COSMOLOGICAL MODEL PARAMETER DETERMINATION FROM SATELLITE-ACQUIRED SUPERNOVA APPARENT MAGNITUDE VERSUS REDSHIFT DATA

SILVIU PODARIU,1 PETER NUGENT,2 AND BHARAT RATRA1

Received 2000 August 17; accepted 2001 January 29

ABSTRACT

We examine the constraints that satellite-acquired supernova (SN) apparent magnitude versus redshift data will place on cosmological model parameters in models with and without a constant or time-variable cosmological constant \( \Lambda \). Data that could be acquired in the near future would result in tight constraints on these parameters. For example, if all other parameters of a spatially flat model with a constant \( \Lambda \) are known, the SN data should constrain the nonrelativistic matter density parameter \( \Omega_m \) to better than 1% (2%, 0.5%) at 1σ with neutral (worst case, best case) assumptions about data quality.

Subject headings: cosmology: observations — large-scale structure of universe — space vehicles — supernovae: general

1. INTRODUCTION

Recent applications of the apparent magnitude versus redshift test based on Type Ia supernovae (SNe Ia) have resulted in interesting constraints on cosmological model parameters (see, e.g., Riess et al. 1998; Perlmutter et al. 1999; Podariu & Ratra 2000; Waga & Frieman 2000; Gott et al. 2001). Higher quality data would result in tighter constraints on cosmological model parameters. A dedicated SN space telescope could provide the high-quality data needed to realize the full potential of this neoclassical cosmological test.

In this paper we examine constraints on cosmological model parameters that would result from such a data set. For definitiveness, we focus on data that could be acquired by the proposed Supernova/Acceleration Probe (SNAP) space telescope (Curtis et al. 2000). That is, we assume a data set of 2000 SNe Ia multifrequency light curves for SNe out to redshift \( z = 2 \), with errors discussed below.

Observational data favor models with a low \( \Omega_m \). The simplest such models have either flat spatial hypersurfaces and a constant or time-variable cosmological “constant” \( \Lambda \) (see, e.g., Peebles 1984; Peebles & Ratra 1988; Sahni & Starobinsky 2000; Steinhardt 1999; Carroll 2001; Binétruy 2000) or open spatial hypersurfaces and no \( \Lambda \) (see, e.g., Gott 1982, 1997; Ratra & Peebles 1994, 1995; Kamionkowski et al. 1994; Górski et al. 1998). For a constant \( \Lambda \) (with density \( \Omega_\Lambda \)), these models lie along the lines \( \Omega_0 + \Omega_\Lambda = 1 \) and \( \Omega_\Lambda = 0 \), respectively, in the more general two-dimensional \(( \Omega_0, \Omega_\Lambda )\) model parameter space. Depending on the values of \( \Omega_0 \) and \( \Omega_\Lambda \), models in this two-dimensional parameter space have either closed, flat, or open spatial hypersurfaces. In this paper we derive constraints on the parameters of the two-dimensional model as well as those of the special one-dimensional cases.

We also derive constraints on the parameters of a spatially flat model with a time-variable \( \Lambda \). The only known consistent model for a time-variable \( \Lambda \) is the model based on a scalar field \( \phi \) with a scalar field potential \( V(\phi) \) (Ratra & Peebles 1988). In this paper we focus on the favored model which at low redshift \((z)\) has \( V(\phi) \propto \phi^{-\alpha}, \alpha > 0 \) (Peebles & Ratra 1988; Ratra & Peebles 1988). This model is in reasonable accord with observational data (see, e.g., Peebles & Ratra 1988; Ratra & Quillen 1992; Podariu & Ratra 2000; Waga & Frieman 2000; Brax, Martin, & Riazuelo 2000).

A scalar field is mathematically equivalent to a fluid with a time-dependent speed of sound (Ratra 1991), and it may be shown that with \( V(\phi) \propto \phi^{-\alpha}, \alpha > 0 \), the \( \phi \) energy density behaves like a cosmological constant that decreases with time. We emphasize that in our analysis of this model we do not make use of the time-independent equation-of-state fluid approximation to the model that has sometimes been used for such computations (see discussion in Podariu & Ratra 2000).

Huterer & Turner (1999), Starobinsky (1998), Nakamura & Chiba (1999), Saini et al. (2000), and Chiba & Nakamura (2000) discuss using SN apparent magnitude versus redshift data to determine the scalar field potential of the time-variable \( \Lambda \) model. This is a difficult task. Maor, Brustein, & Steinhardt (2001) note that even data of the quality anticipated from SNAP will not result in very tight constraints on an arbitrary equation of state. They consider a simple illustrative example with an equation-of-state parameter \( w \) that has two terms, one constant and the other linear in \( z \). Maor et al. show confidence contours (in a two-dimensional plane) for the two parameters in the equation of state for this model in their Figure 2. After marginalizing over \( \Omega_m \), the peak-to-peak spread in their 2σ contour for the equation of state at \( z = 0, w_m = 0 \), is about 0.3 for \( w = -0.7 \), or about 43% of the value of \( w_m \). This corresponds to a symmetrized 2σ uncertainty of about ±22% on \( w \). The corresponding peak-to-peak spread in their 1σ contour is about −0.22, which corresponds to a 1σ uncertainty of about ±16% for \( w_m \). For fixed \( \Omega_m \), the peak-to-peak spread in

4 Such a scalar field potential is present in some high-energy particle physics models (see, e.g., Rosati 2000; Copeland, Nunes, & Rosati 2000; Brax & Martin 2000). Fuji (2000), Cormier & Holman (2000), Faraoni (2000), Baccigalupi, Perrotta, & Matarrese (2000), Dodelson, Kaplinghat, & Stewart (2000), Ziaeepour (2000), Kruger & Norbury (2000), Joyce & Prokopec (2000), Goldberg (2000), Hebecker & Wetterich (2000), Ureña-López & Matos (2000), and Armendariz-Picon, Mukhanov, & Steinhardt (2000) discuss this model and other options.

5 See, e.g., Vishwakarma (2000), Ng & Wiltshire (2001), and Lima & Alcaniz (2000) for observational constraints on related models.

6 We acknowledge helpful discussions with P. Steinhardt on this issue.

1 Department of Physics, Kansas State University, Manhattan, KS 66506.
2 Lawrence Berkeley National Laboratory, MS 50-232, 1 Cyclotron Road, Berkeley, CA 94720.
3 http://snap.lbl.gov.
their 1 σ contour is about -0.09, which corresponds to a
1 σ uncertainty of about ±6.5% for \( w_0 \). While much larger
than the constraints we place on model parameter values
(see below), this is still a reasonably precise determination of
\( w_0 \).

Motivated by the approach adopted in analyses of
current SN apparent magnitude versus redshift data (see,
e.g., Riess et al. 1998; Perlmutter et al. 1999), we instead
focus on how well future SN data will constrain parameters
of various cosmological models. We want to determine
how well SN data distinguish between different cosmo-
logical model parameter values. To do this we pick a model
and a range of model parameter values and compute the
luminosity distance \( D_L(z) \) for a grid of model parameter
values that span this range. Figure 1 shows examples of
\( D_L(z) \) computed in the time-variable \( \Lambda \) model (Peebles
& Ratra 1988).

The error bars on the SN fluxes are the ones that are
most likely to be symmetric (and thus allow for the simplest
comparison between model predictions and observational
data), so we work with flux \( f \propto D_L^{-2} \) for the comparison
between model predictions and anticipated data. For our
purposes, the constant of proportionality in this relation is
unimportant since the SNe in the final reduced data set
have been made standardized candles (see, e.g., Phillips
1993; Riess et al. 1998; Perlmutter et al. 1999).

For computational simplicity we assume SN data from
SNAP will be combined to provide fluxes and errors on
fluxes for 67 uniform bins in redshift, of width \( \Delta z = 0.03 \),
with the first one centered at \( z = 0.03 \) and the last one at
\( z = 2.01 \). In each bin the statistical and systematic errors are
combined to give a flux error distribution with standard
deviation \( \sigma(z) \).

To determine how well SN data will distinguish between
different sets of model parameter values, we pick a fiducial
set of model parameter values which give a flux \( f_P(z) \) and
compute
\[
N_d(P) = \sqrt{\frac{1}{\sum_{i=1}^{67} \left( \frac{f(P, z_i) - f_P(z_i)}{\sigma(z_i) f_P(z_i)} \right)^2}},
\]
where the sum runs over the 67 redshift bins and \( P \) rep-
resents the model parameters, for instance, \( \Omega_m \) and \( \Omega_\Lambda \) in
the general two-dimensional constant \( \Lambda \) case. The term \( N_d(P) \) is
the number of standard deviations the model parameter set
\( P \) lies away from that of the fiducial model. This representa-
tion (eq. [1]) is exact for the case where the correlated errors

![Figure 1](image_url)

**Fig. 1.**—Lines in the panels in upper row show luminosity distance \( D_L(z, a) \) as a function of redshift \( z \) for various values of \( a \) computed for Hubble
parameter \( H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1} \) for the spatially flat time-variable \( \Lambda \) model with scalar field potential \( V(\phi) \propto \phi^{-n} \). In descending order at \( z = 2 \) the lines
correspond to \( z = 0, 2, 4, \) and 8 (solid, dot-dashed, dashed, and dotted curves, respectively). The constant \( \Lambda \) model is \( z = 0 \). From left to right the three panels
correspond to \( \Omega_0 = 0.2, 0.4, \) and 0.6. The three lower panels show the fractional differences relative to the \( z = 0 \) case, \( 1 - D_L(z, a)/D_L(z, a = 0) \), as a function of \( z \), for the values of \( \Omega_0 \) used in upper panels. Here the lines correspond to \( z = 8, 4, \) and 2, in descending order at \( z = 2 \).
between redshift bins for the distance determinations are negligible.

The error budget is summarized in the next section. Results are presented and discussed in § 3 and we conclude in § 4.

2. ERROR BUDGET

The following provides a brief overview of the constraints that a satellite-based SN program can place on the statistical and on many of the potential systematic errors. For a more complete discussion, see the SNAP proposal (Curtis et al. 2000).

2.1. Statistical Errors

Currently a single SN Ia provides a \( \approx 16\% \) measurement of the flux (\( \approx 8\% \) in distance; Jha et al. 1999). A large fraction of this uncertainty almost certainly resides in the correction for extinction. With space-based observations, one will be able to greatly increase the wavelength coverage and precision of the photometric measurements, considerably reducing this uncertainty [a signal-to-noise ratio of \( \sim 30 \) could be achieved for a SN at AB(1.0 \( \mu \)m) = 27.0, with systematics in the absolute photometry of less than 1%].

The SNAP satellite has baselined 15 broadband filters from about 0.3 to 1.7 \( \mu \)m in addition to obtaining spectrophotometry near peak for each SN Ia. A conservative estimate of the intrinsic uncertainty for a given SN Ia with this type of data set would be \( \approx 10\% \) in flux (\( \approx 5\% \) in distance). There is potential for reducing this even further through the identification of additional parameters that constrain the corrected peak luminosity of SNe Ia beyond the single parameter of light-curve shape currently used. Here we will conservatively assume that the statistical uncertainty in satellite-based SNe Ia measurements such as these will be 10% in flux. The \( \sqrt{N} \) statistics on 2000 SNe Ia over the 67 aforementioned bins would provide an uncertainty of less than 2% per bin.

2.2. Systematic Errors

A major advantage of a space telescope is the much better opportunity to control (and study) the many known (and unknown) sources of error. These include environmental effects, evolution, intergalactic dust, unusual cases which bias the distribution, etc. (for discussions of some of these issues see, e.g., Howell, Wang, & Wheeler 2000; Aldering, Knop, & Nugent 2000; Croft et al. 2000; Nomoto et al. 2000; Barber 2000; Hamuy et al. 2000; Livio 2000; Totani 2000; and Gott et al. 2001). Without understanding and limiting these sources of error, an accurate measurement of the cosmological parameters cannot be obtained. The following discusses a few potential sources of systematic errors and how space-based observations could constrain or eliminate them (a more detailed discussion of these and other sources of systematic errors can be found in the SNAP proposal [Curtis et al. 2000]):

Malmquist bias.—This is the sampling bias due to any low-versus-high redshift difference in detection efficiency of intrinsically fainter SNe. For the aforementioned redshift range, the proposed experiment would attempt to detect every SN in the observed region of sky at 10% of its peak brightness, thus eliminating this source of systematic uncertainty.

Extinction by "ordinary" dust.—The proposed experiment will attempt to obtain cross-wavelength-calibrated data with broad wavelength coverage for each SN, so that dimming of the spectrum as a function of wavelength could be measured with high signal-to-noise ratio. Furthermore, SNe Ia in early-type galaxies with little to no extinction will be targeted to precisely determine the intrinsic colors of a SN Ia at a variety of light-curve shapes (see Riess, Press, & Kirshner 1996 for a study of this at low redshift). This would allow study of the ratio of selective to total absorption from dust and would correct for any potential evolution of this ratio as a function of redshift.

Extinction by "gray" dust.—It has been suggested by Aguirre (1999) that certain large (up to \( \sim 0.1 \) \AA), and possibly needle-like, dust grains can be expelled from galaxies via radiation pressure and can have an opacity curve that is shallow in optical bands, thus making them absorptive while producing only small color excess. Such dust would lead the unwary cosmologist into underestimating \( \Omega_m \) or overestimating \( \Omega_\Lambda \), thus producing a systematic bias. If there is gray dust that has had insufficient time to diffuse uniformly in intergalactic space, different lines of sight would have differing amounts of extinction as a result of clumping. This would result in an increase of observed SN magnitude dispersion, an effect that is not seen in current observations and could easily be detected by a space-based experiment. Furthermore, it is also possible to detect \( z < 0.5 \) gray dust by comparing optical and near-IR photometry of SNe (both Ia and II) found in this redshift range since the dust is not completely gray and will show a color excess over a large enough wavelength range (see, e.g., Riess et al. 2000).

SN Ia evolution.—SNe Ia with different progenitor properties should result in explosions with slightly differing properties, even if there is only one mechanism for creating them, and even if this mechanism has a set "trigger" such as the Chandrasekhar limit (Höflich et al. 2000). If these differences are not corrected by the light-curve width-luminosity relation presently in use, and if the distribution of key parameters of the progenitor stars changes with redshift, the SN Ia explosions observed at high redshift could differ in peak luminosity from those at low redshift, leading to a systematic error in the determination of the cosmological parameters. However, a data set acquired from a space telescope should allow corrections for these differences or allow similar SNe Ia to be identified and matched at high and low redshifts, thus mitigating against the effects of changing progenitor properties.

One of the wonderful aspects of using SNe Ia for cosmology is the fact that the SN bares its entire history, from progenitor through explosion, to the observer. Thus, the SN cannot hide the effects of evolution; these effects will make themselves apparent in the light-curves and spectra. Figure 2 illustrates this statement. It shows the temporal spectral evolution of a typical SN Ia. At very early times, we probe the outer, unburned layers left over from the progenitor. As seen in Fisher et al. (1997), this epoch displays spectral features from high-velocity carbon left over from the original progenitor and could be used to tightly constrain various theoretical models. At later times, near peak brightness, we begin to probe the layers of the atmosphere which show the intermediate-mass elements synthesized in the runaway thermonuclear explosion. Nugent et al. (1995) showed how some of the spectroscopic features of these elements (Si II and Ca II) nicely correlate with the peak brightness of the SN Ia. Finally, during the nebular phase, we note the strong
As the SN Ia evolves in time, the rapid expansion of its atmosphere allows the observer to probe to deeper layers as the optical depth falls off with the diminishing density. At early times, one views the outermost layers that are mostly composed of the unburned progenitor. Near peak brightness, the intermediate-mass elements of S II and Si II are quite visible. At later times, shortly after entering the nebular phase, one views the Fe-peak core of the SN Ia where the radioactive decay of $\approx 0.5 M_\odot$ of $^{56}$Ni has taken place since the explosion.

Fe II emission lines at low velocity left over from the radioactive decay of $^{56}$Ni to $^{56}$Co to $^{56}$Fe. These observations allow one to directly probe the total amount of $^{56}$Ni synthesized during the explosion (see Kuchner et al. 1994; Fisher et al. 1995).

Curtis et al. (2000) have identified a series of key observable SN features that reflect differences in the underlying physics of the SN. By measuring all of these features for each SN, one should be able to tightly constrain the physical conditions of the explosion, making it possible to recognize SNe that have similar initial conditions and/or arise in matching galactic environments. The current theoretical models of SN Ia explosions are not sufficiently complete to predict the precise luminosity of each SN, but they are able to give rough correlations between the changes in the physical conditions of the SNe and the peak luminosity (Höflich,
Wheeler, & Thielemann 1998). These conditions include the velocity of the ejecta (a measurement of the kinetic energy of the explosion), the opacity of the inner layers (which affects the overall light-curve shape), the metallicity of the progenitor (which affects the early spectra), $^{56}$Ni mass (a measurement of the total luminosity), and $^{56}$Ni distribution (which might slightly affect the light-curve shape at early time). One can therefore give the approximate accuracy needed for the measurement of each feature in order to ensure that the physical condition of each set of SNe is well enough determined that its range of luminosities is well below the systematic uncertainty bound of $\sim 2\%$ when all the constraints are used together (see Curtis et al. 2000 for a full description).

3. RESULTS AND DISCUSSION

For SNAP data, $\sigma(z)$ (eq. [1]) is estimated to be 2% in each redshift bin up to $z = 1.7$, and then it increases linearly with redshift to 10% at $z = 2$. This is the "neutral" case. The "best" case assumes that errors are limited by $\sqrt{N}$ statistics (with systematic errors at or below the 1% level), giving $\sigma(z) = 1\%$ over the whole redshift range. The "worst" case (this is the baseline SNAP mission) assumes $\sigma(z) = 3\%$ to $z = 1.2$ and $\sigma(z) = 10\%$ from $z = 1.2$ to $z = 2$.

Figure 3 illustrates the ability of anticipated space telescope data to constrain cosmological model parameters for the general two-dimensional constant $\Lambda$ case. SNAP data with even worst-case error bars will lead to greatly improved cosmological parameter determination (for constraints from current data see, e.g., Riess et al. 1998; Perlmutter et al. 1999; and Podariu & Ratra 2000). We note that, as expected, the contours are elliptical, indicating that one combination of the parameters is better constrained than the other orthogonal combination (see, e.g., Goobar & Perlmutter 1995).

Figure 4 illustrates the ability of space telescope data to distinguish between a constant and a time-variable $\Lambda$ in a spatially flat model. The fiducial model here is a constant $\Lambda$ ($\alpha = 0$) model with $\Omega_0 = 0.28$ and $\Omega_\Lambda = 0.72$. SNAP data with even worst-case error bars will result in greatly improved discrimination (see, e.g., Podariu & Ratra 2000 for the current situation). We note again that the contours are elliptical.

Figure 5 illustrates the ability of space telescope data to constrain $\Omega_0$ and $\alpha$ in the spatially flat time-variable $\Lambda$ model (Peebles & Ratra 1988). Here the time-variable $\Lambda$ fiducial model has $\Omega_0 = 0.2$ and $\alpha = 4$. Again, SNAP will allow for tight constraints on these cosmological parameters.

If other data (such as cosmic microwave background anisotropy measurements from MAP and Planck Surveyor and weak-lensing studies from the proposed SNAP mission) pinned down some of the cosmological parameters, the SN data would then be able to provide tighter constraints on the remaining parameters. For instance, Figure 6 shows constraints from space telescope data on $\Omega_0$ in a spatially flat constant $\Lambda$ model and in an open $\Lambda = 0$ model. As expected from the elliptical shape of the contours in Figure 3, anticipated SN data will constrain $\Omega_0$ more tightly in the spatially flat case than in the open case. In both cases SNAP will provide tight constraints on $\Omega_0$. For instance, at 3 $\sigma$, in the spatially flat model we find $\Omega_0 = 0.3 \pm 0.007$.

![Figure 3](image_url)

**Fig. 3.**—Contours of $N_e = 1, 2, 4,$ and 8 for the constant $\Lambda$ model. *Left panel:* anticipated SN data with worst-case errors; *center panel:* neutral-case errors; *right panel:* best-case errors. The fiducial model is spatially flat with $\Omega_0 = 0.28$ and $\Omega_\Lambda = 0.72$. 

![Figure 4](image_url)

![Figure 5](image_url)

![Figure 6](image_url)
Fig. 4.—Contours of $N_c = 1, 2, 4,$ and 8 for the spatially flat time-variable $\Lambda$ model (Peebles & Ratra 1988). Left panel: anticipated SN data with worst-case errors; center panel: neutral-case errors; right panel: best-case errors. The fiducial model has $\Omega_0 = 0.28$ and $x = 0$ (and is thus a constant $\Lambda$ model with $\Omega_\Lambda = 0.72$; this was also the fiducial model used for Fig. 2).

Fig. 5.—Contours of $N_c = 1, 2, 4,$ and 8 for the spatially flat time-variable $\Lambda$ model. Left panel: anticipated SN data with worst-case errors; center panel: neutral-case errors; right panel: best-case errors. The fiducial model has $\Omega_0 = 0.2$ and $x = 4$. 
FIG. 6.—$N_p(\Omega_0)$ for a flat model with a constant $\Lambda$ (left panel) and for an open model with no $\Lambda$ (right panel). In both cases the fiducial model has $\Omega_0 = 0.3$, with $\Omega_\Lambda = 0.7$ and 0, respectively. Dashed lines are for worst-case SNAP errors; solid lines are for neutral-case errors; and dotted lines are for best-case errors.

FIG. 7.—$N_p(\Omega_0)$ (left panel) and $N_p(\alpha)$ (right panel) for the spatially flat time-variable $\Lambda$ model (Peebles & Ratra 1988). In both cases the fiducial model has $\Omega_0 = 0.2$ and $\alpha = 4$. Dashed lines are for worst-case SNAP errors; solid lines are for neutral-case errors; and dotted lines are for best-case errors.
SN space telescope data of the quality assumed here will lead to tight constraints on cosmological model parameters. For instance, in a spatially flat constant $\Lambda$ model where all other parameters are known, anticipated space telescope SN data will determine $\Omega_0$ to about $\pm 0.8\%$, $\pm 1.7\%$, and $\pm 0.4\%$ (for neutral-, worst-, and best-case errors respectively) at 1 $\sigma$. The corresponding errors for $\Omega_0$ for the open case are about $\pm 1.6\%$, $\pm 3.7\%$, and $\pm 0.7\%$. For the time-variable $\Lambda$ model, when $\alpha$ is fixed, $\Omega_0$ will be known to about $\pm 1.5\%$, $\pm 3.1\%$, and $\pm 0.7\%$, while when $\Omega_0$ is fixed, $\alpha$ will be determined to about $\pm 2.2\%$, $\pm 4.2\%$, and $\pm 1.2\%$. This will have important consequences for cosmology.

We acknowledge valuable discussions with G. Aldering, M. Levi, S. Perlmutter, and T. Souradeep. S. P. and B. R. acknowledge support from NSF CAREER grant AST 98-75031 and P. N. acknowledges computational support from the DOE Office of Science under contract DE-AC03-76SF00098.

**REFERENCES**

Aguirre, A. N. 1999, ApJ, 512, L19
Aldering, G., Knop, R., & Nugent, P. 2000, AJ, 119, 2110
Armenariz-Picón, C., Mukhanov, V., & Steinhardt, P. J. 2000, Phys. Rev. Lett., 85, 4438
Baccigalupi, C., Perrotta, F., & Matarrese, S. 2000, in COSMO99, in press
Balbi, A., et al. 2000, ApJ, 545, L19
Barber, A. J. 2000, MNRAS, 318, 195
Brax, P., & Martin, J. 2000, in Energy Densities in the Universe, in press
Brax, P., Martin, J., & Riazuelo, A. 2000, Phys. Rev. D, 62, 103505
Carroll, S. M. 2001, Living Rev. Relativity, 4, 2001
Chiab, T., & Nakamura, T. 2000, Phys. Rev. D, 62, 123130
Copeland, E. J., Nunes, N. J., & Rosati, F. 2000, Phys. Rev. D, 62, 123503
Curtis, D., et al. 2000, Supernova/Acceleration Probe (SNAP), proposal to DOE and NSF
Dodelson, S. 2000, Int. J. Mod. Phys. A, 15, 2629
Dodelson, S., Kaplanhag, M., & Stewar, E. 2000, Phys. Rev. Lett., 85, 5276
Faraoni, V. 2000, Phys. Rev. D, 62, 023504
Fisher, A., Branch, D., Hofflich, P., & Khokhlov, A. 1995, ApJ, 447, L73
Fisher, A., Branch, D., Nugent, P., & Baron, E. 1997, ApJ, 481, L89
Fujii, Y. 2000, Grav. Cosmol., 6, 107
Ganga, K., Ratra, B., Gundersen, J. O., & Sugiyama, N. 1997, ApJ, 484, 7
Ganga, K., Ratra, B., Lim, M. A., Sugiyama, N., & Tanaka, S. T. 1998, ApJS, 114, 165
Goldberg, H. 2000, Phys. Rev. Lett., 429, 153
Goobar, A., & Perlmutter, S. 1995, ApJ, 450, 14
Gördi, K. M., Ratra, B., Stompor, R., Sugiyama, N., & Banday, A. J. 1998, ApJS, 114, 1
Gott, J. R. 1982, Nature, 295, 304
Gott, J. R., Yggeley, M. S., Podarius, S., & Ratra, B. 2001, ApJ, 549, L1
Hamuy, M., Trager, S., C., Pinto, P., Phillips, M. M., Schommer, R. A., Ivanov, V., & Suntzeff, N. B. 2000, AJ, 120, 1479
Hebercker, A., & Wetterich, C. 2000, Phys. Rev. Lett., 85, 3339
Höflinger, P., Nomoto, K., Umeda, H., & Wheeler, J. C. 2000, ApJ, 528, 590
Höflinger, P., Wheeler, J. C., & Thielemann F. K. 1999, ApJ, 517, 617
Huterer, D., & Turner, M. S. 1999, Phys. Rev. D, 60, 081301
Joyce, M., & Prokopec, T. 2000, J. High Energy Phys., 010, 030
Kamionkowski, M., Ratra, B., Spergel, D. N., & Sugiyama, N. 1999, ApJ, 434, L1
Kruger, A. T., & Norbury, J. W. 2000, Phys. Rev. D, 61, 087303
Kuchner, M. J., Kirshner, R. P., Pinto, P. A., & Leibundgut, B. 1994, ApJ, 426, L89
Lange, A. E., et al. 2001, Phys. Rev. D, 63, 042001
Le Dour, M., Douspis, M., Bartlett, J. G., & Blanchard, A. 2001, A&A, 364, 369
Lima, J. A. S., & Alcaniz, J. S. 2000, MNRAS, 317, 593
Livio, M. 2000, in The Greatest Explosions since the Big Bang: Supernovae and Gamma-Ray Bursts, ed. M. Livio, N. Panagia, & K. Sahu (Baltimore: STScI) in press
Maor, I., Brustein, R., & Steinhardt, P. J. 2001, Phys. Rev. Lett., 86, 6
Nakamura, T., & Chiba, T. 1999, MNRAS, 306, 966
Ng, S.C.C., & Wiltshire, D. L. 2001, Phys. Rev. D, 63, 023503
Nomoto, K., Umeda, H., Kobayashi, C., Hachisu, I., Kato, M., & Tsujimoto, T. 2000, in Cosmic Explosions! ed. S. S. Holt & W. W. Zhang (New York: AIP), in press
Nugent, P., Phillips, M. M., Branch, D., & Hauschildt, P. 1995, ApJ, 455, L147
Peebles, P. J. E. 1984, ApJ, 284, 439
Peebles, P. J. E., & Ratra, B. 1998, ApJ, 325, L17
Perlmutter, S., et al. 1999, ApJ, 517, 565
Phillips, M. M. 1993, ApJ, 413, L105
Podariu, S., & Ratra, B. 2000, ApJ, 532, L109
Ratra, B. 1991, Phys. Rev. D, 43, 3802
Ratra, B., Ganga, K., Sugiyama, N., Tucker, G. S., Griffin, G. S., Nguyen, H. T., & Peterson, J. B. 1998, ApJ, 505, 8
Ratra, B., & Peebles, P. J. E. 1988, Phys. Rev. D, 37, 3406
Ratra, B., & Quillen, A. 1992, MNRAS, 259, 738
Ratra, B., Stompor, R., Ganga, K., Rocha, G., Sugiyama, N., & Górski, K. M. 1999, ApJ, 517, 549
Riess, A. G., et al. 1998, AJ, 116, 1009
Riess, A. G., et al. 2000, ApJ, 536, 62
Riess, A. G., Press, W. H., & Kirshner, R. P. 1996, ApJ, 473, 588
Rocha, G., Stompor, R., Ganga, K., Ratra, B., Platt, S. R., Sugiyama, N., & Górski, K. M. 1999, ApJ, 525, 1
Rosati, F. 2000, in COSMO99, in press
Sahni, V., & Starobinsky, A. 2000, Int. J. Mod. Phys. D, 9, 373
Saini, T. D., Raychaudhury, S., Sahni, V., & Starobinsky, A. A. 2000, Phys. Rev. Lett., 85, 1162
Starobinsky, A. A. 1999, Jr. Exp. Theor. Phys. Lett., 68, 757
Steinhardt, P. J. 1999, in Proceedings of the Fritzerk Symposium on the Status of Inflationary Cosmology, in press
Totani, T. 2000, in Dark Matter in 2000, (New York: Springer-Verlag) in press
Urena-López, L. A., & Matos, T. 2000, Phys. Rev. D, 62, 081302
Vishwakarma, R.G. 2000, Classical Quantum Gravity, 17, 3833 preprint (gr-qc/9912105)
Waga, I., & Frieman, J. A. 2000, Phys. Rev. D, 62, 043521
Ziaeepour, H. 2000, preprint (astro-ph/0002400)