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Dark Matter and Dark Energy: The Critical Questions

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Abstract.
Stars account for only about 0.5% of the content of the Universe; the bulk of the Universe is optically dark. The dark side of the Universe is comprised of: at least 0.1% light neutrinos; $3.5\% \pm 1\%$ baryons; $29\% \pm 4\%$ cold dark matter; and $66\% \pm 6\%$ dark energy. Now that we have characterized the dark side of the Universe, the challenge is to understand it. The critical questions are: (1) What form do the dark baryons take? (2) What is (are) the constituent(s) of the cold dark matter? (3) What is the nature of the mysterious dark energy that is causing the Universe to speed up.

1. Introduction

The past five years have witnessed great progress in identifying the basic features of our Universe. It is spatially flat and thus has the critical density ($\rho_{\rm crit} = 3H_0^2/8\pi G \approx 10^{-29}\,{\rm g\,cm^{-3}}$). The expansion is speeding up, not slowing down (i.e., $q_0 < 0$). The mass/energy density is distributed as follows:

- Bright stars: 0.5%
- Baryons (total): $4\% \pm 1\%$
- Nonbaryonic dark matter: $29\% \pm 4\%$
- Neutrinos: at least 0.1% and possibly as large as 5%
- Dark Energy: $66\% \pm 6\%$

The evidence for flatness comes from measurements of the anisotropy of the cosmic microwave background (CMB) on angular scales of about 1 degree. The position of the first acoustic peak at multipole number 200, as determined by the BOOMERanG, MAXIMA, DASI and CBI experiments, implies that $\Omega_0 = 1 \pm 0.04$ (Sievers et al, 2002). This means that the curvature radius of the Universe is greater than about 5 times the Hubble radius since $R_{\rm curv} = H_0^{-1}/|\Omega_0 - 1|^{1/2}$.

In the next sections I will discuss the evidence for the accounting of the various dark components.

I did not mention the cosmic microwave background, which today accounts for $\Omega_{\rm CMB} = 2.47h^{-2} \times 10^{-5}$ (about 0.005%), or the relativistic neutrino backgrounds which account for $\Omega_\nu = 0.56h^{-2} \times 10^{-5}$ per relativistic neutrino species. Though unimportant to the energy budget today, at very early times relativistic particles were dominant.

The existence of (at least) three components that evolve differently with redshift divides the evolution of the Universe into (at least) three epochs: 1. Early ($z > 10^4$ and $t < 10^4\,$yrs) radiation-dominated era (photons, neutrinos, and a spectrum of relativistic particles that grows with temperature); 2. Matter-dominated era ($10^4 > z > 0.2$, $10\,$Gyr $> t > 10^4\,$yrs) during which cosmic structure grew; and 3. Dark-energy dominated era ($z < 0.2$, $t > 10\,$Gyr) characterized by accelerated expansion and cessation of structure formation.

I note that the precision of the present accounting still allows for an unidentified component that contributes perhaps as much as 10% of the critical density.

Now that we can enumerate the components of the Universe, the task is to understand them. Three critical questions arise:

1. What form do the dark baryons take?
2. What is (are) the constituent(s) of the nonbaryonic dark matter?
3. What is the nature of the dark energy?

2. Dark Baryons

For many years the theory of big-bang nucleosynthesis (BBN) and a lower limit to the primordial deuterium abundance were used to argue for a low baryon density (see e.g., Schramm & Turner, 1998), $\Omega_B \lesssim 0.1$. The measurement of the primordial deuterium abundance in high-redshift hydrogen clouds has turned the upper limit into the most precise determination of the baryon density, $\Omega_B h^2 = 0.020 \pm 0.001$, or $\rho_B = 3.8 \pm 0.7 \times 10^{-31}\,{\rm g\,cm^{-3}}$ (Burles et al, 2001; Tytler et al, 2000; O'Meara et al, 2001). When combined with knowledge of the Hubble constant, $h = 0.72 \pm 0.07$ (Freedman et al, 2001), this implies

$$\Omega_B = 0.04 \pm 0.008 \tag{1}$$

Within the past year the credibility of the BBN baryon density got a tremendous boost from the DASI, BOOMERanG, MAXIMA, and CBI CMB experiments (Sievers et al, 2002). Based upon the ratios of the heights of the odd to even acoustic peaks, these experiments imply: $\Omega_B h^2 = 0.022 \pm 0.003$. The agreement with BBN is striking, and the underlying physics is very different: gravity-driven acoustic oscillations at 400,000 yrs vs. nuclear physics at a few seconds. Not only does this give one confidence in a low baryon density, but it also provides a powerful consistency test of the whole framework.

The absorption of light from $z \sim 3 - 4$ quasars by Lyman-alpha clouds provides a lower limit to the fraction of critical density in intergalactic gas which is consistent with BBN and the CMB: $\Omega_B h^2 > 0.018[\Omega_M h^2/0.17]^{1/4}$ (McDonald et al, 2001). This determination of the baryon density depends upon a number of assumptions, including the flux of ionizing radiation, the physics of the Lyman-alpha forest being well described by CDM, and the bulk of the baryons at $z \sim 3-4$ not being in stars or stellar remnants.

Today, baryons in stars account for only about 10% of all baryons; most of the baryons are still unaccounted for. In rich clusters, the census appears to be complete: The ratio of baryons in the hot, intracluster gas to that in stars is close to 10. While clusters provide an environment where it is easier to carry out a baryon census because of their deep gravitational potential, clusters only account for a few percent of the total matter density and a minority of the baryons.

Where then are the bulk of the baryons today? The conventional wisdom is that they reside in hot intergalactic gas or warm gas more closely associated with galaxies (see e.g., Cen & Ostriker, 1999). While unlikely, it is possible that the bulk of the baryons, or even a significant fraction, exist as the remnants of an early generation of stars.

Finally, it is worth noting that at redshifts $z \sim 3, 1000, 10^{10}$ the baryon census is complete and consistent. At BBN the baryons were in neutrons and protons that were in the processing of being fused into the light elements; at last scattering they were in ionized H and He gas; and at $z \sim 3$, they were in intergalactic gas. To complete the picture, we need a baryon census today (see Fukugita et al, 1998 for a preliminary estimate).

3. Nonbaryonic Dark Matter

The total matter density can now be determined by measurements that do *not* depend upon the connection between mass and light (see e.g., Turner, 2001). They include CMB anisotropy (the heights of the acoustic peaks determine $\Omega_M h^2$ and $\Omega_B h^2$), the power spectrum of inhomogeneity (its shape determines $\Omega_M h$ and Ω_M/Ω_B), the cluster baryon fraction (Ω_M/Ω_B) and the primordial deuterium abundance ($\Omega_B h^2$). From these a robust and "unbiased" value of the matter density follows (Turner, 2001):

$$\Omega_M = 0.33 \pm 0.035 \qquad \Omega_B = 0.004 \pm 0.008 \quad \Rightarrow \quad \Omega_{NB} = 0.29 \pm 0.04 \tag{2}$$

With a high degree of confidence, we can say that almost 90% of the matter is in a form other than baryons and yet to be identified! This conclusion receives support from another important, though indirect, argument: Absent nonbaryonic dark matter, there is no model for structure formation that can begin with the level of matter inhomogeneity indicated by the anisotropy of the CMB ($\delta\rho/\rho \sim 10^{-5}$) and explain the structure seen in the Universe today.

For almost 20 years there has been a working hypothesis: the bulk of the dark matter exists in the form of stable (or longlived) relic particles left over from the earliest moments of creation. For almost as long, the leading particle candidates have been: one or more light neutrinos, the axion and the neutralino. Significant progress has been and is being made toward testing all three candidates (see e.g., Turner, 2000a or Griest & Kamionkowski, 2000).

3.1. Neutrinos

Results from the SuperKamiokande (SuperK, Fukuda et al, 1999; Fukuda et al, 2000) and Sudbury Neutrino Observatory (SNO, Ahmad et al, 2002a,b) experiments have provided strong evidence for neutrino oscillations, with two mass differences identified: $\Delta m_{12}^2 \simeq 10^{-4}\,\mathrm{eV}^2$ (SNO/solar neutrinos) and $\Delta m_{23}^2 \simeq 3\times10^{-3}\,\mathrm{eV}^2$ (SuperK/atmospheric). Oscillation experiments only probe relative masses, and not the absolute mass scale. With the simple assumption of a mass hierarchy, $m_3 \gg m_2 \gg m_1$, this implies $m_3 \sim 0.05\,\mathrm{eV}$ and $m_2 \sim 0.01\,\mathrm{eV}$, corresponding to $\Omega_\nu \sim 0.1\%$ (note, $\Omega_\nu = m_\nu/93.2h^2\,\mathrm{eV}$). Hierarchy or not, this provides a lower limit to what neutrinos contribute to the mass budget – in the same ball park as stars – and validates the concept of particle dark matter. Cosmology has long since made its judgment on neutrinos – hot dark matter cannot account for the structure we see today and even a modest of amount of hot dark matter ($\Omega_\nu \gtrsim 0.05$) leads to an unacceptable deficiency of small-scale structure (Croft et al, 1998; Elgaroy et al, 2002).

In setting the absolute scale of neutrino mass, cosmological observations may play an important role. CMB anisotropy and large-scale structure measurements have sensitivity at the tenths of an eV level (see e.g., Hu et al, 1998).

3.2. Cold dark matter

Cosmology has also made its judgment on cold dark matter – the cold dark matter scenario has much, if not all, the truth about structure formation. The two leading CDM particles are the axion, a very light particle ($m \sim 10^{-6}\,\mathrm{eV} - 10^{-5}\,\mathrm{eV}$), which is cold by virtue of being born in a Bose condensate, and the neutralino, a heavy particle ($m \sim 50\,\mathrm{GeV} - 500\,\mathrm{GeV}$) and the lightest of the supersymmetric partners of the known particles, which is cold by virtue of its large mass.

Experiments to detect the axions or neutralinos that may comprise our own halo have reached sufficient sensitivity to begin seriously testing both possibilities. In addition, the neutralino can be produced at an accelerator or detected by its annihilation products (see e.g., Griest & Kamionkowski, 2000). (Neutralinos that accumulate in the sun annihilate and produce high-energy neutrinos; neutralinos in the halo can annihilate and produce photons, antiprotons or gamma rays.)

Like the neutrino, the interactions of the axion and neutralino with ordinary matter are very weak (mean free path $\gg H_0^{-1}$). So far as cosmology goes, axions and neutralinos are particles that only interact via gravity. This fact has made simulation of cosmic structure formation relatively simple (compared to the typical astrophysical simulation). Unfortunately, it also means that axionic cold dark matter and neutralino cold dark matter cannot be distinguished by purely cosmological observations.

There are some indications that CDM does not have all the truth on small scales, namely, the halo cusp problem and the overabundance of substructure (see e.g., Sellwood & Kosowsky, 2000). While plausible astrophysical explanations exist for both problems (see, e.g., Benson et al, 2001; Bullock et al, 2000; Klypin et al, 2001; Merritt & Cruz, 2001; Milosavljevic & Merritt, 2001; Milosavljevic et al, 2001; Somerville, 2001; Weinberg & Katz, 2001), the solution could involve an unexpected property of the dark-matter particle, e.g., large self-interaction cross section (Spergel & Steinhardt, 2000), large annihilation cross section (Kaplinghat et al, 2000), or mass of around 1 keV (i.e., warm dark matter).

At present, there is the tantalizing possibility that further study of cosmic structure on small scales could reveal a new property of the dark-matter particle; in any case, this is the arena where CDM needs to be tested.

4. Dark Energy

Dark energy is my term for the causative agent of the current epoch of accelerated expansion. According to the second Friedmann equation,

$$\ddot{R}/R = -4\pi G\left(\rho + 3p\right)/3; \tag{3}$$

thus, stress-energy with large negative pressure, can produce accelerated expansion (R is the cosmic scale factor).

Dark energy has the following defining properties: (1) it emits no light; (2) it has large, negative pressure, $p_X \sim -\rho_X$; and (3) it is approximately homogeneous (more precisely, does not cluster significantly with matter on scales at least as large as clusters of galaxies). Because its pressure is comparable in magnitude to its energy density, it is more “energy-like” than “matter-like” (matter being characterized by $p \ll \rho$). Dark energy is qualitatively very different from dark matter.

4.1. Two lines of evidence for an accelerating Universe

Two independent lines of evidence point to an accelerating Universe. The first is the measurement of type Ia supernova light curves by two groups, the Supernova Cosmology Project (Perlmutter et al, 1999) and the High-z Supernova Team (Riess et al, 1998). The teams used different analysis techniques and different samples of high-z supernovae and came to the same conclusion: the Universe is speeding up, not slowing down.

The recent discovery of a supernovae at $z \simeq 1.76$ bolsters the case significantly (Riess et al, 2001) and provides the first evidence for an early epoch of decelerated expansion (Turner & Riess, 2002). SN 1997ff falls right on the accelerating Universe curve on the magnitude – redshift diagram, and is a magnitude brighter than expected in a dusty open Universe.

The second, independent line of evidence for the accelerating Universe comes from measurements of the composition of the Universe, which point to a missing energy component with negative pressure (Turner, 2000b). The argument goes like this. CMB anisotropy measurements indicate that the Universe is flat, $\Omega_0 = 1.0 \pm 0.04$ (Sievers et al, 2002). In a flat Universe, the matter density and energy density must sum to the critical density. However, matter only contributes about 1/3rd of the critical density, $\Omega_M = 0.33 \pm 0.04$ (Turner, 2001), leaving two thirds of the critical density missing.

In order to have escaped detection this missing energy must be smoothly distributed. In order not to interfere with the formation of cosmic structure, the energy density in this component must change more slowly than matter, so that it was subdominant in the past. For example, if the missing 2/3rds of critical density were smoothly distributed matter ($p = 0$), then linear density perturbations would grow as $R^{1/2}$ rather than as R. The shortfall in growth since last scattering ($z \simeq 1100$) would be a factor of 30, leading to far too little growth to produce the structure seen today.

The pressure associated with the missing energy component determines how it evolves:

$$\rho_X \propto R^{-3(1+w)} \quad \Rightarrow \quad \rho_X/\rho_M \propto (1+z)^{3w} \tag{4}$$

where w is the ratio of the pressure of the missing energy component to its energy density (here assumed to be constant). Note, the more negative w, the faster the ratio of missing energy to matter goes to zero in the past. In order to grow the structure observed today from the density perturbations indicated by CMB anisotropy measurements, w must be more negative than about $-\frac{1}{2}$ (Turner & White, 1997), and since $q_0 = \frac{1}{2} + \frac{3}{2}w\Omega_X \sim \frac{1}{2} + w$, this implies $q_0 < 0$ and accelerated expansion.

4.2. Gravity can be repulsive in Einstein's theory

In Newton's theory mass is the source of the gravitational field and gravity is always attractive. In general relativity, both energy and pressure source the gravitational field, cf. Eq. 3. Sufficiently large negative pressure leads to repulsive gravity, and so accelerated expansion can be accommodated. Of course, that does not preclude that the ultimate explanation for accelerated expansion lies in a fundamental modification of Einstein's theory.

Repulsive gravity is a stunning feature of general relativity. It leads to a prediction every bit as revolutionary as black holes – the accelerating Universe. If the explanation for the accelerating Universe fits within general relativity, it will be a major new triumph for Einstein's theory.

4.3. The biggest embarrassment in theoretical physics

Einstein introduced the cosmological constant to balance the attractive gravity of matter in order to create a static cosmological model. He quickly discarded the cosmological constant after the discovery of the expansion of the Universe.

Quantum field theory makes the consideration of the cosmological constant obligatory not optional. The only possible covariant form for the energy of the (quantum) vacuum,

$$T^{\mu\nu}_{\rm VAC} = \rho_{\rm VAC} g^{\mu\nu},$$

is mathematically equivalent to the cosmological constant. It takes the form for a perfect fluid with energy density $\rho_{\rm VAC}$ and isotropic pressure $p_{\rm VAC} = -\rho_{\rm VAC}$ (i.e., $w = -1$) and is precisely spatially uniform. Vacuum energy is the *almost* perfect candidate for dark energy.

Here is the rub: the contributions of well-understood physics (say up to the 100 GeV scale) to the quantum-vacuum energy add up to 10^{55} times the present critical density. This is the well known cosmological-constant problem (see e.g., Weinberg, 1989; Carroll, 2001).

While string theory currently offers the best hope for a theory of everything, it has shed precious little light on the problem; in fact, it has raised some new issues. The deSitter space associated with the accelerating Universe poses serious problems for the formulation of string theory (Witten, 2001).

The cosmological constant problem leads to a fork in the dark-energy road: one path is to wait for theorists to get the "right answer" (i.e., succeed in showing that indeed quantum vacuum energy contributes $\Omega_\Lambda \simeq 2/3$); the other path is to assume that even quantum nothingness weighs nothing and something else with negative pressure must be causing the Universe to speed up. Of course, theorists follow the advice of Yogi Berra: where you see a fork in the road, take it.

4.4. Parameterizing dark energy: for now, it's w

Theorists have been very busy suggesting all kinds of interesting possibilities for the dark energy: networks of topological defects, rolling or spinning scalar fields (quintessence and spintessence), influence of "the bulk", and the breakdown of the Friedmann equations (Carroll, 2001; Turner, 2000a).

The uniformity of the CMB testifies to the near isotropy and homogeneity of the Universe. This implies that the stress-energy tensor for the Universe must take the perfect fluid form. Since dark energy dominates the energy budget, its stress-energy tensor must be to a good approximation

$$T_X{}^\mu_\nu \approx \mathrm{diag}[\rho_X, -p_X, -p_X, -p_X] \tag{5}$$

where p_X is the isotropic pressure and the desired dark energy density is

$$\rho_X = 2.8 \times 10^{-47}\,\mathrm{GeV}^4$$

(for $h = 0.72$ and $\Omega_X = 0.66$). This corresponds to a tiny energy scale, $\rho_X^{1/4} = 2.3 \times 10^{-3}\,\mathrm{eV}$.

The pressure can be characterized by its ratio to the energy density (or equation-of-state):

$$w \equiv p_X/\rho_X$$

which need not be constant; e.g., it could be a function of ρ_X or an explicit function of time or redshift.

For vacuum energy $w = -1$; for a network of topological defects $w = -N/3$ where N is the dimensionality of the defects (1 for strings, 2 for walls, etc.). For a minimally coupled, rolling scalar field, w is time dependent and can vary between -1 and $+1$.

I believe that for the foreseeable future getting at the dark energy will mean trying to measure its equation-of-state, $w(t)$.

4.5. The Universe: the lab for studying dark energy

Dark energy by its very nature is diffuse and a low-energy phenomenon. It probably cannot be produced at accelerators; it isn't found in galaxies or even in clusters of galaxies. The Universe itself is the natural lab – perhaps the only lab – in which to study it.

The primary effect of dark energy on the Universe is on the expansion rate. The first Friedmann equation can be written as

$$H^2(z)/H_0^2 = \Omega_M(1+z)^3 + (1-\Omega_M)\exp\left[3\int_0^z [1+w(x)]d\ln(1+x)\right] \tag{6}$$

where Ω_M is the fraction of critical density contributed by matter today, a flat Universe is assumed, and the dark-energy term follows from energy conservation, $d(\rho_X R^3) = -p_X dR^3$. For constant w the dark-energy term becomes $(1-\Omega_M)(1+z)^{3(1+w)}$. In a flat universe $H(z)/H_0$ depends upon only two parameters: Ω_M and $w(z)$.

While $H(z)$ is probably not directly measurable (however see, Loeb, 1998), it does affect significantly two observable quantities: the (comoving) distance to an object at redshift z,

$$r(z) = \int_0^z \frac{dz}{H(z)}, \tag{7}$$

and the growth of (linear) density perturbations, governed by

$$\ddot{\delta}_k + 2H\dot{\delta}_k - 4\pi G\rho_M = 0, \tag{8}$$

where δ_k is the Fourier component of comoving wavenumber k and overdot indicates d/dt.

The comoving distance $r(z)$ can be mapped out with the aid of standard candles (e.g., type Ia supernovae) by measuring luminosity distances $d_L(z) = (1+z)r(z)$. It can also be probed by counting objects of a known intrinsic comoving number density, through the comoving volume element, $dV/dzd\Omega = r^2(z)/H(z)$.

Both galaxies and clusters of galaxies have been suggested as objects to count (Newman & Davis, 2000; Holder et al, 2001). For each, their comoving number density evolves (in the case of clusters very significantly). However, it is believed that much, if not all, of the evolution can be modelled through numerical simulations and semi-analytical calculations. In the case of clusters, evolution is so significant that the number count test probe is affected by dark energy through both $r(z)$ and the growth of density perturbations, with the latter being the dominant effect.

The various cosmological approaches to ferreting out the nature of the dark energy have been studied extensively. Based largely upon my work with Dragan Huterer (Huterer & Turner, 2001), I summarize what we know about the efficacy of the cosmological probes of dark energy:

- Present cosmological observations prefer $w = -1$, with a 95% confidence limit $w < -0.6$ (e.g., Perlmutter, Turner & White, 1999).

- Because dark energy was less important in the past, $\rho_X/\rho_M \propto (1+z)^{3w} \to 0$ as $z \to \infty$, and the Hubble flow at low redshift is insensitive to the composition of the Universe, the most sensitive redshift interval for probing dark energy is $z = 0.2 - 2$.

- The CMB has limited power to probe w (e.g., the projected precision for Planck is $\sigma_w = 0.25$) and no power to probe its time variation.

- A high-quality sample of 2000 SNe distributed from $z = 0.2$ to $z = 1.7$ could measure w to a precision $\sigma_w = 0.05$. If Ω_M is known independently to better than $\sigma_{\Omega_M} = 0.03$, σ_w improves by a factor of two and the rate of change of $w' = dw/dz$ can be measured to precision $\sigma_{w'} = 0.16$.

- Counts of galaxies and of clusters of galaxies may have the same potential to probe w as SNe Ia. The critical issue is systematics (including the evolution of the intrinsic comoving number density, and the ability to identify galaxies or clusters of a fixed mass).

- Measuring weak gravitational lensing by large-scale structure over a field of 1000 square degrees (or more) could have comparable sensitivity to w as type Ia supernovae. However, weak gravitational lensing does not appear to be a good method to probe the time variation of w (Huterer, 2001). The systematics associated with weak gravitational lensing have not yet been studied carefully and could limit its potential.

- Some methods do not look promising in their ability to probe w because of irreducible systematics (e.g., Alcock – Paczynski test and strong gravitational lensing of quasars). However, both could provide important independent confirmation of accelerated expansion.

5. References

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