such a model for microlensing surveys and the \((l,v)\) diagrams of CO and HI. If those predictions disagree with observations, the CDM paradigm would be strongly weakened. Gentile et al. (2004) have shown that the paradigm encounters similar difficulties reproducing the rotation curves of a sample of five external galaxies.

In MOND, there are two free parameters \((\Upsilon, a_0)\), the latter a constant of nature and one free function \((\mu)\), to be fixed by an underlying theory of MOND). Once those quantities are known, the gravitational force field is completely determined by the baryon density. We have investigated what circular-speed curves MOND predicts from completely determined by the baryon distribution. A full list of galaxies for which Milgrom’s formula (1) is successful in predicting the rotation curve from the baryon distribution. The next step towards exploring the agreement between the data and the predictions MONDian gravity makes from the Basel model involves using a potential solver (e.g. Brada & Milgrom 1999) for the nonlinear Bekenstein–Milgrom equation to determine the MOND force generated by the non-axisymmetric components of the Basel model with the parameters and interpolating functions of our Models I, III and IV. Another test for the relevance of MOND as an alternative to dark matter in the Milky Way will be provided by the measurement of the velocity dispersions in distant globular clusters orbiting the Galaxy in the outer halo, well into the deep-MOND regime (Baumgardt, Grebel & Kroupa 2005).

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