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CONSTRAINTS ON Λ-DECAYING COSMOLOGY FROM OBSERVATIONAL POINT OF VIEW

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ABSTRACT

To constrain the values of the model parameters for the cosmological models involving the time-decaying Λ term, we have computed sets of theoretical predictions for the N-m relation of galaxies as well as the CMB angular power spectrum: three types of variation, viz., $\Lambda \propto \tau^{-l}$, a^{-m}, and H^n are thereby assumed following Overduin & Cooperstock (1998), although we concentrate here on the discussion of the results obtained from the first type. Our results for the N-m relation indicate that the observed excess of the galaxy counts N in the faint region beyond the blue apparent magnitude 24 can be reasonably well accounted for with the value of l in the range between 0.2 and 1. Furthermore, a comparison of our computational results of the CMB spectra with the observational data shows that the models with a mild degree of the Λ term decay, viz., with the value of $l \lesssim 0.4$, are favorable. In this case, the age of our universe turns out to be larger than or equal to 14 Gyr, the lower limit inferred from some Uranium datings.

Key words : cosmology — cosmological term — time variation — galaxy number counts — galaxy merger — CMB spectra

I. INTRODUCTION

Today, based on observational results of the magnitude versus redshift relation of high redshift Type Ia supernovae, the existence of the Einstein's cosmological constant is strongly being advocated and widely accepted by the majority of the cosmologists (e.g., Perlmutter et al. 1999).

In addition, possibilities of certain types of variations of the cosmological constant have been investigated by some authors (see, e.g., Peebles & Ratra 2003 for recent review). The models with a time-varying cosmological term can be classified into three groups: i) (light) scalar field models, ii) explicit time decaying cosmological term models, and iii) modified equation of state models. In the present work, we direct our attention to the second group, i.e., the decaying cosmological term models. In order to assess the models of this kind and constrain their parameters, we take up the galaxy number counts versus their apparent magnitudes relation, or the N-m relation, and the observed CMB spectra.

The N-m relation has been and still is one of the most practicable cosmological tests (Yoshii & Takahara 1988). However, it is inflicted by the so-called faint blue galaxy problem (FBGP), in which the number counts of galaxies beyond 24 mag observed in the B-band are larger by a factor of five or more than those theoretically predicted using the standard cosmological models (Ellis 1997). The usual means to circumvent this problem is to take into account the effect of either galaxy merging, chemical evolution, a possible upturn of the faint end of the galaxy luminosity function, or an underestimation of the number of dwarf galaxies (Ellis 1997).

In this work, we examine to what extent we can alleviate or resolve the FBGP by employing the Λ decaying cosmological models coupled with the effect of galaxy merging, presumably the most influential factor for the N-m relation.

Nevertheless, a determination of the cosmological parameter values in comparison with the observed CMB spectra is now considered to be the most reliable procedure (Spergel et al. 2003), so that we have formulated the necessary equations to compute the CMB spectra for the Λ-decaying models.

II. COSMOLOGICAL MODELS

(a) Basic Equations

The energy-momentum tensor appearing in the Einstein's field equation is consisted of two parts, viz., the one due to the cosmological constant Λ, which is defined as

$$T^{(\Lambda)}{}_{\mu\nu} = \frac{c^2\Lambda}{8\pi G} g_{\mu\nu}, \quad (1)$$

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and the other due to the matter including that for the CDM, ${T^{(c)}}_{\mu\nu}$. Here we assume that the sum of ${T^{(\Lambda)}}_{\mu\nu}$ and ${T^{(c)}}_{\mu\nu}$ is to be conserved, so that we have

$$\{{T^{(c)}}_{\mu\nu} + {T^{(\Lambda)}}_{\mu\nu}\}_{;\nu} = 0, \qquad (2)$$

(b) Solutions of Einstein Equation

The Einstein's field equation yields the following evolution equation for the scale factor a relevant to the cosmological models of our interest:

$$\begin{aligned} \frac{\mathrm{d}^2 a}{\mathrm{d}\tau^2} &= -\frac{1}{2a}\left(\frac{da}{d\tau}\right)^2 - \frac{1}{2a}\Omega_{K,0} - \frac{1}{2a^3}\Omega_{\mathrm{rad},0} \\ &\quad + \frac{3a}{2}\Omega_{\Lambda,0}\frac{\Lambda_0}{\Lambda}, \end{aligned} \qquad (3)$$

with the proper time in units of the Hubble time defined as

$$\tau \equiv H_0 t, \qquad (4)$$

where $\Omega_{K,0}$, Ω_{rad} and, Ω_Λ are the density parameters due to the curvature of the space, radiation, and the Λ-term, respectively. The suffix 0 attached to each quantity designates its present value as usual. The conservation condition for the energy-momentum tensor due to the CDM and the Λ-term (Eq.(2)) then leads to the following energy conservation law:

$$\frac{d\rho_c}{d\tau} + 3\frac{1}{a}\frac{da}{d\tau}\rho_c = -\frac{d\rho_\Lambda}{d\tau}, \qquad (5)$$

where ρ_c and ρ_Λ are the energy densities of the CDM and the Λ-term, respectively.

(c) Functional Forms for Λ-Term Decay

To obtain a closed set of equations., we need the functional forms to represent the Λ-term decay, for which we adopt the following based on Overduin & Cooperstock (1998):

Type I : $\Lambda = 3H_0^2\Omega_{\Lambda,0}(\tau_0/\tau)^l/c^2$
Type II : $\Lambda = 3H_0^2\Omega_{\Lambda,0}a^{-m}/c^2$
Type III : $\Lambda = 3H_0^2\Omega_{\Lambda,0}(H/H_0)^n/c^2$,

However, it turns out that these three types tend to produce qualitatively similar results, and hence we shall primarily concerned about the Type I. Note that the Type III gives rise to a big bang event irrespective of the value of n, whereas the Types I and II would not necessarily cause any depending on the values of l and m even for the spatially flat case.

(d) Cosmological Parameters

Because of the time variation of the Λ-term, we must redefine the density parameters used in Eq.(3). For the Type I models, we then get

$$\tilde{\Omega}_\Lambda = \Omega_{\Lambda,0}\frac{H_0^2}{H(\tau)^2}\left(\frac{\tau_0}{\tau}\right)^l, \qquad (6)$$

$$\tilde{\Omega}_{\mathrm{m}} = \Omega_{\mathrm{m},0}\frac{H_0^2}{H(\tau)^2} \times \left(1 - \frac{\Omega_{\Lambda,0}}{\Omega_{\mathrm{m},0}} l\tau_0^l \int_\tau^{\tau_0} a^{3\gamma}(\tau)\tau^{-l-1}\mathrm{d}\tau\right), \qquad (7)$$

$$\tilde{\Omega}_K = \Omega_{K,0}\frac{H_0^2}{a^2 H(\tau)^2}, \qquad (8)$$

III. COSMOLOGICAL TESTS

In order to investigate the viability of the Λ-decaying models, we employ the counting of the surface number density of galaxies in the sky as a function of the apparent magnitude, or the N-m relation and the CMB angular spectrum as probes.

(a) N-m Relation

Many observations have been performed to construct the N-m relation reaching down to $15 \sim 30$ mag (e.g., Metcalfe et al. 2001). We compute theoretical N-m relations closely following the procedure delineated by Yoshii & Takahara(1988): we use the SEDs of five morphological Hubble types (E/S0, SaB, SBc, Scd, Sdm). As an evolutionary model of the SEDs, we adopt Arimoto and Yoshii (1987). For simplicity, the time dependence of the SEDs are assumed to be the same for all of the Hubble types.

Unlike Yoshii and Takahara(1988), however, we take into account the effect of galaxy number evolution of the following form (Rocca-Volmerange 1990):

$$\phi(M,z) = \phi(M,0)(1+z)^\eta, L(z) = L(0)(1+z)^{-\eta}, \qquad (9)$$

Using the ratio of the number of merging galaxies to the total number of galaxies observed, we obtain the number-redshift relation of the following form:

$$N(z) = \frac{N(z=0)}{\Pi_{k=1}^n\{1 - f_{\mathrm{mg}}(z_k)\}}, \qquad (10)$$

Here, $N(z)$ is the number counts of galaxies with the redshift z, f_{mg} is the number ratio of the merging galaxies relative to the total number observed (Patton 2002), n is the cycle number of mergings that have taken place since the epoch corresponding to the redshift z_{mg} when the apparent merger began. Note that by the term 'apparent merger', we simply mean a pair of galaxies coming close to each other, and not a dynamical merging of the two (Barnes 1988).

Using the assumption mentioned above and putting $N(z)/N(0)=\phi(z,M)/\phi(0,M)$, we have derived the merging parameter η by means of the least squares method, and their iso-contours are shown in Fig. 1 as functions of $\Omega_{\Lambda,0}$ and the decay parameter l. It should

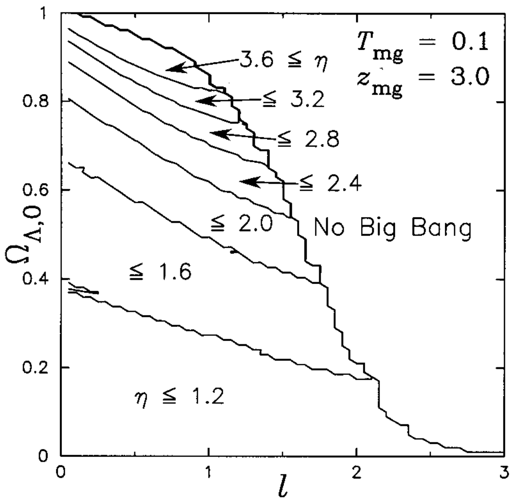

Fig. 1.— The iso-lines of the merging parameter η as functions of l and Ω_Λ. Also shown is the domain in which the universe does not undergo any big bang event.

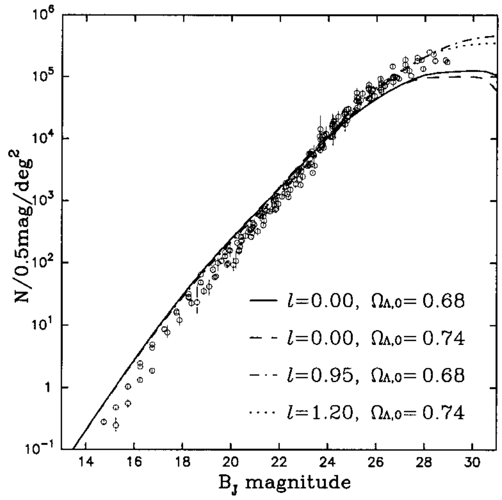

Fig. 2.— Comparison of the theoretical N-m relations with the representative observational data of Metcalfe (2001). The ordinate is the galaxy number count, while the abscissa is the B_J-band mag. The best-fit parameter values obtained from the χ^2 tests of the computed N-m relations as well as the corresponding curves are shown in the diagram.

be mentioned that the age of the universe grows with the value of $\Omega_{\Lambda,0}$, thereby increasing the frequency of galaxy merging, which in turn increases the value of η.

(b) CMB Anisotropy

We have carried out sets of computations of the CMB anisotropy spectrum using a public domain computer code CMBFAST (Seljak & Zaldarriaga 1996): for this purpose, we have formulated the time evolution of the synchronous gauge tensors to find the density perturbation, and incorporated them into the code. For instance, considering Eq.(2), we find the scalar component of the CDM density fluctuation to be

$$\delta_c' = \frac{\bar{\rho}_\Lambda'}{\bar{\rho}_c}\delta_c - \frac{1}{2}h', \qquad (11)$$

where $\delta_c(\equiv \delta\rho_c/\bar{\rho_c})$ is the first-order perturbation of ρ_c, and h is the trace part of the metric perturbation in the synchronous gauge. It should be mentioned that the Boltzmann equation remains unchanged because of Eq.(2) coupled with the fact that the CDM exhibits only the gravitational interaction.

IV. COMPARISON WITH OBSERVATIONAL DATA

To systematically assess the results of the computed N-m relations and the CMB spectra in comparison with the observational data, we have applied a likelihood analysis based on the χ^2 test, which is defined as

$$\chi^2 \equiv \sum_i \left(\frac{N_{i,\mathrm{cal}} - N_{i,\mathrm{obs}}}{\sigma_i}\right)^2, \qquad (12)$$

where $N_{i,\mathrm{cal}}$ is a theoretical prediction, $N_{i,\mathrm{obs}}$ is the corresponding observed value, and σ_i is its error. We have also computed the tolerance regions of the parameter space based on $\Delta\chi^2(=\chi^2 - \chi^2_{min})$ as shown later.

As for the N-m relation, Fig. 2 shows that the Λ-decaying models are definitely in better agreement with the observational data especially in the the region for 24 mag or fainter in comparison with the the F-L models.

In the case of the CMB spectrum, the effect of Λ variation manifests itself in the region for $l < 40$ as can be clearly noticed in Fig. 3.

Fig.4 indicates the 1σ-domain on the $\Omega_{\Lambda,0}$ vs. l-plane based on both the N-m relation and the CMB spectrum. Also shown in the diagram are the isochrones of the resulting ages of the universe. It is interesting to note that none of the F-L models selected on the basis of the N-m relation analysis fall on this 1σ domain.

V. DISCUSSION

In this work, we have successfully derived the value of the galaxy merging parameter η in the form dependent on cosmological model parameters as shown in Fig. 1. Our results are rather consistent with the values of η estimated by various investigators from observations of galaxies and/or numerical simulations. Note that for a given value of the timescale for an apparent merging event T_{mg}, η depends critically on the number of merging cycles undergone to the present day (z=0) since the time of initial galaxy merging (z=z_{mg}). Since this number of cycles increases with the age of the universe, so does the value of η.

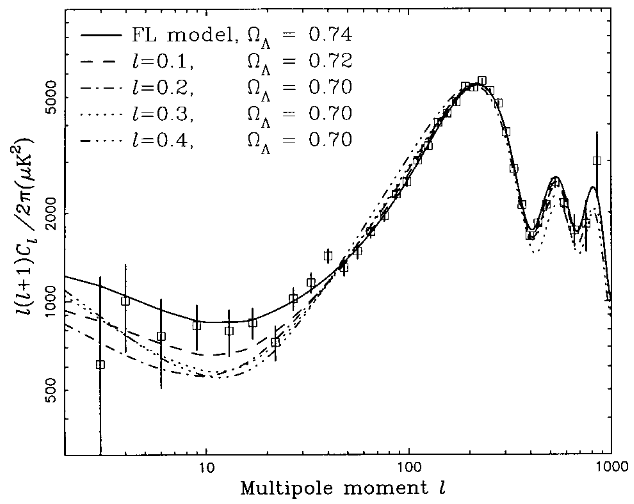

Fig. 3.— Comparison of the computed CMB angular spectra with the WMAP data. The ordinate is the angular correlation function C_l, and the abscissa is the multipole moment l. The best-fit parameter values and the corresponding curves obtained from the χ^2 tests are shown in the diagram.

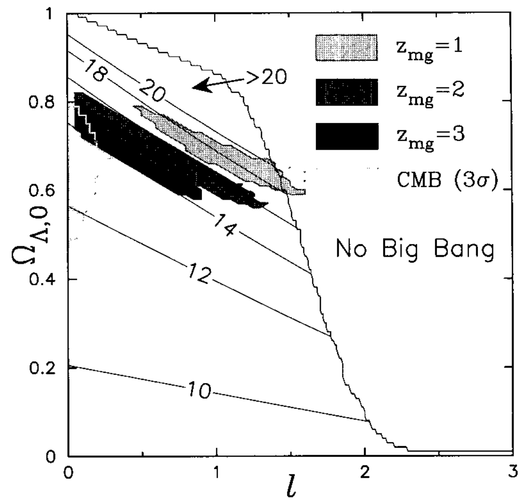

Fig. 4.— Comparison between the 1σ confidence region obtained from the N-m relation analysis and that from the CMB spectral analysis. Also shown are the isochrones of the ages of the model universe.

The usual interpretation of the FBGP relies either on the possibility of an underestimation of the number of brown dwarf galaxies, the evolutionary effects of the SED and/or the luminosity functions of galaxies, or on a possible presence of an upturn of the number of galaxies in the faint magnitude region. However, we have shown that we can reasonably well account for this FBGP by introducing cosmological models with slowly decaying Λ-term together with the effect of galaxy merging, the most influential and conceivable factor of all. The high galaxy number counts in the faint magnitude region result from our models, because the comoving volumes per unit redshift tend to increase as the age of the universe becomes larger due to the higher Λ-term allowed in the past. The fact that the N-m relations produced by the F-L models (l=0) fall outside the 1σ domain of Fig. 4 lends further support to the possible existence of a slowly decaying Λ-term ($l < 0.7$).

Let us now turn to the CMB spectrum analysis. As indicated in Fig. 4, the effect of the Λ-term decay shows up rather prominently in large spatial scales corresponding to the multipole moments l less than about 40. In our models, the growth of any density perturbation of the Newtonian scale tends to be suppressed, so that the presence of larger scale perturbations are required in the past to attain the present day density contrasts. Under such circumstance, the temperature perturbations of the large spatial scales are then enhanced through the Sachs-Wolfe effect.

Fig. 4 indicates that the models with $0.1 \leqq l \leqq 0.4$ and $0.7 \leqq \Omega_{\Lambda,0} \leqq 0.8$ satisfactorily reproduce both the N-m relation and the CMB spectrum observations. It must be mentioned that all of these models are free from the 'age problem', since their ages exceed 14 Gyr, a lower limit for the cosmic age inferred from some Uranium datings (Schatz et al. 2002).

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