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AN INTRODUCTION TO COSMOLOGICAL DARK MATTER

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ABSTRACT

Although presented as a Summary Talk at the International School on Cosmological Dark Matter, this highly selective overview would, perhaps, have been of more value to the students had it been scheduled as an Introductory Talk. It is in this spirit that I outline, very briefly, the – several – cosmological dark matter problems and their proposed solutions. My approach is tied firmly to the many fine lectures presented at this very timely School. However, my motivation is to provide the novice in the field of cosmological dark matter with the context in which to better appreciate and comprehend the subsequent articles in this volume. It should be noted that virtually every topic covered in this Introduction is discussed in detail in one or more of the articles in this volume. I have therefore included no references in this Introduction.

AN INTRODUCTION TO COSMOLOGICAL DARK MATTER

1. The Dark Matter Problems

At the very outset it is important to appreciate that there are several – indeed, a continuum of – dark matter problems. Roughly speaking, as the length/mass scale increases from that of individual galaxies, to small collections of galaxies (binaries and small groups), to larger aggregates (clusters of galaxies), and beyond (voids, walls, large scale flows, etc.), the amount of mass inferred from the dynamics (effectively, from Newton's laws of mechanics) increases while the luminosity does not. Thus, on larger and larger scales there is more mass but not more "light". Hence, the dark matter (or, missing light) problems.

Much of what we know about the Universe has been learned by studying the sky in the visible part of the electromagnetic spectrum. There is, of course, NO a priori reason that the Universe should have chosen to reveal itself that way. And, indeed, as the infrared (IR), X- and γ-ray parts of the spectrum have come to be explored, a new richness in the Universe has been revealed. This expansion of the explored part of the electromagnetic spectrum has, unfortunately, introduced a confusing semantic aspect to the dark matter issue. Is matter revealed in the IR (e.g., dust) or X-ray (e.g., hot gas) part of the spectrum, "dark"? Different authors don't always agree and this gives rise to the potential for confusion – especially for the uninitiated. Keep this in mind when reading the articles in this volume – and, in the literature generally.

As will be seen in this volume, there are a variety of approaches to measuring the mass on different scales. Now, one way (not very useful) to determine the average mass density in the Universe ($<\rho>$) would be to sample a very large, "representative" volume V and to add up – in that volume – the total masses of different systems (i.e., field galaxies, small groups, rich clusters, etc.).

$$<\rho>=\frac{1}{V}\sum_i M_i. \tag{1}$$

This approach is not very practical. It is, instead, easier to add up all the light coming from each system (L_i is the luminosity (e.g., erg/sec) contributed by system i). Thus, if each system has a typical/average "mass-to-light" ratio $(M/L)_i$,

$$<\rho>=\frac{1}{V}\sum_i(\frac{M}{L})_i L_i. \tag{2}$$

Doing the sum in (2) is not much more practical than that in (1). However, *if* there is one system – perhaps the largest (e.g., rich clusters of galaxies) – which is "typical" of the Universe as a whole, so that $(M/L)_i =< M/L >$, then (2) reduces to,

$$< \rho >=< \frac{M}{L} > \frac{1}{V}\sum_i L_i =< M/L > \mathcal{L}. \tag{3}$$

In (3), $\mathcal{L}$ is the average luminosity density of the Universe which may be inferred from observations independently of mass determinations.

Now, the expansion of the Universe provides a "critical" value of the average density, ρ_C. For $\rho > \rho_C$, the gravitational attraction of the matter in the Universe is sufficient to slow down and stop the current expansion; such a Universe is "closed" and the present expansion will be succeeded by collapse to the *Big Crunch*. For $\rho \leq \rho_C$, the expansion rate is sufficiently large that gravity will not halt it – the Universe will continue expanding, becoming more and more dilute. This critical density depends on the expansion rate (as measured by the current value of the Hubble parameter H_0) and the strength of gravity (as set by Newton's Gravitational Constant G).

$$\rho_C = \frac{3H_0^2}{8\pi G} \approx 10h_0^2\ keVcm^{-3}, \tag{4}$$

where $H_0 = 100h_0 kms^{-1}Mpc^{-1}$. Note that a measure of the age of the Universe is given by $H_0^{-1} = 9.8\ h_0^{-1}Gyr$; it is likely that $0.4 < h_0 < 1$.

ρ_C is the "standard" by which other densities are measured,

$$\Omega \equiv \frac{\rho}{\rho_C} = \frac{8\pi G\rho}{3H_0^2}, \tag{5a}$$

$$\Omega h_0^2 \approx \frac{\rho}{10^4 eVcm^{-3}}. \tag{5b}$$

Ω provides a means for quantifying the – several – dark matter problems.

On larger and larger mass/length scales, more and more mass is inferred without a concommittant increase in the observed light; $(M/L)_i$ increases with scale. For example, if the mass-to-light ratio associated with the optically visible parts of galaxies is presumed to be "typical" of the matter in the Universe $\big((M/L)_{GAL} = < M/L >\big)$, then $\Omega_{GAL} \approx 0.006$. However, on the scale of binary galaxies and of small groups of galaxies, the mass-to-light ratio has increased. Thus, if $(M/L)_{BIN} = \, < M/L >$, $\Omega_{BIN} \approx 0.01 - 0.06$. On the scale of binaries and small groups there is a dark matter problem *relative to visible galaxies* (i.e., $(M/L)_{BIN} \approx 2 - 10(M/L)_{GAL}$). This trend continues up to the scale of rich clusters of galaxies where $\Omega_{CL} \approx 0.1 - 0.3$ (so that $(M/L)_{CL}/(M/L)_{GAL} \approx 20 - 50$). Remember, though, for any of these Ω_i to be equal to the Universal value Ω, the matter must be "typical" $\big((M/L)_i = \, < M/L >\big)$. If there is a background of matter which is smoothly distributed on even the largest scales thus far probed (e.g., "hot dark matter" (HDM) or a cosmological constant), then $\Omega > \Omega_i$. Large scale flows (LSF) – the velocity distribution of galaxies on very large scales – provide, at present, the probes of the largest scales: $\Omega_{LSF} \approx 0.3 - 1$. Although this latter work is beset by possible systematic effects and biases, it provides the first quantitative evidence that the Universe may be at the critical density ($\Omega = 1$). If so, then the luminous matter in the Universe provides less than 1% of all the matter in the Universe ($\Omega_{LUM} \approx \Omega_{GAL} \lesssim 0.01$).

2. Baryonic Dark Matter?

Big Bang Nucleosynthesis (BBN) calculations predict the primordial abundances of the light nuclides D, ^{3}He, ^{4}He and ^{7}Li. The predictions depend on the nucleon (baryon) abundance and, consistency with observations is found for,

$$\Omega_{BBN} h_{50}^2 \approx 0.05 \pm 0.01, \tag{6}$$

where $h_{50} \equiv H_0/50 = 2h_0$. For $H_0 < 100 kms^{-1} Mpc^{-1}$, $\Omega_{BBN} \gtrsim 0.01$, suggesting that some – perhaps most – baryons in the Universe are *dark* ($\Omega_{BBN} > \Omega_{LUM}$). Another dark matter problem (but, why should most baryons shine?).

If, indeed, most baryons are dark, where are they? One place is rich clusters of galaxies. As the reader will discover elsewhere in this volume, many/most rich clusters of galaxies are embedded in a hot gas (of nucleons and electrons). This gas is optically dark but, visible to x-ray detectors. If the mass of the hot gas is compared to that in the (luminous) galaxies in the cluster, $M_{HG}/M_{LUM} \approx 5 - 10$. At least in the environment of x-ray clusters, roughly 90% of the baryons are "dark". This suggests that – if this material were "typical" – $\Omega_{HG} \approx 0.03 - 0.1$. This is consistent with Ω_{BBN} but, would require that $\Omega_{CL} \ll \Omega$ if $\Omega = 1$.

In the very different environment of field galaxies, as well as those in binaries and small groups, the dark baryons may be hiding in the halos of galaxies. Indeed, the highlight of this School has been the presentation of the data from the MACHO and EROS collaborations in support of gravitational microlensing in the halo of our Galaxy. If, indeed, dark halo baryons are being revealed then, if a fraction of the halo mass f_B is due to such "Machos" made of baryons and, if the typical lens is a distance R from the center of the Galaxy,

$$\Omega_B \approx 0.02 f_B (R/20kpc). \tag{7}$$

Note that even for $f_B = 1$ and $10 \lesssim R \lesssim 60kpc$, $\Omega_B \approx \Omega_{BIN}$ so that halos on the scale of binaries and small groups may be purely baryonic (which is also consistent with Ω_{BBN}).

3. Non-Baryonic Dark Matter?

Even with generous bounds on the Hubble parameter ($40 \leq H_0 \leq 100kms^{-1}Mpc^{-1}$) BBN limits the baryon density of the Universe significantly: $\Omega_{BBN} \lesssim 0.1$. If, as the data on clusters and large scale flows suggests, $\Omega \gtrsim 0.1 - 0.3$, most of the mass in the Universe must be non-baryonic. What is it?

The formation of structure in the Universe depends on the "kind" of matter which dominates the universal mass density. Considerations of structure formation have led to a convenient classification scheme for non-baryonic dark matter candidates. "Hot dark matter" (HDM) candidates are moving rapidly (or relativstically) when structure begins to form. If HDM dominates Ω then the free-streaming of such particles tends to damp perturbations on small scales and to delay structure formation. HDM generally has difficulty clustering on small scales in shallow potential wells and thus might provide a smooth background on such scales.

In contrast, "cold dark matter" (CDM) candidates are moving slowly – if at all – at the epoch of structure formation. CDM can cluster on all scales. But, since $\Omega_{GAL} < \Omega_{BIN} < \Omega_{CL} < \Omega_{LSF} \lesssim 1$, if Ω is dominated by CDM, then "bias" is required (i.e., what you see is not what you get or, light does not trace mass). That is, luminous objects must have formed preferentially in regions of high total mass density.

Until recently, the two simplest models have received the most attention. In the HDM model, $\Omega = \Omega_{BBN} + \Omega_{HDM} = 1$. This model produces too much large scale power (i.e., structure) and structure formation occurs too recently. In the CDM model, $\Omega = \Omega_{BBN} + \Omega_{CDM} = 1$. This model has the virtue of an additional adjustable parameter – the bias factor. Nonetheless, here too structure formation is relatively late and, although it appears to work well on small scales ($\lesssim$ few Mpc), yields too little power on larger scales (e.g., large scale flows, cluster-cluster correlations, etc.)

COBE, which has probed the small anisotropy in the large scale distribution of the cosmic microwave background radiation (CMBR), provides the nail in the coffins of the two simple models described above. The observed temperature fluctuation of $\Delta T/T \sim 10^{-5}$ permits us to normalize our models of structure formation. The simple HDM and CDM models are inconsistent with this normalization as is a purely baryonic Universe ($\Omega = \Omega_{BBN} \lesssim 0.1$).

Several alternatives to the simple HDM or CDM models have received increasing attention lately and are discussed in this volume. They are, naturally, more complex than the simple models. It is anticipated that new data will replace scientific taste as the discriminant among such models.

One such "mixed" model postulates that the Universe consists of baryons ($\Omega_{BBN} \sim 0.05$), HDM ($\Omega \sim 0.25$) and CDM ($\Omega_{CDM} \sim 0.70$). Preliminary studies, described in this volume, provide encouragement for this model. In such a model, the HDM may be due to the presence of relic neutrinos with $m_\nu \sim$ few eV. Note that in this model $M_{BBN}/M_{CDM} \lesssim 0.1$ so that halos of galaxies should be dominated by CDM (and not by baryonic Machos).

In another popular cosmic cocktail, some 80% of the universal mass-energy density is in a cosmological constant $\Lambda(\Omega_\Lambda \sim 0.8)$, with the remaining 20% divided between ordinary baryons ($\Omega_{BBN} \sim 0.05$) and CDM. In this model, a significant – but not necessarily dominant – fraction of galaxy halos may be in the form of Machos ($\Omega_{BBN}/\Omega_{CDM} \sim 1/3$).

Yet another model attracting attention at present is the "old" HDM model ($\Omega_{HDM} \sim 0.95$, $\Omega_{BBN} \sim 0.05$) supplemented by "seeds" (i.e., topological defects such as cosmic strings) whose function it is to preserve small scale perturbations erased in the "seedless" HDM model. In this case, galaxy halos are dominated by baryonic dark matter (the baryonic fraction of halo dark matter $f_B \approx 1$).

4. Cosmological Dark Matter Candidates

Clearly, neutrinos are the most natural dark matter candidates. Their major virtue is, they exist! Since neutrino interactions with ordinary matter (leptons, baryons, photons) are known, the present abundance of relic neutrinos is known – and, it is large. If one (or more) flavor of neutrinos has a mass in excess of a few eV, relic neutrinos would be significant contributors to cosmological dark matter. The solar neutrino problem and the possible atmospheric neutrino problem hint at non-zero neutrino masses. The problem with light but massive neutrinos is that they are HDM candidates and, until its recent revival, HDM has been scorned by cosmologists concerned with large scale structure formation. This may be changing.

A favored CDM candidate is the axion. Introduced to solve the strong CP problem, the axion is thus far undiscovered. Of course, absence of evidence is not evidence of absence and, with an appropriate choice of parameters – consistent with laboratory and astronomical data – axions may provide the dominant cosmological dark matter.

Extensions of the standard model of particle physics require supersymmetric partners to all known particles. The lightest supersymmetric particle (LSP) may be stable and could provide an excellent CDM candidate.

As the many fine lectures at this School remind us, the dark matter problems are still with us – in many cases, stronger than ever. The good news is that there is no lack of interesting ideas for well-motivated dark matter candidates and, more important, an increasing wealth of astronomical and terrestrial data which have the potential of testing these ideas. There is every reason for optimism that new light will be shed on old dark matter problems.

5. Acknowledgements

The organizers of this School are to be congratulated on their excellent taste and exquisite timing. The subject of cosmological dark matter is clearly emerging from adolescence to maturity. Many of the most active researchers in this active field lecturered at this School and their articles in this Volume will be a valuable resource to the community at large.