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Properties of the Dark Energy

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Abstract. A non-zero cosmological constant is only one of many possible explanations for the observed accelerating expansion of the Universe. Any smoothly distributed, "dark" energy with a significant negative pressure can drive the acceleration. One possible culprit is a dynamical scalar field, but there are many less popular models such as tangled cosmic strings or domain walls. Soon theorists are likely to think up a number of new energies that can accelerate the expansion, meaning that only better observations can solve this question. Dark energy can be parameterized by its equation of state, $w = p/\rho$, which in the most general form can vary over time. Unlike the CMB, supernova observations cover a range of redshift so they can, in principle, probe the variation in the equation of state of the unknown component. The current SN observations loosely constrain the equation of state to $w < -0.6$, ruling out non-intercommuting strings and textures ($w = -\frac{1}{3}$), but consistent with a cosmological constant ($w = -1$). The constraints achievable from future large SN surveys are limited by our ability to understand systematic effects in SN Ia luminosities. But a large sample of supernovae reaching out to $z \sim 2$ should at least discriminate between a cosmological constant and a dynamical scalar field as the source of the observed acceleration.

1. Introduction

Type Ia supernovae appear to make excellent distance indicators. Their dispersion about the distance-redshift relation in the Hubble flow is only 0.16 mag (Jha et al. 1999) after a correction for the fact that they are not standard candles (Phillips 1993; Riess, Press & Kirshner 1995). Applying these bright distance indicators to cosmological problems has been the goal of two groups, the High-Z Supernova Search (Schmidt et al. 1998; Garnavich et al. 1998; Riess et al. 1998) and the Supernova Cosmology Project (Perlmutter et al. 1999). Their results suggest that the universe has begun a period of accelerated expansion and this has launched a small industry manufacturing theories which can explain the source of the acceleration.

While a cosmological constant term (vacuum energy) in the Einstein equations provides the simplest explanation of the current SN Ia data, other forms of energy (quintessence, topological defects, etc) have also been studied (e.g. White 1998; Garnavich et al. 1998; Steinhardt, Wang, & Zlatev 1999; Efstathiou 1999; Podariu & Ratra 2000; Waga & Frieman 2000). Many of these models conflict

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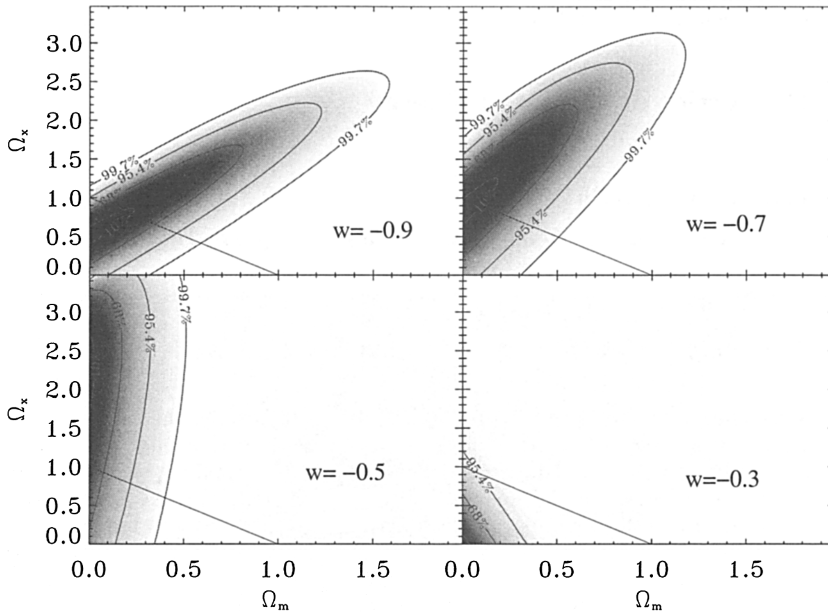

Figure 1. The probability density distribution for the supernovae studied by the High-Z Supernova Search for four values of the equation of state parameter of the dark energy component.

with expectations of particle physics or require fine tuning in relation to other energy components or can be simply be described as ugly. Since cosmology has matured into a phenomenological science at the turn of the new millennium, observational data will dominate aesthetics in the selection of cosmological models.

2. The Equation of State

Every component in the Universe can be parameterized by the way its energy density varies as the Universe expands. For example, the density of ordinary matter falls as the cube of the cosmic scale factor, so $n = 3$ where $\rho = r^{-n}$. Through the conservation of energy, this exponent is related to the equation of state, $w = p/\rho = 1/3n - 1$, where p is the pressure exerted by the component. In principle, w can vary with time, but initially we will consider it a constant and see how present supernova observations constrain its value.

Figure 1 shows probability density distributions for the High-Z Supernova Search data assuming a universe consisting of gravitating matter ($w = 0$) plus an unknown energy component with a fixed equation of state with a range of $-1 < w < 0$. No assumption is made on the geometry. For $w < -0.6$, the results are hardly distinguishable from a Λ dominated universe with $w = -1$. When $w > -0.6$, the dark energy is not efficient at creating the observed acceleration and large values of the dark energy density are required to compensate. Even with minimal assumptions it is clear that the supernova observations require a dark energy component with $w < -0.5$.

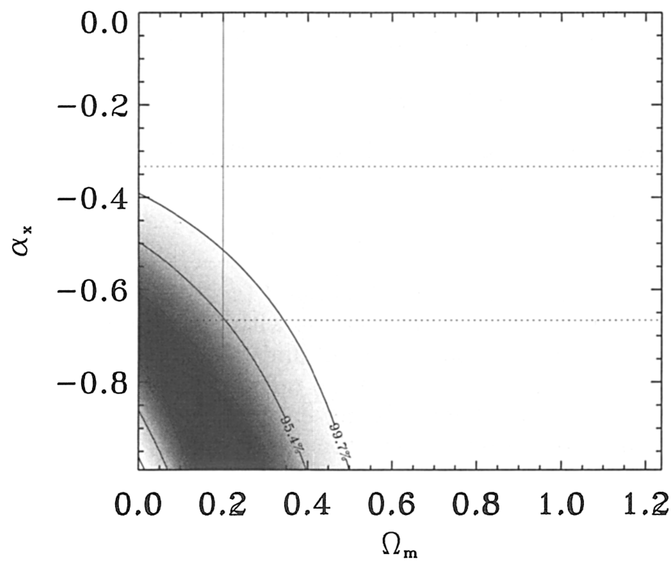

Figure 2. The probability density distribution for supernovae assuming a flat Universe. Here, α_X is the equation of state parameter for the unknown component.

Recent cosmic microwave background (CMB) results suggest that the universe is geometrically flat (de Bernardis et al. 2000; Balbi et al. 2000). Adding this constraint means that the probability density distribution can be plotted as a function of just two variables, the fixed equation of state and the matter density (or equivalently $1 - \Omega_X$). Figure 2 shows the constraints on these two variables given the supernova observations. Again, w is probably less than -0.5, but it is clear that independent knowledge of the matter density can further limit properties of the dark energy. For example, if the density of gravitating matter is more than 20% of the critical density, then the equation of state of the unknown component is likely to be less than -0.67. So under the assumptions of a flat geometry and a substantial matter component, the supernova results suggest that topological defects such as domain walls, strings or textures are not the source of the observed acceleration.

3. A Varying Equation of State

Many models of the dark energy component require that its equation of state vary with cosmic time. Dynamical scalar field models such as quintessence (e.g. Caldwell, Dave, & Steinhardt 1998) and 'k-essence' (Armendariz-Picon, Mukhanov, & Steinhardt 2000) are two of the most popular alternatives to a vacuum energy, but other models will no doubt be developed. Observationally, $w(z)$ must be considered as essentially unconstrained except that its average value since $z \sim 2$ has to be $\bar{w} \leq -0.6$ to provide the observed degree of acceleration.

A further constraint on $w(z)$ comes from the weak energy condition (Wald 1984) which merely requires that the total energy density be non-negative. If

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we define the dark energy density to be an arbitrary function, $f(z)$, so that

$$\rho(z) = \rho_0 f(z) , \tag{1}$$

and $f(0) = 1.0$, then it is straightforward to show that (Wang & Garnavich 2001)

$$w(z) = \frac{1}{3}(1+z)\frac{f'(z)}{f(z)} - 1 . \tag{2}$$

The weak energy condition simply implies that $f'(z) \geq 0$, or in an expanding universe the dark energy density can not increase with time since the big bang. So the weak energy condition provides a useful limit on the functional form of $w(z)$. Figure 3 shows that indeed, $f(z)$ can be reconstructed from large, high redshift supernova surveys, but differentiating between competing models will be difficult with a study consisting of a few thousand events.

4. The Future

It is clear that the observations of high redshift supernovae provide an excellent probe of the expansion history of the universe going back to more than half its present age. But what are the limits of this technique and what can it not tell us? It is relatively easy to create simulated data sets from future supernova surveys. The difficulty lies in finding the optimal way of analyzing this fake data and eventually the real data. Maor, Brustein, & Steinhardt (2000) have taken a pessimistic stand and point out that the equation of state is three integrals removed from the SNIa Hubble diagram. This indeed severely limits the amount of information that can be extracted from noisy data and it is likely that a complete time history of the dark energy can not be reconstructed from SNIa alone. But to simply show that the equation of state of the unknown component varies with time or even that it is greater than -1 would be an outstanding discovery.

The most critical problem facing any future large survey for SNIa will be understanding the supernovae themselves. Up to the present, systematic errors in SNIa luminosities as a function of redshift have been acceptable at the $\sim 10\%$ level since the observed acceleration dims the supernovae at the $\sim 25\%$ level. Even this 10% limit can be questioned and much observing time is being spent to confirm the reliability of SNIa as distance indicators. As the case of the Hubble Constant demonstrates, 10% accuracy is difficult to achieve in astrophysics. But using SNIa to extract details of the dark energy history will require understanding of SNIa systematics to 5% or better. Figure 3 demonstrates that a systematic supernova luminosity error as small as 5% at $z = 1$ will make it impossible to reliably distinguish between dark energy models. Understanding the systematics to a few percent is currently the major obstacle in determining the true nature of the dark energy with supernovae.

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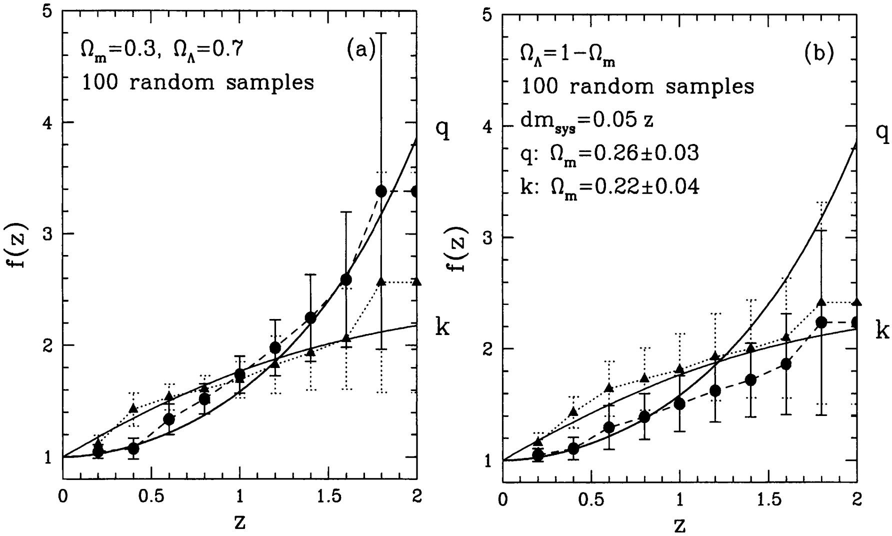

Figure 3. Panel (a) shows the recovery of two dark energy models (q=quintessence and k=k-essence) from a future supernova survey with 2000 events distributed evenly out to $z = 2$. Panel (b) is the same, but a systematic error of 0.05 mag per unit redshift interval has been added to the data.

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