Dark Energy and the New Cosmology

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ABSTRACT

A successor to the standard hot big-bang cosmology is emerging. It greatly extends the highly successful hot big-bang model. A key element of the New Standard Cosmology is dark energy, the causative agent for accelerated expansion. Dark energy is just possibly the most important problem in all of physics. The only laboratory up to the task of studying dark energy is the Universe itself.

1 The New Cosmology

Cosmology is enjoying the most exciting period of discovery ever. Over the past three years a new, improved standard cosmology has been emerging. It incorporates the highly successful standard hot big-bang cosmology [1] and extends our understanding of the Universe to times as early as 10^{-32} sec, when the largest structures in the Universe were still subatomic quantum fluctuations.

This New Standard Cosmology is characterized by

- Flat, accelerating Universe
- Early period of rapid expansion (inflation)
- Density inhomogeneities produced from quantum fluctuations during inflation
- Composition: 2/3rds dark energy; 1/3rd dark matter; 1/200th bright stars
- Matter content: $(29 \pm 4)\%$ cold dark matter; $(4 \pm 1)\%$ baryons; $\sim 0.3\%$ neutrinos

The New Standard Cosmology is certainly not as well established as the standard hot big bang. However, the evidence is mounting.

With the recent DASI observations, the evidence for flatness is now quite firm [2]: $\Omega_0 = 1.0 \pm 0.04$. As I discuss below, the evidence for accelerated expansion is also very strong. The existence of acoustic peaks in the CMB power spectrum and the evidence for a nearly scale-invariant spectrum of primeval density perturbations ($n = 1 \pm 0.07$) is exactly what inflation predicts (along with a flat Universe). CMB anisotropy measurements (by MAP, Planck and a host of other experiments) as well as precision measurements of large-scale structure coming soon from the SDSS and 2dF will test inflation much more stringently.

The striking agreement of the BBN determination of the baryon density (from D/H measurements [3, 4]) with recent CMB anisotropy measurements [2] make a strong case for a small baryon density compared to the total matter density [5]. The many successes of the cold dark matter scenario – from the sequence of structure formation (galaxies first, clusters of galaxies and larger objects later) and the structure of the intergalactic medium to its ability to reproduce the power spectrum of inhomogeneity measured today – makes it clear that CDM holds much, if not all, of the truth in describing the formation of structure in the Universe.

Cosmological measurements and observations over the next decade or more will test (and probably refine) the New Standard Cosmology [6]. If we are fortunate, they will also help us to make sense of it all. The most pressing item to make sense of is dark energy. Its deep connections to fundamental physics – a new form of energy with repulsive gravity and possible implications for the divergences of quantum theory and supersymmetry breaking – put it very high on the list of outstanding problems in particle physics.

2 Dark Energy

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

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\left(\rho + 3p\right) \tag{1}$$

this stuff must have negative pressure, with magnitude comparable to its energy density, in order to produce accelerated expansion [recall $q = -(\ddot{R}/R)/H^2$; R is the cosmic scale factor]. Further, since this mysterious stuff does not show its presence in galaxies and clusters of galaxies, it must be relatively smoothly distributed.

That being said, 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.

It has been said that the sum total of progress in understanding the acceleration of the Universe is naming the causative agent. While not too far from the truth, there has been progress which I summarize below.

3 Dark Energy: Seven Lessons

3.1 Two lines of evidence for an accelerating Universe

Two lines of evidence point to an accelerating Universe. The first is the direct evidence based upon measurements of type Ia supernovae carried out by two groups, the Supernova Cosmology Project [7] and the High-z Supernova Team [8]. These two 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 $z = 1.755$ bolsters the case significantly [9] and provides the first evidence for an early epoch of decelerated expansion [10]. 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 or an open Universe in which type Ia supernovae are systematically fainter at high-z.

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. The argument goes like this. CMB anisotropy measurements indicate that the Universe is flat, $\Omega_0 = 1.0 \pm 0.04$ [2]. 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, $\Omega_M = 0.33 \pm 0.04$ [5]. (This is based upon measurements of CMB anisotropy, of bulk flows, and of the baryonic fraction in clusters.) Thus, two thirds of the critical density is missing!

In order to have escaped detection this missing energy must be smoothly distributed. In order not to interfere with the formation of structure (by inhibiting the growth of density perturbations) 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, far too little growth to produce the structure seen today.

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

$$\begin{aligned} \rho_X &\propto R^{-3(1+w)} \\ \rho_X/\rho_M &\propto (1+z)^{3w} \end{aligned} \tag{2}$$

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 $-\frac{1}{2}$ [11].

For a flat Universe the deceleration parameter today is

$$q_0 = \frac{1}{2} + \frac{3}{2} w \Omega_X \sim \frac{1}{2} + w$$

Therefore, knowing $w < -\frac{1}{2}$ implies $q_0 < 0$ and accelerated expansion.

3.2 Gravity can be repulsive in Einstein's theory, but ...

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. This fact is reflected in Eq. 1. Sufficiently large negative pressure leads to repulsive gravity. Thus, accelerated expansion can be accommodated within Einstein's theory.

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 new 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 the Einsteinian framework, it will be an important new triumph for general relativity.

3.3 The biggest embarrassment in theoretical physics

Einstein introduced the cosmological constant to balance the attractive gravity of matter. He quickly discarded the cosmological constant after the discovery of the expansion of the Universe. Whether or not Einstein appreciated that his theory predicted the possibility of repulsive gravity is unclear.

The advent of quantum field theory made 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 almost the 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. (Put another way, if this were so, the Hubble time would be 10^{-10} sec, and the associated event horizon would be 3 cm!) This is the well known cosmological-constant problem [12, 13].

While string theory currently offers the best hope for a theory of everything, it has shed precious little light on the problem, other than to speak to the importance of the problem. Thomas has suggested that using the holographic principle to count the available number of states in our Hubble volume leads to an upper bound on the vacuum energy that is comparable to the energy density in matter + radiation [14]. While this reduces the magnitude of the cosmological-constant problem very significantly, it does not solve the dark energy problem: a vacuum energy that is always comparable to the matter + radiation energy density would strongly suppress the growth of structure.

The deSitter space associated with the accelerating Universe poses serious problems for the formulation of string theory [15]. Banks and Dine argue that all explanations for dark energy suggested thus far are incompatible with perturbative string theory [16]. At the very least there is high tension between accelerated expansion and string theory.

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., $\Omega_X = 2/3$); 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.

3.4 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 [13, 18]. An intriguing recent paper suggests dark matter and dark energy are connected through axion physics [17].

In the absence of compelling theoretical guidance, there is a simple way to parameterize dark energy, by its equation-of-state w [11].

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 [1]. Since dark energy dominates the energy budget, its stress-energy tensor must, to a good approximation, take the form

$$T_X{}^{\mu}_{\nu} \approx \mathrm{diag}[\rho_X, -p_X, -p_X, -p_X] \tag{3}$$

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

$$\rho_X = 2.7 \times 10^{-47}\,\mathrm{GeV}^4$$

(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. (Note, w can always be rewritten as an implicit function of 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,

$$w = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \tag{4}$$

which is time dependent and can vary between -1 (when potential energy dominates) and $+1$ (when kinetic energy dominates). Here $V(\phi)$ is the potential for the scalar field.

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

3.5 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 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

$$H^2(z)/H_0^2 = \Omega_M(1+z)^3 + \Omega_X \exp\left[3\int_0^z [1+w(x)]d\ln(1+x)\right] \tag{5}$$

where Ω_M (Ω_X) is the fraction of critical density contributed by matter (dark energy) 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 is simply $\Omega_X(1+z)^{3(1+w)}$. Note that for 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 Ref. [19]), it does affect two observable quantities: the (comoving) distance to an object at redshift z,

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

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

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

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

The comoving distance $r(z)$ can be probed by standard candles (e.g., type Ia supernovae) through the classic cosmological observable, luminosity distance $d_L(z) = (1+z)r(z)$. 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 [20]. 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 CDM picture. 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 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 (see other articles in this *Yellow Book*). Based largely upon my work with Dragan Huterer [21], 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 $w < -0.6$ [23].

- 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 $z = 0.2 - 2$ [21].

- 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 [21].

- A high-quality sample of 2000 SNe distributed from $z = 0.2$ to $z = 1.7$ could measure w to a precision $\sigma_w = 0.05$ (assuming an irreducible error of 0.14 mag). If Ω_M is known independently to better than $\sigma_{\Omega_M} = 0.03$, σ_w improves by a factor of three and the rate of change of $w' = dw/dz$ can be measured to precision $\sigma_{w'} = 0.16$ [21].

- 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) [20].

- 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 [22]. 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 QSOs). However, both could provide important independent confirmation of accelerated expansion.

3.6 Why now?: the Nancy Kerrigan problem

A critical constraint on dark energy is that it not interfere with the formation of structure in the Universe. This means that dark energy must have been relatively unimportant in the past (at least back to the time of last scattering, $z \sim 1100$). *If* dark energy is characterized by constant w, not interfering with structure formation can be quantified as: $w \lesssim -\frac{1}{2}$ [11]. This means that the dark-energy density evolves more slowly than $R^{-3/2}$ (compared to R^{-3} for matter) and implies

$$\begin{aligned} \rho_X/\rho_M &\rightarrow 0 \qquad \text{for } t \rightarrow 0 \\ \rho_X/\rho_M &\rightarrow \infty \qquad \text{for } t \rightarrow \infty \end{aligned}$$

That is, in the past dark energy was unimportant and in the future it will be dominant! We just happen to live at the time when dark matter and dark energy have comparable densities. In the words of Olympic skater Nancy Kerrigan, “Why me? Why now?”

Perhaps this fact is an important clue to unraveling the nature of the dark energy. Perhaps not. And God forbid, it could be the basis of an anthropic explanation for the size of the cosmological constant.

3.7 Dark energy and destiny

Almost everyone is aware of the connection between the shape of the Universe and its destiny: positively curved recollapses, flat; negatively curved expand forever. The link between geometry and destiny depends upon a critical assumption: that matter dominates the energy budget (more precisely, that all components of matter/energy have equation of state $w > -\frac{1}{3}$). Dark energy does not satisfy this condition.

In a Universe with dark energy the connection between geometry and destiny is severed [24]. A flat Universe (like ours) can continue expanding exponentially forever with the number of visible galaxies diminishing to a few hundred (e.g., if the dark energy is a true cosmological constant); the expansion can slow to that of a matter-dominated model (e.g., if the dark energy dissipates and becomes sub dominant); or, it is even possible for the Universe to recollapse (e.g., if the dark energy decays revealing a negative cosmological constant). Because string theory prefers anti-deSitter space, the third possibility should not be forgotten.

Dark energy holds the key to understanding our destiny!

4 The Challenge

As a New Standard Cosmology emerges, a new set questions arises. (Assuming the Universe inflated) What is physics underlying inflation? What is the dark-matter particle? How was the baryon asymmetry produced? Why is the recipe for our Universe so complicated? What is the nature of the Dark Energy? All of these questions have two things in common: making sense of the New Standard Cosmology and the deep connections they reveal between fundamental physics and cosmology.

Of these new, profound cosmic questions, none is more important or further from resolution than the nature of the dark energy. Dark energy could well be the number one problem in all of physics and astronomy.

The big challenge for the New Cosmology is making sense of dark energy.

Because of its diffuse character, the Universe is likely the lab where dark energy can best be attacked (though one should not rule other approaches – e.g., if the dark energy involves a light scalar field, then there should be a new long-range force [25]).

While type Ia supernovae look particularly promising – they have a track record and can in principle be used to map out $r(z)$ – there are important open issues. Are they really standardizable candles? Have they evolved? Is the high-redshift population the same as the low-redshift population?

The dark-energy problem is important enough that pursuing complimentary approaches is both justified and prudent. Weak-gravitational lensing shows considerable promise. While beset by important issues involving number evolution and the determination of galaxy and cluster masses [20], counting galaxies and clusters of galaxies should also be pursued.

Two realistic goals for the next decade are the determination of w to 5% and looking for time variation. Achieving either has the potential to rule out a cosmological constant: For example, by measuring a significant time variation of w or by pinning w at 5σ away from -1. Such a development would be a remarkable, far reaching result.

After determining the equation-of-state of the dark energy, the next step is measuring its clustering properties. A cosmological constant is spatially constant; a rolling scalar field clusters slightly on very large scales [26]. Measuring its clustering properties will not be easy, but it provides an important, new window on dark energy.

We do live at a special time: There is still enough light in the Universe to illuminate its dark side.

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