Supernovae Ia, Evolution and Quintessence

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Abstract. Quintessence models with a dark energy generated by pseudo Nambu–Goldstone bosons provide a natural framework in which to test the possibility that type Ia supernovae luminosity distance measurements are at least partially due to an evolution of the sources, since these models can have parameter values for which the expansion of the Universe is decelerating as well as values for which it is accelerating, while being spatially flat in all cases and allowing for a low density of clumped matter. The results of a recent investigation [1] of current observational bounds which allow for SNe Ia source evolution are discussed. It is found that models with source evolution still favour cosmologies with an appreciable amount of acceleration in the recent past, but that the region of parameter space which is most favoured shifts significantly.

As has been described in many other talks at this conference, many independent measurements – for example, the spectrum of cosmic microwave background radiation (CMBR) anisotropies, galaxy clustering statistics, peculiar velocities, the baryon mass fraction in clusters of galaxies – all appear to agree in estimating that the density of matter which is clumped is relatively low compared to the critical density, being of order \( \Omega_m \sim 0.2 - 0.3 \). On the other hand, the recent measurement of the position of the first acoustic peak in the angular power spectrum of CMBR anisotropies by the BOOMERANG-98 and MAXIMA-I experiments now gives unequivocal evidence that the Universe is close to being spatially flat [2].

A natural conclusion to draw from these observations is that a significant proportion of the energy density of the Universe is in the form of a dark component which is smooth, rather than clumped, on cosmological scales. The form of dark energy which we are most familiar with, for historical reasons, is a cosmological constant. It leads to models in which the expansion of the universe is accelerating.

In the last few years, Type Ia supernovae (SNe Ia) have come to be used as a cosmological distance indicator, with the conclusion that there is very good evidence that the expansion of the Universe is indeed accelerating [3,4]. Unfortunately, in terms of the physical basis of the measurements, the SNe Ia result remains the most poorly understood component of the present “concordance model”, and it remains possible that there are systematic uncertainties that have not been accounted for,

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such as an evolution of the sources or extinction by dust. In particular, cosmological parameters are fitted by normalizing the peak luminosities of supernovae on the basis of a purely empirical correlation which has been observed at low redshifts between the peak luminosity and the decay time of SNe Ia events as measured in their rest frames: the resulting “Phillips relations” [5]–[7] reduce the dispersion in the distance moduli to about 0.15 [6,7] as compared to an intrinsic dispersion of 0.3–0.5 in peak absolute $B-V$ magnitudes of suitably selected nearby events.

Many of the details of the physics behind SNe Ia remain unclear. It is believed that each SNe Ia event is formed by a white dwarf in a binary system, accreting matter from its companion until it undergoes a catastrophic thermonuclear conflagration, possibly at a sub-Chandrasekhar limit stage. Given their common physical origin such systems might be reasonably expected to be somewhat “insensitive” to much of the individual histories of the progenitor systems, which provides the basis for their use as a standard candle. However, while much progress has been made in attempting to numerically model the explosions [8], huge uncertainties remain because of a lack of knowledge of the details of particular nuclear cross–sections and the fluid dynamics of flame propagation. Attempts to find a physical origin for the Phillips relations are at a very preliminary stage [9].

Given that the prospect of understanding the physical basis of the SNe Ia events is not going to be resolved without much more detailed measurements and calculations, it would be prudent to test the conclusions that have been derived cosmologically, allowing for the possibility that there has been some evolution of the peak luminosities insofar as they affect the Phillips relations over cosmological timescales. Such an analysis has been instigated by Drell, Loredo and Wasserman [10] in the case of open Friedmann–Robertson–Walker (FRW) models.

I wish to argue, however, that since we now have remarkably good evidence that the Universe is close to flat with a low density fraction of ordinary clumped matter, $\Omega_{m0} \sim 0.2–0.3$, it makes much better sense to test the evolution hypothesis in the context of models which have these features but which make no assumptions regarding the acceleration or deceleration of the Universe at the present epoch. This is not possible within the class of Friedmann-Lemaître models with $\Omega_m + \Omega_\Lambda = 1$. However, cosmological models with a quintessence field in the form of a dynamical pseudo Nambu–Goldstone boson have precisely the desired properties.

It may come as a surprise that “quintessence” does not necessarily entail an accelerated expansion of the Universe, since one of the most common approaches to seeking a particle physics origin for the vacuum energy is to look for a scalar field, $\phi$, with a potential, $V(\phi)$, which gives homogeneous isotropic cosmological solutions for which the Universe undergoes an accelerated expansion at late times. However, such an approach does not fully utilize the fact that the effective equation of state for the quintessence field, $P_\phi = w_\phi \rho_\phi$, has a variable coefficient $w_\phi$ which can generically take all values consistent with the dominant energy condition. Furthermore, such an approach often leads to the study of potentials whose physical origin is not particularly well motivated.

The PNGB model, on the other hand, is well–motivated from a particle physics
point of view as being a very natural way of obtaining an ultra–light scalar field [11]. The models [1,11,12] are based on a potential
\[ V(\phi) = M^4[\cos(\phi/f) + 1] \]
characterized by two mass scales, a purely spontaneous symmetry breaking scale \( f \sim 10^{18} - 10^{19} \) GeV , and an explicit symmetry breaking scale \( M \sim 10^{-3} \) eV .

The solutions, for a model consisting of the quintessence field plus a spatially flat homogeneous isotropic cosmology with clumped matter in the form of dust, have the property that at late times the energy density fractions in the scalar field and clumped matter tend to constants \( \Omega_{\phi f} \) and \( \Omega_{mf} \), with \( \Omega_{\phi f} + \Omega_{mf} = 1 \), while the scalar field oscillates about the minimum of \( V(\phi) \). The values of \( \Omega_{\phi f} \) and \( \Omega_{mf} \) depend on the values of the parameters \( M, f \) and the initial value \( \phi_i \) of the scalar field at the onset of the matter domination. As the scalar field oscillates about the potential minimum the deceleration parameter oscillates from a minimum value of \( q = \frac{1}{2}(1 - 3\Omega_{\phi f}) \) to a maximum value \( q = \frac{1}{2}(1 + 3\Omega_{\phi f}) \) about a mean of \( \langle q \rangle = \frac{1}{2} \).

After many oscillations it is the mean value \( \langle q \rangle \) which is significant, and the luminosity distance relation becomes indistinguishable from that of the Einstein-de Sitter universe. Thus a cosmological acceleration can have an appreciable effect at the present epoch provided that (i) \( \Omega_{\phi f} > \frac{1}{3} \); and (ii) at the present epoch the scalar field is still undergoing its first oscillation.

I now wish to briefly describe some of the results of recent work [1], in which Cindy Ng and I investigated the luminosity distance confidence limits on the parameter space \( (M, f, \phi_i) \) of PNGB quintessence models, allowing for an additional continuous redshift–dependent magnitude shift of the form \( \beta \ln(1 + z) \) in the distance modulus relation for the SNe Ia sample, as suggested by Drell, Loredo and Wasserman [10]. The parameter \( \beta \) is assumed to have a Gaussian prior distribution with mean \( \beta_0 \) and standard deviation \( b \). We investigated two types of evolution: (i) models with non-zero \( \beta_0 \); (ii) models with \( \beta_0 = 0 \) but non-zero dispersion \( b \) (see Fig. 1). The former models can be regarded as ones with a possibly strong evolution. In the second case it is assumed that the Phillips relations still apply on average over cosmological scales, but that evolutionary effects result in an additional dispersion. This is potentially a weaker form of correction that may apply to a variety of possible sources of evolutionary effects.

We determined confidence limits by analytic marginalization, using the 60 SNe Ia published by Perlmutter et al. [4]. We found that the models with evolution provided a better fit to the data. In the case of type (i) models with non-zero \( \beta_0 \) the best fit value occurred at \( \beta_0 = 0.414 \) for \( \phi_i = 1.5f \), or \( \beta_0 = 0.435 \) for \( \phi_i = 0.2f \). This corresponds to SNe Ia being intrinsically dimmer by 0.17–0.18 magnitudes at a redshift \( z = 0.5 \). The \( \beta_0 = 0 \) slice of parameter space included regions which still lie within the 2σ confidence region relative to the best-fit value of \( \beta_0 \), however, for all values of \( b \). What is perhaps even more interesting is that in the case of type (ii) models with \( \beta_0 = 0 \), if \( \phi_i \) is suitably large – e.g., for \( \phi_i = 1.5f \) as in Fig. 1 – a non-zero dispersion \( b \approx 0.36 \) can lead to a slightly better fit than the case of non–evolutionary models with \( b = 0 \).
FIGURE 1. Confidence limits on $M, f$ parameter values, with $\phi_i = 1.5f$, $\beta_0 = 0$, and $b = 0.36$ (best-fit value), for the 60 SNe Ia in the Perlmutter dataset [4]. Parameter values excluded at the 95.4% level are darkly shaded, while those excluded at the 68.3% level are lightly shaded.

The assignment of 1$\sigma$ and 2$\sigma$ confidence bounds of course depends on the dispersion, $b$, and thus the conclusions one can draw at this stage will remain somewhat qualitative until a better physical understanding of any evolutionary effects is obtained. What is perhaps most important is that for type (ii) models with $b > 0.17$ most of the 1$\sigma$–included region is located in the region marked II in Fig. 1, in which the scalar field has already passed through its minimum once and is rolling back towards the minimum for the second time. By contrast, for the non-evolutionary case, $b = 0$, the 1$\sigma$–included region is entirely within in the area marked I (see Fig. 8 of [1]), in which the scalar field is rolling down the potential for the first time at the present epoch without yet having reached the minimum. Region I corresponds to parameter values for which the conventional quintessence scenario applies, since the deceleration parameter is negative (c.f. Fig. 2). For the strongly evolving type (i) models the picture is similar, except that relative to the best–fit $\beta_0$ all of region I is 1$\sigma$–excluded for values $b \leq 0.5$ (c.f. Figs. 9–11 of [1]). For parameter values in region II it is much easier to accommodate gravitational lensing statistic constraints from quasars than for parameter values in region I [1].

In region II, although the deceleration parameter is positive at the present epoch, the universe would have experienced a significant amount of acceleration at modest redshifts within the SNe IA dataset, as can be seen from the plot of $q(z)$ in Fig. 2 for some typical parameter values. It is interesting therefore that even with the inclusion of source evolution the SNe Ia data best fits parameter values for which the cosmological evolution differs markedly from that of open FRW models. With future data from the proposed SNAP mission [13] it would become possible to
FIGURE 2. The deceleration parameter for two models with $\Omega_{m0} \simeq 0.2$ and $\phi_i = 1.5 f$:
(i) the dashed line shows $q(z)$ for $M = 0.0029 h^{1/2} \text{eV}$, $f = 3.5 \times 10^{18} \text{GeV}$, a point in region I;
(ii) the solid line shows $q(z)$ for $M = 0.0066 h^{1/2} \text{eV}$, $f = 2.3 \times 10^{18} \text{GeV}$, a point in region II.

observationally distinguish region II PNGB quintessence models from Friedmann-Lemaître models and other quintessence scenarios.

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