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Summary of cosmology workshop

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Abstract. Cosmology is passing through a golden phase of rapid advance. The cosmology workshop at ICGC-2004 attracted a large number of research contributions to diverse topics of cosmology. I attempt to classify and summarize the research work and results of the oral and poster presentations made at the meeting.

Keywords. Cosmology; observations; theory.

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1. Introduction

Recent developments in cosmology have been largely driven by huge improvement in quality, quantity, and the scope of cosmological observations. While the observations have constrained theoretical scenarios and models more precisely, some of these observations have thrown up new challenges to theoretical understanding and others have brought issues from the realm of theoretical speculation to observational verification. The contributions to the workshop on cosmology at the ICGC-04 reflect this vibrancy in the field.

In this article, I summarize both the oral and poster presentations made at the workshop. The two short talks on cosmology by S Majumdar and M Kaplinghat are included as separate articles in this issue. Other contributions have been divided into five broad themes. A brief introduction to each of the themes in the context of the ICGC-04 contributions is given in this section. Sections 2–6 summarize the contributions in each of the following five themes.

1.1 *Structure formation*

The formation of large-scale structure in the universe has been a very important aspect of modern cosmology. The 'standard' model of cosmology must not only explain the dynamics of the homogeneous background universe, but also (eventually) satisfactorily describe the perturbed universe – the generation, evolution and finally, the formation of large-scale structures in the universe. Recently, large red-shift surveys such as the Las Campanas red-shift survey (LCRS), 2 degree field (2dF) and SDSS have mapped out the distribution of matter in the universe [1]. In conjunction with other observations, these surveys have contributed to the community-wide effort in cosmological parameter estimation [2,3].

There exist a number of systematic effects that arise in extracting cosmological information from red-shift surveys. Contributions to ICGC-04 dealt with some such issues. The distances to distant galaxies are measured in terms of red-shifts. It is important to understand in finer detail the mapping from the red-shift space to real space known as the red-shift space distortions. Galaxies are just tracers of the underlying distribution of dark matter in the universe. Understanding the 'bias' in translating from the distribution of galaxies to the dark matter remains an important area of research. Finally, to compare observed large-scale structures with theory, it is important to devise statistics that can distinguish true morphological features from chance alignments in terms of robust statistics.

1.2 *Cosmic microwave background anisotropy*

The cosmic microwave background has played a crucial role in cosmology. In the past decade, the measured anisotropy in the temperature of the cosmic microwave background has spearheaded the ongoing transition of cosmology into a precision science [4]. In particular, the exquisite measurements of the angular power spectrum of CMB fluctuations have played a crucial role in identifying an emerging concordance cosmological model. The high quality of data, the good theoretical understanding of CMB anisotropy and polarization, and the relatively unambiguous connection between the two have encouraged a number of researchers to use the CMB data to probe the universe beyond estimating a set of cosmological parameters. Contributions in ICGC-04 have observationally addressed theoretical assumptions such as the statistical isotropy of CMB fluctuations, scale invariance in the primordial power spectrum, and parity conservation in electromagnetic interactions. Efforts to mine the CMB deeper pose data analysis challenges in particular to account for the finer systematic effects in observations, such as accounting for the non-circularity of the experimental beam response function presented in the meeting.

1.3 *Dark energy*

Observations of the luminosity distance using high red-shift supernovae Ia have indicated that the present expansion rate of the universe may be accelerating. Within the Friedman–Robertson–Walker cosmology (and general relativity), this implies that the present matter content of the universe is dominated by dark energy – a yet unidentified, exotic matter with negative pressure. Modeled as an ideal hydrodynamic fluid with equation of state w ($p = w\rho$), the acceleration of the universe implies that $w < -1/3$. Phenomenologically, the simplest model of dark energy is the cosmological constant (or, vacuum energy) where $w \simeq -1$ is consistent with data. Concordant results are also obtained from the formation of large-scale structures in the universe by combining the exquisite measurements of the angular spectrum of CMB anisotropy with recent measurements of the power spectrum of density perturbation from large red-shift survey. Various combinations of the CMB, high-z SN 1a and galaxy red-shift survey data constrain $w \lesssim -0.8$. If the strong energy condition $w \geq -1$ is not imposed as prior then the likelihood appears to spill over and peak in the $w < -1$ regime. Dark energy with $w < -1$, is rather unusual, if interpreted in terms of a hydrodynamic fluid or scalar field energy density. A number of contributions in the workshop are theoretical models and scenarios attempting to explain dark energy with $w < -1$. An interesting possibility, which is explored in a contribution to this meeting is to recover the evolution of the equation of state, w, with red-shift from the data without imposing the strong energy condition.

1.4 *Early universe and extra dimensions*

In the hot Big Bang scenario, the present universe is inescapably linked to the ultra-high energy physics of the early universe. It is fair to say that cosmology will remain incomplete without adequate understanding of the early universe. The initial singularity of the Big Bang remains an enigma that time and again attracts imaginative solutions. The recent proposal to 'cap' the initial FLRW model with a static Einstein universe is explored in the context of higher derivative extensions of gravitation in one of the workshop contributions. The primordial perturbations believed to be generated during inflation is one of the most promising probe of physics at ultra-high energies, possibly, even up to trans-Planckian energy scales. A contribution here has explored the signature of trans-Planckian physics that respects Lorentz symmetry. Besides scalar density perturbations, the gravity wave background from inflation is an important clue to the early universe physics. For example, overproduction of gravity waves can severely constrain some brane-world inflation models with steep inflaton potential, unless, as shown in one of the contributions, the mechanism of reheating is reworked. Although cosmic defects produced during the phase transition in the early universe seem unlikely to be the dominant source of primordial perturbations, the possibility that they play a sub-dominant role in structure formation is still an open possibility. A formalism for studying perturbations from defects was presented in the workshop.

In the past few years, the possibility of large extra dimensions has caught the fancy of both theoretical high energy physicists and cosmologists. These brane-world scenarios, where the observed $3+1$ dimensions and all interactions other than gravity reside on a brane embedded in a higher dimension, are usually motivated by string theory. These scenarios, initially invoked to address the hierarchy problem of disparity between the SUSY breaking and the Planck scale, have been used and studied in a variety of other contexts. The observed accelerating universe and dark energy have been linked to brane-world scenario. Construction of stable brane configurations that may do this was discussed in the meeting. Brane-world scenarios can have interesting consequences for inflation as shown by some contributions in the meeting.

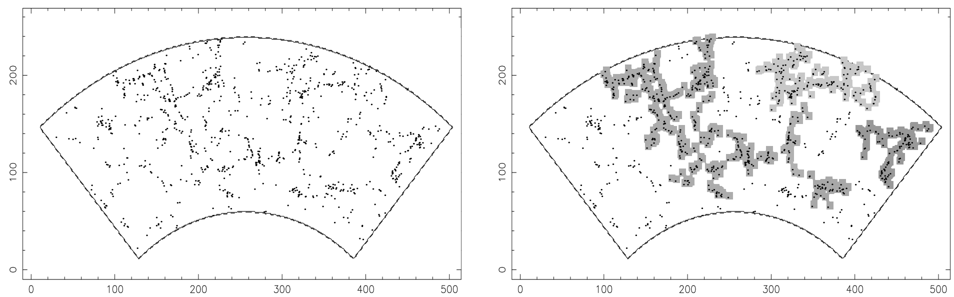

Figure 1. The distribution of galaxies in a volume limited subsample of the LCRS slice at declination −3 is shown in the figure on the left. The figure on the right shows a coarse grained distribution of galaxies. Some of the largest clusters are identified and highlighted. These filamentary clusters can be shown to be statistically significant.

1.5 *Alternative approaches*

Despite the emergence of the concordant cosmological model, there is enough width left in cosmology for exploring radically different ideas. The reason is that recent advances in cosmology have been more on the phenomenological, rather than on the conceptual aspects. Alternative ideas may be the key to some of the intriguing puzzles of contemporary cosmology. While many of these ideas face increasingly difficult challenges to match observations, it is important to allow them to be judged by observations, and not by theoretical prejudices.

2. Large-scale structures in the universe

The morphology of the structures in the large-scale distribution of matter in the universe seen in the recent red-shift surveys has to be quantified with statistically robust measures. One of the most striking visual features in red-shift surveys is that galaxies appear to be distributed along filaments that are interconnected to form a network which extends across the entire survey like a cosmic web. Figure 1 shows the distribution of galaxies in one of the slices of the Las Campanas red-shift survey (LCRS) and highlights the filamentary structures that appear within it. S Bharadwaj reported a novel analysis (with S Bhavsar and J Sheth) of the Las Campanas red-shift survey (LCRS) to determine the extent to which the filaments are genuine, statistically significant features as against the possibility of their arising from chance alignments [5]. They find that one of the LCRS slices has statistically significant filamentary features spanning scales as large as 70–80h^{-1} Mpc, whereas filaments spanning scales larger than this are not statistically significant (see figure 1). For the five other LCRS slices, filaments of lengths 50–70h^{-1} Mpc are statistically significant, but not beyond. The reality of the 80h^{-1} Mpc filamentary features in the LCRS slice make them the longest coherent features presently known.

The galaxy two-point correlation function measured from red-shift surveys exhibits deviations from the predictions of linear theory on scales as large $20h^{-1}$ Mpc where we expect linear theory to hold. Any attempt at analysing the anisotropies in the red-shift correlation function and determining the linear red-shift distortion parameter requires these effects to be taken into account. Usually these non-linear effects are attributed to galaxy random motions, and a heuristic model where the linear red-shift correlation is convolved with the random pair-wise velocity distribution function is used. S Bharadwaj reported investigations (with B Pandey) of a different model which is derived under the assumption that linear theory holds in real space, and which takes into account all non-linear effects that are introduced by the mapping from the real to red-shift space [6]. They test this model using N-body simulations and find that the pair-wise velocity dispersion predicted by all the models considered are in excess of the values determined directly from the N-body simulations. This indicates a shortfall in the understanding of the statistical properties of peculiar velocities and their relation to red-shift distortion.

The distribution of galaxies is believed to trace the underlying distribution of dark matter quantified by a bias factor. J Bagla presented results from a study (with S Ray) of the moments of counts in cells for a set of models in real space and red-shift space. A comparison of the moments for the entire distribution as well as for regions with over-density above a certain threshold offers insight into the differences between clustering of galaxies and dark matter. They focus mainly on non-linear scales. Tree-PM simulations were used to generate the distribution of particles. They find that at non-linear scales the bias for the second moment of the distribution is scale dependent. The scale dependence is such that the variation of σ with scale is the same for all the models studied here. The amplitude of σ is very different for these models, and models with a more negative index have a larger linear bias. Skewness for different models studied here is very different for the entire distribution and has expected values for the power law models in the linear as well as the extreme non-linear regime. Skewness for over-dense regions in all of these models is the same in red-shift space in the non-linear regime. This startling result implies that in the non-linear regime the skewness of the distribution of particles in over-dense regions is not sensitive to initial conditions.

S Ray reported the development of a parallel version of the Tree-PM code optimized for cluster computing. The Tree-PM method is a hybrid method for cosmological N-body simulations that uses both the tree- and mesh-based methods to compute force. The force is divided into two parts and mesh method is used to compute the long-range force and the tree method is used for computing the short-range force [7]. They use domain decomposition for distributing the computation of short-range force on a set of processors. Functional decomposition is used to assign the tasks for computing long-range and short-range forces. They also introduce optimizations to reduce the communication overheads. The present version of the code scales almost linearly up to 34 processors for simulations with 1.6×10^7 particles. Time taken per step per particle for these simulations is about 18 μs.

J Prasad reported initial results on a study (with S Ray and J Bagla) of the interaction of fluctuations at very different scales by simulating collapse of a plane wave with varying amount of substructure [8]. The substructure is modeled as power in a narrow range of scales at $k_{\rm s} \gg k_{\rm l}$, where $k_{\rm l}$ is the wave number for the long-range wave mode. The substructure is along three directions whereas the plane wave collapses along one direction. In the absence of substructure they find the usual structure where a pancake forms and has an increasing number of streams as one nears the center. In the presence of small-scale fluctuations, they find that the size of the multi-stream region shrinks by a small amount as the amplitude of substructure is increased. They believe that this is due to the transfer of kinetic energy in directions transverse to the plane wave due to interaction of clumps. The plane wave strongly influences the evolution of small-scale fluctuations. Formation of clumps is suppressed in the regions made under-dense by the plane wave, whereas merging in the over-dense regions leads to a rapid growth of fluctuations at small scales.

A study of density perturbations of a cosmological scalar field addressing the possibility of using the instability mechanism of Jeans theory, to form self-gravitating configurations from a real scalar field approach to Jeans mass calculation was presented by Joy and Kuriakose [9]. They consider a massive scalar field arbitrarily coupled to a gravitational background, with the stress–energy tensor expectation values of the quantum field fluctuations computed in a coherent state. It is shown that the self-interaction of the scalar field influences the character of instability and the value of the Jeans wave number is altered by the effects of self-interaction.

The observations of clustering in the distribution of HI can be used to study large-scale structures at high red-shift. S Bharadwaj presented a study of the possibility of using giant meter-wave radio telescope (GMRT) to probe large-scale structures in the universe at high red-shift by studying fluctuations in the red-shifted 1420 MHz emission from the neutral hydrogen (HI) [10]. The study focuses on the cross-correlations between the visibility signal measured at different baselines and frequencies in radio interferometric observations. They show that the visibility correlations directly probe the power spectrum of HI fluctuation, and present analytic estimates of the signal expected in two of the GMRT bands centered at 325 and 610 MHz. They also simulate GMRT observations including the expected HI signal, galactic and extragalactic foregrounds and system noise. The preliminary results indicate that it may be possible to detect the HI signal in around 1000 hours of observations.

3. Cosmic microwave background anisotropy

The statistical expectation values of the temperature fluctuations of cosmic microwave background (CMB) are assumed to be preserved under rotations of the sky. The assumption of statistical isotropy (SI) of the CMB anisotropy should be observationally verified since detection of violation of SI could have profound implications for cosmology. The bipolar power spectrum (BiPS) has been recently proposed as a measure of violation of statistical isotropy in the CMB anisotropy map [11]. A Hajian reported results from a BiPS analysis (with T Souradeep) statistical isotropy of the CMB anisotropy maps obtained from the first year of data from the WMAP satellite [12]. The CMB maps were smoothed by a family of window functions to isolate and test the SI in the different regions of the multipole space. Figure 2 shows the BiPS of three different CMB maps obtained from the WMAP data filtered to retain power with $20 \lesssim l \lesssim 45$. Preliminary results indicate that the CMB anisotropy maps from WMAP do not strongly violate statistical isotropy.

The non-circularity of the experimental beam has become progressively important as CMB experiments strive to attain higher angular resolution and sensitivity. Recent CMB experiments such as ARCHEOPS, MAXIMA, WMAP have significantly non-circular beams. Future experiments like Planck are expected to be even more seriously affected by non-circular beams. S Mitra reported a study of the effect of a non-circular beam on CMB power spectrum estimation (done with A Sengupta and T Souradeep) [13]. They compute the bias introduced in estimating the power spectrum. They construct an unbiased estimator using the bias matrix. The covariance matrix of the unbiased estimator is computed for non-rotating smooth beams. The WMAP beam maps are fitted and shown to be significantly non-circular. The effect of a non-circular beam on power spectrum estimate is calculated for a CMB map made by an experiment with a beam which is non-circular at a level comparable to the WMAP beam.

Cosmological parameters estimated from CMB anisotropy assume a specific form for the spectrum of primordial perturbations believed to have seeded the large-scale structure in the universe. Accurate measurements of the angular power spectrum C_l over a wide range of multipoles from the Wilkinson microwave anisotropy probe (WMAP) [14] has opened up the possibility to deconvolve the primordial power spectrum for a given set of cosmological parameters. A Shafieloo presented results from a work (with T Souradeep) on the direct estimation of the primordial power spectrum from WMAP measured angular power spectrum of CMB anisotropy using an improved Richardson–Lucy deconvolution algorithm [15]. The most prominent

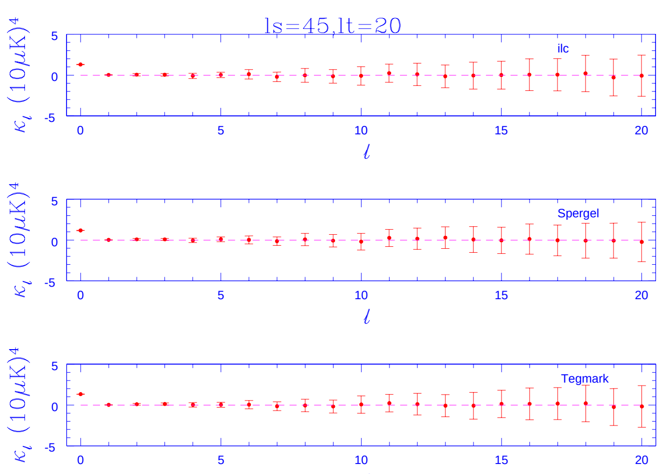

Figure 2. The bipolar power spectrum of three different CMB maps obtained from the WMAP data filtered by window function to retain power only on multipole values in the range $20 \lesssim l \lesssim 45$. The maps appear to be statistically isotropic.

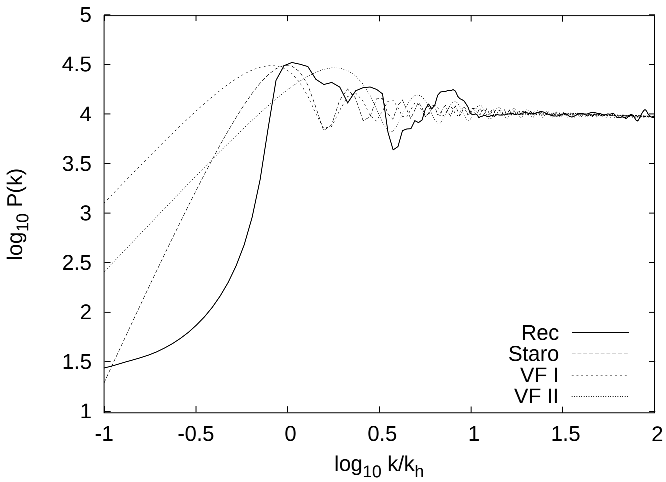

Figure 3. The $P(k)$ recovered from the WMAP is plotted (solid). The predictions of two simple theoretical scenarios mentioned in the text that remarkably match the gross features of the infra-red cut-off in the recovered spectrum are also shown in the figure.

feature of the recovered $P(k)$, shown as the solid curve in figure 3, is a sharp, infra-red cut-off on the horizon scale. It also has a localized excess just above the cut-off which leads to great improvement of likelihood over the simple monotonic forms of model infra-red cut-off spectra considered in the post WMAP literature. The form of infra-red cut-off is robust to small changes in cosmological parameters. Remarkably similar forms of infra-red cut-off is known to arise in very reasonable extensions and refinements of the predictions from simple inflationary scenarios. In figure 3, the curve labeled 'staro' is the primordial spectrum when the inflaton potential has a kink – a sharp, but rounded, change in slope [16] and two curves labeled 'VF' are the modification to the power spectrum from a pre-inflationary radiation dominated epoch [17].

In addition to temperature fluctuations, the CMB photons coming from different directions have a random, linear polarization. The polarization of CMB can be decomposed into E part with even parity and B part with odd parity. Besides the angular spectrum C_l^{TT}, the CMB polarization provides three additional spectra, C_l^{TE}, C_l^{EE} and C_l^{BB} which are invariant under parity transformations. The level of polarization of the CMB being about a tenth of the temperature fluctuation, it is only very recently that the angular power spectrum of CMB polarization field has been detected. The degree angular scale interferometer (DASI) has measured the CMB polarization spectrum over limited band of angular scales in late 2002 [18]. The WMAP mission has also detected CMB polarization [19]. WMAP is expected to release the CMB polarization maps very soon.

Parity violating interactions open up the possibility for measuring non-zero C_l^{TB} and C_l^{EB} power spectra. One such possibility is a parity-violating interaction of the antisymmetric tensor Kalb–Ramond (KR) gauge field and the electromagnetic field [20]. P Majumdar presented results that show that parity forbidden C_l^{TB}

spectra can arise due to such interactions [21]. The coupling also leads to an effective time-dependent fine-structure constant in the current cosmological epoch, pointing thereby to possible correlations between these two disparate phenomena.

4. Accelerating universe and dark energy

Improvements in the measurements of luminosity distance as a function of red-shift from high red-shift SN 1a may eventually allow direct recovery of the evolution of the equation of state of the dark energy component in the universe at low red-shifts. U Alam reported results from a new study (with V Sahni, T D Saini, A A Starobinsky) where dark energy parameters are reconstructed from the latest data set of 194 supernovae [22,23] without any priors on the equation of state w [24]. They find that dark energy evolves rapidly and metamorphoses from dust-like behavior at high red-shift ($w \simeq 0$ at $z \sim 1$) to a strongly negative equation of state at present ($w \lesssim -1$ at $z \simeq 0$), as shown in figure 4. Dark energy metamorphosis appears to be a robust phenomenon which manifests for a large variety of supernova data samples provided one does not invoke the weak energy prior $\rho + p \geq 0$. These results indicate that dark energy with a rapidly evolving equation of state may provide a compelling alternative to a cosmological constant if data are analysed in a prior-free manner.

Typical scalar field models do not provide a scenario with $w < -1$. A radical possibility is to consider a phantom scalar field which has negative kinetic energy and violates null dominant energy condition – now popularly referred to as a 'phantom field'. P Singh, reported work (with M Sami and N Dadhich) on a model of phantom field motivated S-brane dynamics using the supernova Ia observations to constrain the parameters of the model [25]. They find that the model fits high red-shift supernova data fairly well for a large range of parameters and favors a $w < -1$.

The negative kinetic energy term in the Lagrangian of a phantom field is not very well-motivated and also suffers from severe instability. S Das reported work on explaining dark energy with $w < -1$ in the Brans–Dicke theory of gravity. The results indicate that $w < -1$ could be obtained if the gravitational constant is slowly varying with time in a canonical Brans–Dicke theory of gravity without conflict with the solar system constraints.

The de Broglie–Bohm approach to quantum mechanics helps to demonstrate that the Wheeler–De Witt equation is equivalent to the corresponding classical equation for a special potential, i.e., the universe is both quantum and classical at the same time. M John presented a comparison of prediction of this approach with observations of high-red-shift supernova data. They claim that at the observational level, this special solution to cosmology is as good as the conventional matter-Λ cosmologies.

5. Early universe and brane world

Curing the initial singularity of standard FLRW models has been a long standing endeavor of cosmologists. Recently, Ellis and Maartens [26] studied a class of

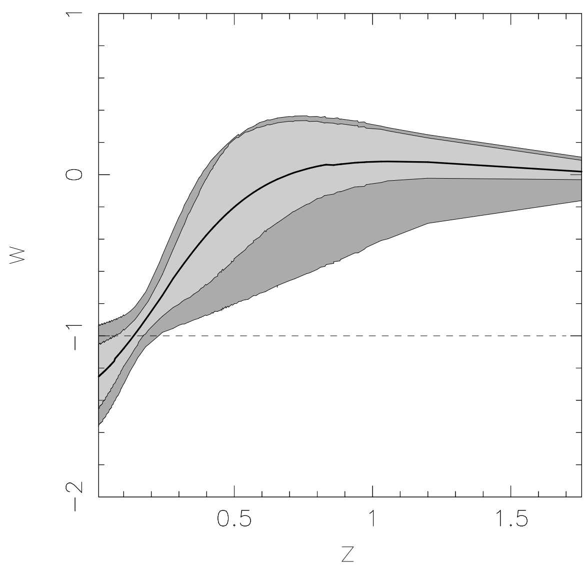

Figure 4. The evolution of $w(z)$ with red-shift for $\Omega_{0\mathrm{m}} = 0.3$. The reconstruction is done using a polynomial fit to dark energy, for the latest HZT sample of 194 type Ia SNe. The thick solid line shows the best-fit, the light gray contour represents the 1σ confidence level, and the dark gray contour represents the 2σ confidence level around the best-fit. The dashed line represents ΛCDM. No priors are assumed on $w(z)$.

cosmological models in which there is no singularity, no beginning of time and no horizon problem. The universe starts out as an almost static universe and expands slowly, eventually evolving into a hot Big-Bang era. An example of this scenario is a closed model with a minimally coupled scalar field, with a special self-interaction potential. This potential may be obtained after a conformal transformation of the metric of a higher derivative theory. S Mukherjee reported a detailed study (with B Paul, S Maharaj and A Beesham) of higher derivative theories, including a cosmological constant and a quadratic term (R^2) in the Lagrangian density, where R is the scalar curvature. The field equations are analysed to determine the general characteristics of the evolution and some quantities of cosmological interest are calculated. The results are compared with those of the proposed emergent universe. The stability of the results have been studied by considering an R^3 term as a perturbation of the quadratic Lagrangian density. The possibility of a quantum creation of the emergent universe in quantum cosmology has also been considered.

B Modak presented application of Noether symmetry as a powerful tool to find the solution of the field equations for scalar tensor theory including curvature quadratic term. A few physically reasonable solutions like power-law inflation were presented.

Quintessential inflation describes a scenario in which both inflation and dark energy are described by the same scalar field. In conventional brane-world models of quintessential inflation, gravitational particle production is used to reheat the universe. This reheating mechanism is very inefficient and results in an excessive production of gravity waves which can even violate nucleosynthesis constraints and invalidate the model [27]. M Sami described a new method of realizing quintessential inflation on the brane in which inflation is followed by 'instant preheating'. The larger reheating temperature in this model is shown to result in a smaller amplitude of relic gravity waves which is consistent with nucleosynthesis bounds. The relic gravity wave background has a 'blue' spectrum at high frequencies and is a generic by-product of successful quintessential inflation on the brane.

S Biswas presented a study of fermion particle production in early universe using the complex trajectory WKB method developed earlier. They study the particle production in periodic potential, generally used in inflationary cosmology. Using this method, they recover results obtained in literature earlier, such as [28].

Due to the tremendous red-shift that occurs during the inflationary epoch in the early universe, it has been realized that trans-Planckian physics may manifest itself at energies much lower than the Planck energy. The presence of a fundamental scale suggests that local Lorentz invariance may be violated at sufficiently high energies. However, certain astrophysical observations seem to indicate that local Lorentz invariance may be preserved to extremely high energies. This suggests considering models of trans-Planckian effects that preserve local Lorentz invariance. L Sriramkumar (with S Shankaranarayanan) presented one such model and evaluated the spectrum of density perturbations during inflation in the model [29]. They find that, in the case of exponential, as well as, power-law inflation, the corrections to the standard scale-invariant perturbation spectrum (in the Bunch–Davies vacuum) turn out to be small.

Several promising models (e.g. D-brane inflation) of high-energy physics inspired inflationary scenarios terminate with the production of topological defects. In order to investigate the observational implications of such models, G Amery described a complete 4-d synchronous gauge formalism that may include non-zero curvature and cosmological constants, multiple scalar fields, and topological defects or other active sources [30]. The formalism provides a concise and geometrically sound description of energy–momentum conservation on all scales, from which appropriate initial conditions may be obtained. They present preliminary investigations of the possible contributions by active sources to the CMB data.

B C Paul presented a study of chaotic inflationary universe in a brane-world model [31]. They study the evolution of the universe with a minimally coupled self-interacting scalar field when the kinetic energy dominates the potential energy and vice versa and obtain cosmological solutions which permit inflation. In four-dimensional gravitation (GTR), the initial value of the inflaton field $\phi_i \gtrsim \text{few}\, M_4$ required for a sufficient inflation is physically unrealistic. In contrast, they show that in brane-world model sufficient inflation may be obtained even with an initial scalar field having value less than the usual four-dimensional Planck scale.

H K Jassal reported on some cosmological consequences of the five-dimensional, two-brane Randall–Sundrum brane-world scenario. The radius of the compact extra dimension is taken to be time dependent. Integrating over extra dimensions, the four-dimensional action reduces to that of scalar tensor gravity. The radius of the extra dimension stabilizes to a non-zero separation of branes very quickly. A simple quadratic potential with minimum at zero leads to stabilization at comparable level but also allows for accelerated expansion. After stabilizations the potential does not play any other role except contributing the dark energy component at later times. It is shown that the requirements for solving the hierarchy problem and getting an effective dark energy can be satisfied simultaneously.

6. Alternative views and ideas in cosmology

If confirmed, the often discussed periodicity in the red-shift distribution of quasars may not be readily explained in the standard Big Bang model. P K Das presented results that indicate that the variable mass hypothesis scenario of Hoyle–Narlikar theory red-shift quantization can be invoked to explain any observed periodicity or quantization of quasar red-shift distribution.

By considering the thermodynamics of open systems in cosmology, Prigogine has proposed an irreversible matter creation process accompanied with large-scale entropy production. P Gopakumar and G V Vijayagovindan discussed the application of this scenario in 3-brane world cosmology in five dimensions. The matter creation rate is found to affect the evolution of the scale factor both at high- and low-energy densities. In the standard brane-world scenario, cooling is much slower than in the FLRW case at high-energy densities. With the matter creation in the brane-world, the standard FLRW evolution is regained. As a consequence the temperature at the freezing-out of neutrons-to-protons ratio is the same as in the standard scenario.

M Govinder presented a simple method, which generalizes the static isothermal universe first studied by Saslaw *et al* [32]. The cosmic fluid in the static model obeys a barotropic equation of state of the form $p = \alpha\rho$ [33]. It has been argued that the isothermal cosmological model of Saslaw *et al* could represent the asymptotic state of the Einstein–de Sitter model. The generalized model could describe an isothermal sphere of galaxies in quasi-hydrostatic equilibrium with heat dissipation driving the system to equilibrium. A thermodynamical treatment within the framework of extended irreversible thermodynamics of the model is carried out [34].

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