Conference overview

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Abstract. This is an expanded version of the summary talk given at the conclusion of the ICGC-2004 held at Kochi. Brief introductory remarks are included to provide a slightly wider context to the theme talks.

1. Introduction

The fifth conference in the series of conferences titled 'International Conference on Gravitation and Cosmology' (ICGC-2004) was held at Kochi during 5–10 January 2004. It had 17 plenary talks and as a new feature it also had 8 short talks which were more specialized than the plenary talks but still accessible to a wider audience. There were three focus themes: cosmology, gravitational waves and quantum gravity. The summary below is a 'bird's eye view' more in the spirit of: 'What do I take home from the conference?'

The summary is organized into sections corresponding to the theme topics. Apart from the talks on the theme topics, there were also a few which formed a group by themselves, not directly related to the main themes. I have grouped them together under a somewhat lighter heading of 'Culture Talks'. Of course, these were lighter neither in their content nor in their importance, but relative to the more tightly focused set of theme talks, they were more relaxing. A grouping of the talks is given in table 1 below.

2. The 'culture talks'

Although believers don't always need a proof, it is nice to be assured there are some who help us keep our faith after a scrutiny. Clifford Will told us that GR continues to fare well in the traditional tests. With the possibility of direct detection of gravitational waves in the near future, further tests become conceivable. Notable among these are tighter bounds on scalar–tensor theories and testing of speed of

Table 1. Grouped list of talks and speakers.

'Culture'	Testing GR	Clifford M Will
	Collapse and naked singularities	Tomohiro Harada
	Statistics of short GRBs	Patrick Das Gupta
	Traversable wormholes	Sayan Kar
	Kerr–Schild space-times	Roy P Kerr
Cosmology	CMBR	Robert Crittenden and Manoj Kaplinghat
	Complementary observations	Jerry Ostriker
	Cluster surveys	Subhabrata Majumdar
	Weak lensing	Bhuvnesh Jain
	Dark energy desperation	Robert Crittenden (Edmund Copeland)
Gravitational waves	Detector runs	Gabriela Gonzalez
	Event rate expectations	Vicky Kalogera
	Instrumentation physics	Biplab Bhawal
	Data analysis	Sanjeev Dhurandhar
	Wave-form computations	Luc Blanchet and Masaru Shibata
	Neutron star equation of state	Frederic A Rasio
Quantum gravity	Strings	Sandip Trivedi
	Brane cosmology	Misao Sasaki
	Loop quantum gravity	Jorge Pullin
	Loop quantum cosmology	Martin Bojowald
	Black hole entropy	Saurya Das and Parthasarathi Majumdar
	Testing quantum gravity	Jorge Pullin

gravity (or mass of the graviton). Since non-GR theories generically predict a dipole radiation from an unsymmetrical binary system, the gravitational wave experiments are expected to provide constraints on such theories. The 'phasing formula' can provide bounds on the ω parameter, but the real improvement is expected only after LISA. Speed of gravity influences the form of the chirp signal from the in-spiral and hence its detection would also help put bounds on the graviton mass.

Naked singularities refuse to go away completely. Tomohiro Harada gave a status report of their occurrence mostly in the context of spherical collapse. Notably, in the perfect fluid models with an equation of state of the form $p = k\rho$, occurrence of naked singularities is *generic*. Stability with respect to non-spherical perturbations, however, is not known. Not much definitive seems to be known about non-spherical collapse (except for Hayward's result that there is no horizon in cylindrical collapse). Regarding the possibility of gravitational wave emission from the vicinity of a naked singularity, it was mentioned that it is possible and although some of the Weyl curvatures diverge at the Cauchy horizon, the GW flux remains finite. Another interesting aspect was the articulation of the notion of an 'effective naked singularity', i.e., region of high enough curvature, where classical GR may break

down, being visible from infinity. Their occurrence with non-zero probability could be taken as a violation of censorship. Here some quantum gravity input may be needed to decide the regime of the breakdown of classical GR.

Patrick Das Gupta filled us in, on the topic of gamma ray bursts. These seem to fall into two classes demarcated by burst duration of about 2 s. He presented a statistical study of the sample of 156 short GRBs belonging to the Burst and Transient Source Experiment (BATSE) 4B catalog. One of the features that emerges is the further division of these GRBs according to whether the softer photons (energy less than 1 keV) arrive before the harder ones or the other way around. The latter types form a larger class and have further distinguishing features in terms of correlations among GRB parameters. Some of the implications for theoretical modeling of GRBs were also discussed.

Sayan Kar reported on the issue of quantifying the notion of 'small' violation of averaged energy condition and its relevance to traversable wormholes, while Roy Kerr reminded us of the classic topic of the 'Kerr–Schild' geometries.

3. Cosmology

The emphasis in this theme was almost exclusively on the observational aspects of cosmology. Observations of anisotropies of the CMB, first conclusively detected by COBE and most recently determined in unprecedented details by WMAP, are perceived as heralding the age of 'precision cosmology'. This particular relic of the hot Big Bang is, the essentially undisturbed, record of directly observable earliest event in the cosmic history ($z \sim 1100$). On the one hand, its anisotropies are correlated with the matter and gravitational perturbations of the FRW models which are supposed to provide seeds for the subsequent structure formation while on the other hand its gross level isotropy necessitates some form of an earlier inflationary era. The inflationary era in turn provides a possibility of linking the perturbations at the decoupling era to the earlier (pre-inflation) primordial perturbations presumably resulting from quantum fluctuations. Because of this linkage, CMB also provides a means of (at least partially) constraining the inflationary models. The availability of power spectra of perturbations (as inferred from the CMB anisotropies) and the currently available as well as future surveys of structures on smaller length scales, offers a means for studying other unknown ingredients of the universe such as dark matter and dark energy. This aspect makes the complementary observations other than the CMB as important. For a general perspective, see [1].

Robert Crittenden surveyed the hot news from the latest star of observational cosmology, the WMAP. With its special features of all sky observations down to about $(1/2)^\circ$ angular resolution together with determination of polarization anisotropies, it is currently the most precise tool of observational cosmology. Among its main confirmations are:

- Perturbations are adiabatic,
- The spectrum is scale invariant,
- Integrated Sachs–Wolf effect (red-shifting of CMBR photons after LSS) is seen,

- Reionization is rather early,
- Gaussianity tests seem okay.

In the 'not confirmed beyond reasonable doubt' category are:

- Presence of Sunyaev–Zeldovich effect (Compton scattering of CMBR photons),
- The suppression of the power of low multipoles is not beyond doubt and the issue of topology of the universe is also not settled yet,
- North–South hemispherical asymmetry in the data?

Manoj Kaplinghat elaborated on the reionization information contained in the polarization anisotropies in CMBR. He argued that apart from the 'optical depth' (epoch of reionization), CMBR contains more information. Although the amplitude of the scalar perturbation and the optical depth are measured in combination, detection of the so-called B-mode would indicate the presence of tensor perturbation and/or weak lensing. The tensor perturbations have implications for both inflation and structure formation. However, at present WMAP cannot distinguish between different models of reionization. Future probes such as Planck and James Webb Space Telescope could give information about the reionization era.

Jerry Ostriker surveyed the current status of observational cosmology. He emphasized that although the most precise tool is CMBR observations, it alone is not enough. Both Λ and quintessence models fit the WMAP data well and even the future Planck data may not be able to resolve these models. Further observational tools such as Lyman-α cloud surveys, Sloan digital sky survey, supernovae surveys, cluster surveys etc. need to be used to gather information about small scale. All this information is needed to constrain the 'concordance model' as well as inflationary models. Over all, cold dark matter with Λ fares well on the large scale. The nature of dark matter is as mysterious as that of dark energy and theorists were challenged to come up with well-motivated alternatives.

Among the complementary set of observations, two were discussed in some details. Subhabrata Majumdar discussed surveys of clusters of galaxies. The galaxy clusters have a lot of structure and so are amenable to a variety of probes such as X-rays, SZ effect, lensing etc. In contrast to the presently available surveys consisting of about 100 clusters, the future surveys will have about 10,000 clusters which will permit statistical methods (e.g. 'self calibration') to be applied.

Bhuvnesh Jain discussed the so-called weak lensing and associated 'tomography' which can provide a direct handle on the equation of state of the dark energy. While lensing refers to (typically) multiple images of a distant source galaxy due to intervening matter distribution, weak lensing refers to distortions in the images typically at a less than 1% level. This is deduced by statistical analysis and has been detected about three years back. The ellipticity of images (shear effects) is sensitive to the intervening gravitational potential and by doing a tomographic analysis one can get observational information on the evolution at different red-shifts. Jain also discussed the uses of weak lensing in the context of galaxy halos and dark matter. Within the time frame of about 10 years, one can expect to see these two tools contributing to our understanding of cosmology at smaller scales.

Robert Crittenden kindly delivered the talk of Edmund Copeland who could not attend the conference, and described the desperation with regard to models of dark

energy. Given that dark energy exists and there is no observational information regarding its properties and nature, theorists can have a field day. However the so-called coincidence problem, in particular, why the universe seems to be accelerating just about now, places severe constraints on models of dark energy. Generically, accommodating a large Λ in the early universe and a small but dominant one now, leads to the fine-tuning problem. He described various, and some quite desperate, theoretical attempts in modeling dark energy. It seems we have to await somewhat direct observational inputs regarding the nature of dark energy.

4. Gravitational waves

Gravitational waves is one of the qualitatively distinct implications of general relativity. While indirect evidence for these has already been seen in the Taylor–Hulse binary pulsar system, their direct detection has remained elusive. Historically, the first efforts for a direct detection were by J Weber using a room-temperature resonant bar detector. Currently, there are three types of detectors at various stages of development/deployment – resonant bar detectors (ALLEGRO, AURIGA, EXPLORER, NAUTILUS, NIOBE), (laser) interferometric detectors (LIGO, VIRGO, GEO600, TAMA300, ACIGA and the futuristic space-based LISA) and resonant spherical detectors (MiniGRAIL, Sfera, graviton). Their respective inherent designs make them most suitable for different types of sources or frequency ranges of gravitational waves. As LIGO-I is currently at the science runs stage, at the conference, the focus was on the LIGO-I experiment. The most promising sources for these detectors are compact binary systems and the focus of theoretical talks was on wave-forms from such sources. If (or perhaps one should say when) the gravitational waves are detected to the extent of mapping their sources, one can hope for a gravitational wave astronomy which will be a completely different (non-electromagnetic) window to the universe. A nice introduction to gravitational waves and their detection can be found, for instance, in [2].

Gabriela Gonzalez gave a status summary of the LIGO-I experiment. It has passed the stage of engineering runs and has had two science runs already with the third one underway at the time of the conference. The science runs have lasted for a duration of about 1–2 months indicating the stability of the operation of the detector. The sensitivity has progressively increased and is expected to reach the design goal in the next couple of years. At present, the detector can 'see' out to a distance of about 1 Mpc but it should reach out to about 3 Mpc (for about $1.4M_\odot$ NS–NS inspirals). With these runs, real data (output of the detector) are available to test the data analysis strategies as well as to provide some preliminary bounds on some of the parameters.

An essential component of gravitational wave experiments is the expectation of what kind of sources can be detected and at what rate. The main focus has been inspiralling binary systems as the most promising sources of gravitational waves. Estimation of such sources is based on the knowledge of the properties of actual binary systems already seen by optical/radio means. In this regard the discovery of a new, highly relativistic (double) pulsar system provides for further types of source populations, pushing up the expected event rates. One could also take into

account the precessional effects, relevant mostly for NS–BH and BH–BH binaries, for detection templates. Vicky Kalogera gave the details of event rate estimations.

In a complex detector assembly such as LIGO, the physics of the detector subsystems and their integration itself acquires a life of its own. To ensure reliable and predictable behavior of the detector so that detector output can be considered as 'data' (signal + noise), a good deal of work is needed. Biplab Bhawal discussed, in quite some details, the complexities involved as well as the various simulation checks needed.

After being given a reliable data, comes the crucial step of extracting a 'signal' from the 'noise'. Given that the potential signals are buried at a 1% level in the data, very sophisticated techniques are required for signal extraction. Sanjeev Dhurandhar gave a grand tour of the types of signals of anticipated variety (chirps, periodic, etc), from unknown types of sources and a variety of methods of analysis. Eventually, the data analysis has to identify specific kinds of wave-forms coming from specific types of sources with specific locations in the sky. The role of abstract methods in data analysis as well as the computational requirements were highlighted.

Of course one has to know what signal to extract. As mentioned earlier, waveforms from coalescing binaries are the most promising signals. Of the three main phases in a coalescence, inspiral-merger-ring down, the first is amenable to analytical methods while the latter two need numerical simulations. Luc Blanchet discussed the analytical computation of chirps in the perturbative framework consisting of post-Newtonian (c^{-1}), post-Minkowskian (G), far zone (R^{-1}) and (source) multipole expansions. The non-linearities of the evolution of the metric perturbations make the relation between the 'source multipoles' and the 'radiative multipoles' non-trivial. Back reaction of the radiation on the motion of the emitting source tends to make the orbits circular. The components of a binary are treated as point objects supplemented by a method to regularize the self-field effects. The Hadamard regularization used until now appears incomplete at 3PN order whereas one needs to go up to 3.5PN order for the calculation of the chirp signals. The regularization introduces two arbitrary parameters: λ in the equation of motion and θ in the flux. The λ parameter has been fixed by requiring matching of (new extended) Hadamard regularization and the coordinate invariant dimensional regularization with minimal subtraction, however the parameter θ remains. Modulo this parameter, computations to 3.5PN order are available. The PN expansion seems to converge well even near the innermost circular orbit to the numerical estimates of the binding energy.

Masaru Shibata summarized the status of numerical simulations of binaries and also of collapse. The newer inputs in these are (a) BSSN evolution system which is stable with respect to constraint imposition, (b) hydrodynamical evolutions have a more physical 'high resolution shock capturing' scheme incorporated and (c) the gauge conditions are dynamical. A minimum grid of about $600 \times 600 \times 300$ is required and a supercomputer capable of dealing with this size is available. In the absence of black holes, long-term simulations are possible and quantitative runs to about 1% accuracy are possible. For template computations, however, better accuracy is needed and the future looks optimistic.

Frederic Rasio discussed how gravitational waves from binaries involving neutron stars can be used to obtain constraints on the NS equation of state. The compactness ratio, M/R, can be inferred from deviations of GW energy spectrum from point mass behavior at the end of inspiral phase. Combining with numerical simulations of the merger phase one can constrain the NS equation of state.

5. Quantum gravity

Now we come to the quantum gravity theme of the conference. While all other known fundamental interactions have been incorporated in a perturbative quantum framework, gravity has resisted such attempts. Several researchers are involved in the enterprise of constructing a quantum theory of gravity. There are two main streams (represented at the conference) of such people: 'the unifiers' (string theorists) and 'the background independents' (loopy quantum geometers). They are distinguished by their pursuits of almost orthogonal strategies.

The string theorists aim to build a theory which includes matter (known and unknown) and gravity in a single framework. This is sought to be achieved by imagining a set of 'elementary quanta' interacting via mutual exchanges. This is naturally arranged by excitations of a string propagating in some, typically ten-dimensional, background space-times. The joining and splitting of strings is thought to encode the interactions among the excitations. Since strings can propagate in a large set of backgrounds, one has a large class of first quantized string theories (i.e. a special class of two-dimensional conformal field theories). The various (partially verified) duality conjectures, suggest that many of these are actually alternative descriptions of the 'same theory' giving the hope that there exists a master theory, 'M-theory'. Its 'phases' are described by 'equivalence classes' of various first quantized strings while each of the first quantized string is thought to be small fluctuations about a possible M-theory 'vacuum' or ground state in the sense of a local minimum. Much effort has gone into developing such a picture [3]. It naturally leads to the questions: Is there any phase which corresponds to the world as we know it so far? How do we identify such a phase? Is there any reason for us to be in our particular phase?

The possibility of admitting compactifications consistent with standard model as well as various grand unified models seems to say 'yes' to the first question. Continuing in the same vein, the discovery of cosmic acceleration with its leading explanation in terms of a positive cosmological constant was a serious challenge to the string theorists. The various no-go theorems made it virtually impossible to arrange a positive cosmological constant in any (conventionally) compactified string theory. Recently this block has been removed and Sandip Trivedi discussed how this is achieved, as well as its implications.

The crucial new ingredient in bypassing the no-go theorems is the so-called 'compactification with fluxes' – various form fields when integrated over appropriate submanifolds of the compact space have non-zero values. This permits SUSY breaking in a controlled manner to admit de Sitter vacua. The mechanism leads to a very, very,... very rich ($\sim 10^{100}$ local minima) structure for the superpotential. One possible implication suggested was that there could be several 'inflatons' as well as

several epochs prior to observable inflation. Which of these vacua is selected (and how) is unclear at present – it could be that special initial condition chooses our phase or that we happen to live in our phase because that is where we can live.

String theory suggests more than four space-time dimensions and admits the so-called p-dimensional Dirichlet brane solutions in which open strings have their ends fixed on p-dimensional 'planes' with Dirichlet boundary conditions. By contrast, the closed strings are free to wander in the full ten-dimensional space-times. Via the Randall–Sundrum proposals, this has led to brane cosmology. Misao Sasaki discussed this now popular, string-inspired brane cosmology. In particular, he discussed the idea that apart from the graviton, the dilaton also propagates in higher dimensions which can be used to drive the inflationary scenario. He argued in detail that such an inflation, driven by a higher dimensional scalar is indistinguishable from the usual slow role, four-dimensional field to the leading order of computations.

While a unified quantum theory of 'everything' must include gravity, the converse need not be true. A quantum theory of gravity does not have to be a unified theory of all interactions. The loopy quantum geometers focus precisely on constructing a quantum theory of geometry/gravity without insisting on unification. They however insist on manifest background independence. They argue that a quantum theory of gravity/geometry should not pre-suppose any preferred background geometry in its basic formulation. Once such a formulation is constructed together with coupling of presently known forms of matter (also formulated in a background independent manner), one may worry about the possibility of a theory of matter with or without unification. Such an enterprise is actually realized and has come to be known as loop quantum gravity (LQG). This is a non-unified but non-perturbative quantum theory of gravity.

Jorge Pullin traced the main steps in the development of LQG:

- The connection formulation – viewing Einstein gravity as a canonical system with the phase space of a gauge theory together with the Gauss, the diffeomorphism and the Hamiltonian constraints,
- Loop representation and discrete spectra of (spatial) geometrical operators such a area, volume, length,
- Construction of the connection representation – availability of a precise kinematical Hilbert space,
- Concrete proposal for the Hamiltonian constraint including standard model matter.

Currently, LQG is regarded as a mathematically well-defined theory. However doubts are expressed regarding whether it 'is' a quantum theory of gravity, i.e. does it have a correct semiclassical limit – an issue which is still unresolved.

Taking the underlying discrete structure of the spatial geometry, suggested by LQG, and possibly also of space-time as a point of departure, Pullin discussed recent ideas of his and his collaborators' about *ab initio* discrete formulations of (constrained) theories. Focusing on discrete 'time' (an integer) in particular, the dynamical evolution is achieved by finite (i.e. non-infinitesimal) canonical transformations. For theories with constraints, preservation of constraints can be used to solve for the Lagrange multipliers and get a constraint-free theory which can be quantized in the usual manner. He argued that the twin problems associated with

a Hamiltonian constraint, namely (a) clock variable as a Dirac observable will have a constant value and hence cease to be useful as a clock ('Problem of Time') and (b) solutions of the Hamiltonian constraint being generically distributional need a new physical inner product to be defined, both disappear once the continuum theory with constraint is replaced by a discrete, constraint-free theory. In the context of quantum cosmological models, one can also 'avoid singularity' essentially because discretizations which encounter the singularity form a 'set of measure zero' in the space of all possible discretization. (This is very different from the singularity avoidance in loop quantum cosmology.) The proposed method can also 'solve' the information loss problem by having a non-unitary evolution (with respect to a clock variable distinct from the discrete label 'time' with respect to which the evolution is unitary). This approach has been demonstrated to work for the Yang–Mills and BF theories as well as for quantum cosmological models.

Loop quantum cosmology (LQC), an area pioneered by Martin Bojowald, was surveyed by Bojowald himself. By systematically carrying out the symmetry reduction of LQG one arrives at LQC. This can also be construed as carrying out a 'loopy' quantization (distinct from the usual Wheeler–DeWitt quantization) of the classically symmetry reduced cosmological models. In this quantization, the discrete geometry revealed by LQG survives the symmetry reduction in a subtle technical sense – eigenvalues of the triad operator take all real values but each has a corresponding (normalizable) eigenvector. Nevertheless, adaptation of the Thiemann procedures lead to a difference equation for selecting the solutions of the Hamiltonian constraint and also to the definitions of the inverse triad operators with bounded spectra. On the one hand, this allows one to 'evolve' through the classically indicated singularity (at zero triad eigenvalues) and on the other hand, it permits only a bounded growth of spatial curvatures and matter densities even as the singularity is approached.

Among the applications of LQC are:

- For the isotropic models with scalar matter, one can get inflation with graceful exit,
- For the closed isotropic models, one can see the freezing of the matter field and its subsequent bounce as well as avoidance of the big crunch singularity,
- It is possible to have a running spectral index and a suppression of power at low multipoles in CMBR,
- The singularity avoidance continues to hold even for more general diagonal, homogeneous cosmologies,
- The anisotropic, vacuum Bianchi-IX evolution is non-chaotic and in conjunction with the BKL conjecture suggests a simpler picture of approach to the general singularity.

One point worth emphasizing is that LQC is being developed as a simpler setting to unravel LQG and is not being arranged to address specific phenomenological issues of cosmology. That it naturally admits phenomenologically viable mechanisms is an attractive but somewhat incidental feature.

Is there any way of 'testing' a quantum theory of gravity?

At a theoretical level, a microscopic explanation of the black-hole entropy has been a 'traditional' testing ground for QG. The test involves reproducing the

Bekenstein–Hawking formula for entropy in terms of the horizon area. Saurya Das reviewed this entropy test for various approaches such as horizon CFT, isolated horizons in LQG, string theory, AdS/CFT etc. Most QG candidates reproduce the entropy formula in the leading behavior. Strings get it for extremal or near-extremal black holes while LQG gets it for any isolated horizon modulo the value of the Barbero–Immirzi parameter to be fixed by normalizing to any one black hole. There are however logarithmic corrections at the next leading order. These seem to be different for different approaches and as such could be considered discriminatory. He also surveyed efforts to understand the Hawking radiation in various approaches and discussed the information loss problem.

Parthasarathi Majumdar discussed the micro-canonical and the canonical entropy for general relativistic systems with a boundary. Assuming only the area spectrum from LQG, area law for the micro-canonical entropy and a power law relation between the energy and the area, he argued that leading thermal fluctuation corrections to the canonical entropy are also logarithmic with a universal coefficient. The universal form for canonical entropy is independent of the index of the power law relation between energy and area.

Works regarding testing QG on a more direct observational level were reviewed by Jorge Pullin. The observation that although tiny, QG effects could be observable due to cumulative enhancement, forms a basis for hopes for manifestation of QG. Effects on the propagation of light and neutrinos as well as the modified dispersion relation with attendant Lorentz invariance violations have been investigated. The hope is that gamma ray bursts signals could contain a signature of these effects. These ideas are however preliminary with a rather weak theoretical basis/understanding.

6. Concluding remarks

In summary, the conference had a very strong emphasis on observational aspects emphasizing applications of GR to an understanding of the cosmos at ever more detailed level. By the next ICGC, one may hope to get some glimpse of the universe through the gravitational wave window. On the quantum gravity front, strings seem to 'suffer' from embarrassing riches of de Sitter vacua ($\sim 10^{100}$), while loops have still to make a reliable contact with low-energy (or semiclassical) limit.

The summary will not be complete without mentioning the delightful 'Cosmos in Cartoons' by Vishu (C V Vishveshwara). These just have to be seen and enjoyed.

References

[1] George F R Ellis, *Class. Quantum Gravit.* **16**, A37 (1999)
[2] Bernard F Schutz and Franco Ricci, in *Gravitational waves* edited by I Cinfolini, V Gorini, U Moschella and P Fre (Institute of Physics Publishing, 2001)
[3] For a brief overview, see The Nag Memorial Lecture by Ashoke Sen at the Institute of Mathematical Sciences in December 2003; http://www.imsc.res.in/∼sankaran/naglect/index.html