MOND in the Early Universe

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Abstract. I explore some consequences of Milgrom’s modified dynamics for cosmology. There appear to be two promising tests for distinguishing MOND from CDM: (1) the rate of growth of structure and (2) the baryon fraction. These should be testable with observations of clusters at high redshift and the microwave background, respectively.

STANDARD COSMOLOGY

The standard hot big bang cosmology has many successes; too many to list here. The amount of data constraining cosmic parameters has increased rapidly, until only a small region of parameter space remains viable. This has led to talk of a ‘concordant’ cosmology with $\Omega_M \approx 0.3$ and $\Omega_\Lambda \approx 0.7$ [1].

This is a rather strange place to end up. The data do not favor these parameters so much as they disfavor other combinations more. A skeptic might suspect that concordance is merely the corner we’ve painted ourselves into prior to the final brush stroke.

This is not an idle concern, as there remains one major outstanding problem: dark matter. Something like 90% of the universe is supposedly made of stuff we can not see. There are, to my mind, two ironclad lines of reasoning that require the dark matter to be nonbaryonic, cold dark matter (CDM) like WIMPs or axions.

1. $\Omega_M \gg \Omega_b$.

2. Structure does not have time to grow from a smooth microwave background to the rich structure observed today without a mass component whose perturbations can grow early without leaving an imprint on the CMBR.

BUT we have yet to detect WIMPs or axions. Their existence remains an unproven, if well motivated, assumption.

IS THERE ANY DARK MATTER?

It is often stated that the evidence for dark matter is overwhelming. This is not quite correct: the evidence for mass discrepancies is overwhelming. These might be attributed to either dark matter or a modification of gravity.
Rotation curves played a key role in establishing the mass discrepancy problem, and remain the best illustration thereof. There are many fine-tuning problems in using dark matter to explain these data. I had hoped that the resolution of these problems would become clear with the acquisition of new data for low surface brightness galaxies. Instead, the problems have become much worse [2].

These recent data are a particular problem for CDM models, which simply do not fit [3]. Tweaking the cosmic parameters can reduce but not eliminate the problems. No model in the concordant range can fit the data unless one invokes some deus ex machina to make it so.

There is one theory which not only fits the recent observations, but predicted them [4]. This is the modified dynamics (MOND) hypothesized by Milgrom [5]. The basic idea here is that instead of dark matter, the force law is modified on a small acceleration scale, $a_0 \approx \frac{1}{2} A \, \text{s}^{-2}$. For $a \gg a_0$ everything is normal, but for $a \ll a_0$ the effective force law is $a = \sqrt{a_N a_0}$, where $a_N$ is the usual Newtonian acceleration.

This hypothesis might seem radical, but it has enormous success in rectifying the mass discrepancy. It works exquisitely well in rotating disks where there are few assumptions [6–9]. MOND also seems to work in other places, like dwarf Spheroidals [4,10–12], galaxy groups [13], and filaments [14]. The only place in which it does not appear to completely remedy the mass discrepancy is in the cores of rich clusters of galaxies [15], a very limited missing mass problem.

It is a real possibility is that MOND is correct, and CDM does not exist. Let us examine the cosmological consequences of this.

**SIMPLE MOND COSMOLOGY**

There exists no complete, relativistic theory encompassing MOND, so a strictly proper cosmology can not be derived. However, it is possible to obtain a number of heuristic results in the spirit of MOND. The simplest approach is to assume that $a_0$ does not vary with cosmic time. This need not be the case [16,17], but makes a good starting point. I do not have space to derive anything here, and refer the reader to detailed published work [16–18].

Making this simple assumption, the first thing we encounter is that it is not trivial to derive the expansion history of the universe in MOND [18,19]. This might seem unappealing, but does have advantages. For example, a simple MOND universe will eventually recollapse irrespective of the value of $\Omega_M$. There is no special value of $\Omega_M$, so no flatness problem.

Conventional estimates of $\Omega_M$ are overly large in MOND. Instead of $0.2 < \Omega_M < 0.4$, MOND gives $0.01 < \Omega_M < 0.04$. So a MOND universe is very low density, consistent with being composed purely of baryons in the amount required by big bang nucleosynthesis.

This makes some sense. Accelerations in the early universe are too high for MOND to matter. This persists through nucleosynthesis and recombination, so
everything is normal then and all the usual results are retained. MOND does not appear to contradict any empirically established cosmological constraint.

The universe as a whole transitions into the MOND regime \((cH_0 \sim a_0)\) around \(z \sim 3\), depending on \(\Omega_M\). Sub-horizon scale bubbles could begin to make this phase transition earlier, providing seeds for the growth of structure and setting the mass scale for galaxies [18]. Nothing can happen until the radiation releases its grip on the baryons \((z \sim 200)\), by which time the typical acceleration is quite small. As a result, things subsequently behave as if there were a lot of dark matter: perturbations grow fast. This provides a mechanism by which structure grows from a smooth state to a very clumpy one rapidly, without CDM.

Now recall the two ironclad reasons why we must have CDM. In the case of MOND

1. \(\Omega_M = \Omega_b \approx 0.02\)

2. There is no problem growing structure rapidly from a smooth CMBR to the rich amount seen at \(z = 0\) with baryons alone.

**PREDICTIONS**

The simple MOND scenario makes two predictions which distinguish it from standard CDM models.

1. Structure grows rapidly and to large scales.

2. The universe is made of baryons.

There are indications that at least some galaxies form early, and are already clustered at \(z \approx 3\) [20]. At low redshifts, we are continually surprised by the size of the largest cosmic structures. It makes no sense in the conventional context that fractal analyses should work as well as they do [21]. A MOND universe need not be precisely fractal, but if analyzed in this way it naturally produces the observed dimensionality [18]. So there are already a number of hints of MOND-induced behavior in cosmic data.

A strong test may occur for rich clusters. These are rare at \(z > 1\) in any CDM cosmology [22]. In the simple MOND universe, clusters form at \(z \approx 3\) [18]. Upcoming X-ray missions should be able to detect these [23].

The rapid growth of perturbations in MOND overcomes the usual objections to purely baryonic cosmologies. The baryon fraction makes a tremendous difference to the bumps and wiggles in the CMBR power spectrum (Figure 1) [24]. CDM smooths out the acoustic oscillations due to baryons in a way which can not happen if \(f_b = 1\).

This should leave some distinctive feature in the CMBR that can be measured by upcoming missions like MAP [25]. Unfortunately, it is easy only to predict the spectrum as it emerges shortly after recombination. Since the growth of structure is rapid and nonlinear in MOND, there might be a strong integrated Sachs-Wolfe
effect. I would expect this to erase any hint of the oscillations in the $z = 0$ galaxy distribution, but not necessarily in the CMBR. The initial spectrum in the CMBR is sufficiently different in the CDM and MOND cases that there is a good prospect of distinguishing between the two.

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