Abhay Ashtekar: pushing the horizons of gravity

'At the big-bang and black hole singularities the worlds of the very large and of the very small meet. Therefore, although they seem arcane notions at first, these singularities are our gates to go beyond general relativity.'[1]

Image courtesy:
http://unophilosophyphysics.blogspot.in

Einstein's general theory of relativity 'consists primarily in relating, in juxtaposition, two concepts of space and time on the one hand and the concepts of matter and motion on the other', writes Chandrashekhar[2]. This theory was essential to explain the many puzzles existing then in astronomy. Besides resolving those puzzles, it went ahead of its time in predicting many bizarre consequences, including gravitational lensing and the slowing down of clocks in a gravitational field. The beauty and brilliance of the theory, as Pauli[3] says, is in 'this fusion of two previously quite disconnected subjects – metric and gravitation'.

Despite its grandeur, the general theory of relativity is encumbered with an important inadequacy. Einstein's equations fail at the centre of a black hole. They cannot explain how, why and what happened during the big bang. As a result, there has been a constant uneasiness among physicists, and they are seriously attempting to go beyond Einstein to fuse the currently disconnected subjects – quantum mechanics and general relativity.

In the 1980s, Abhay Ashtekar made a new beginning to bring about this fusion. Jayant Narlikar[4] says 'To understand the macroscopic world around us, we have Newton's laws – classical mechanics and at a microscopic level we need a new approach which is quantum mechanics. Similarly, space–time and gravity is understood macroscopically by general relativity and for a microscopic understanding, we need quantum gravity. Abhay Ashtekar has developed a novel approach: Loop Quantum Gravity. There are many approaches to quantize gravity and we are all stuck in a maze with many routes leading to it. Abhay has gone very far in his path, but is yet to reach the ultimate goal.'

'He may very well be called the founding father of Loop Quantum Gravity/Cosmology' says Ajit Kembhavi[5] (IUCAA, Pune). In a similar tone Roger Penrose says of Ashtekar's work, 'The most important of all the attempts at quantizing general relativity'[6]. Exactly a hundred years after Einstein's general relativity was published, I was fortunate to have interviewed Abhay Ashtekar for *Current Science* at IUCAA. He spoke about his work on loop quantum gravity, its relevance to the future of physics and reflected on his life.

Gamow's influence

In the calm town of Kolhapur, located on the banks of Panchaganga, young Abhay Ashtekar discovered his inclinations for physics and mathematics. His father was a civil servant and his mother wrote short stories. Any bright child's aspirations during that time would be to become an engineer or doctor, or to get into civil service. But having been deeply influenced by the book '*One Two Three to Infinity*' by George Gamow, Ashtekar was fixated on studying physics. His parents were not religious, nor did they compel him to follow any rituals. He reflects, 'They were only religious in the social sense: when their neighbours expected them to be!' This freedom not only urged him to discover his own beliefs and philosophies, but also encouraged him to boldly tread the unconventional path of studying quantum gravity.

Doctoral studies at Chicago

After having convinced his parents about becoming a physicist, Ashtekar moved to the University of Texas, USA. Later, he pursued his Ph D in the University of Chicago, USA and a postdoctoral fellowship at University of Oxford, where he met the three giants of physics Robert Geroch (his Ph D advisor), Roger Penrose and S. Chandrasekhar, who as Ashtekar acknowledges have been the most influential people in his life. He adds, 'Prof. Geroch has deeply influenced me as a Ph D advisor. He was so talented that S. Chandrasekhar once commented: "apart from Von-Neumann, I have never seen anyone as brilliant as Geroch" '. He continued, 'While groping in the dark, we use methodology that is not well defined; it's a creative process that I have tried to learn from Penrose. Chandra on the other hand has helped me develop the right attitude and ethics required in science'. Ashtekar seems to have adopted Chandra's advice in ethics sincerely. For instance, in his paper 'New variables for classical and quantum gravity'[7], Ashtekar cites a private discussion between Lee Smolin and P. Renteln on an idea that they were pursuing. It is in Chicago that Ashtekar's love for physics bloomed and he completed his Ph D degree in 1974 for studies on 'Asymptotic structure of the gravitational field at spatial infinity'. He continued to work in classical general relativity and quantum field theory in curved space–times, but also continued to think about quantum gravity, a challenging field in physics in which several workers have faced more disappointments than successes. However, by 1980s his work on loop quantum gravity (LQG) began to be recognized seriously. In 1986, he introduced a set of variables now famous as the 'Ashtekar variables', which 'provide new, non-perturbative approaches to problems in both classical and quantum gravity'[8]. In 2006, with his postdocs, Ashtekar published the landmark paper 'Quantum nature of the big bang'[9], thus weaving the intractable big bang into the manageable mathematics of space–time – loop quantum cosmology (LQC).

To Paris and back

In February 1983, Ashtekar moved to Universite de Paris VI to assume the Chair of gravitation. 'I was very excited to go to Paris. It's a beautiful city and I thought it was a wonderful opportunity'. However very soon, in October 1985, he resigned from his post and joined the

Syracruse University to pursue greater scientific opportunities in the United States.

'The academic atmosphere in Paris was very different from that of the United States. The system was highly centralised and I was an outsider there. I was offered the Chair of gravitation; naturally I had fresh ideas and ambitious plans. I wanted to introduce modern general relativity, but the establishment was too rigid and was controlled by higher-ups who weren't particularly amenable. The worst part, I didn't even realise what the constraints were. Though I was appointed to the Chair of gravitation, I was allotted only UG classes to handle while I wanted to teach advanced courses. Perhaps if I were 10 years older, I would've stayed and patiently worked towards a change. But I was young, impatient and wanted to bring about changes much more quickly. So I resigned and shifted back to the US.' He now serves as the Eberly Professor of Physics and Director of the Institute for Gravitation and the Cosmos at the Pennsylvania State University, USA.

Loop quantum gravity/cosmology

Abhay Ashtekar introduces the subject to a general audience and clarifies several persisting questions in the subject.

Why do we need LQG?

History of physics tells us that we cannot have disjoint theories – one for a certain phenomenon and the other for another kind. At the conceptual level, there should be one description of Nature. This is what led Einstein to formulate the general theory of relativity (a grander version of the special theory of relativity) which makes it clear that gravity is encoded in the very geometry of space–time. But even general relativity is inadequate to address certain issues and we believe there should be a better, more complete theory that goes under the name quantum gravity. LQG is one of the prominent approaches to this goal of unifying general relativity with quantum physics. Once there is a deeper, more complete theory, quantum mechanics and general relativity will become its special cases. It will have applications and predictions which are far beyond what one could imagine independently in these theories. That is why the chase for a grander theory is very exciting[10].

Why is it called loop quantum gravity and not just quantum gravity?

Frankly, it is a slight misnomer. Just as what one currently does in string theory has little to do with strings, the current version of LQG has little to do with loops. In both cases, the names refer to initial ideas that have now been transcended. The main ideas underlying LQG are the following. Einstein showed that the geometry, which everyone had thought of as a mathematical entity, is in fact physical. Now, a physical object such as a table looks smooth, but when looked at through an electronic microscope we will find that it has a discreet structure (Figure 1). Similarly, geometry of space–time looks like a smooth continuum to us in the macroscopic sense. However, since Einstein already taught us that it is a physical entity, we expect it to have an 'atomic' structure at the microscopic level (Figure 2).

The simplest mathematical description of these fundamental 'atoms of space–time', or as I would like to call them, fundamental excitations of quantum geometry, is one-dimensional. The most convenient description is to say that they are one-dimensional, polymer-like structures. Initially, it was thought that these excitations would be closed, forming a loop which led to the name loop quantum gravity. But that is not necessary and that is why the name is a bit of a misnomer. LQG is a theory that unifies general relativity with quantum physics in which geometry itself is subject to the principles of quantum physics. So geometry is no more a classical entity, there are fluctuations of geometry; that are probability distributions of geometry. These are the aspects that are explored in LQG.

Can LQG be the theory of everything?

No. LQG is not a theory of everything. I feel theories of quantum gravity are promising ideas but are not final solutions – not theories of everything. But whatever the final solution is, I do believe that the idea that geometry is quantum mechanical will be deeply embedded in it. I don't think LQG is a complete or the final theory. 'Theory of everything'

Figure 1. A steel table looks smooth. However, an electroscopic image of steel (10 µm) is not smooth.

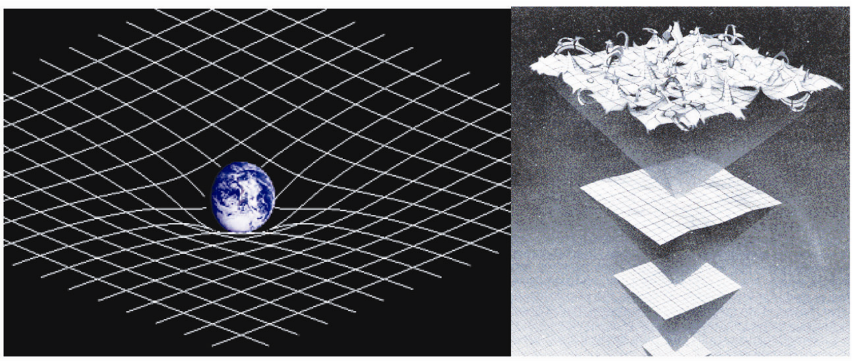

Figure 2. Space–time looks like a smooth continuum, but at the quantum level it may not be so. Artist's depiction of space–time at the quantum level. (Image credit: http://en.wikipedia.org/wiki/File:Spacetime_curvature2.png and http://abyss.uoregon.edu/~js/ast123/lectures/lec17.html.)

seems a little too amateurish to me. Several 'theories of everything' have been proposed over the years and all these attempts proved to be futile, few even edging towards foolishness, in retrospect. Perhaps we should not be treading this path again. Eddington had a theory of everything. Heisenberg also had a nonlinear quantum field theory which was supposed to explain everything then known. Stephen Hawking gave his Lucasian lecture, titled 'Is end of physics at sight?'. I don't know why history continues to repeat itself. To me it seems immature to proclaim that one has a final theory that can account for everything. Physics has advanced by successive improvements, not by trying to arrive at the final theory in the very next step.

How is LQG different from string theory?

LQG is not trying to unify all the interactions; it is only trying to understand the quantum nature of gravity. The goal of string theory is to relate/unify *all* the fundamental interactions of physics. This goal remains elusive but arose from the fact that string theory has its origins in particle physics. LQG on the other hand, has its base in general relativity and does not per se offer new ideas to particle physics phenomenology. In recent years, the emphasis in string theory has shifted to using ideas and techniques from classical gravity to address open issues in other areas of physics, while in LQG the focus continues to be on fundamental conceptual issues of quantum gravity itself.

Are there any experimental evidences for LQG?

To date there are no direct experimental verifications for any theory of quantum gravity. However, cosmology of the very early universe offers a promising window. The best way of explaining the origin of the temperature anisotropies observed in the cosmic microwave background (CMB) is in terms of quantum fluctuations of gravitational and matter fields. This is all at the *perturbative* level where we are looking at small fluctuations and not at full nonlinear effects of gravity. In LQC, these fluctuations propagate on quantum geometry in the Planck era and there are concrete calculations showing that quantum geometry can leave imprints on the longest wavelength modes seen in CMB. In particular, LQC opens up a new avenue that traces back the so-called 'anomalies' observed by the Planck collaboration to the underlying quantum geometry in the Planck epoch and makes some predictions for future observational missions.

How does LQG treat the big bang? Does it tell us what was before the big bang?

The big bang singularity is replaced by a big bounce in LQG. General relativity can be used to describe the universe back to a point at which matter becomes so dense that its equations do not hold up[11]. Beyond that point, we needed to apply quantum tools that were not available to Einstein. Using quantum modifications of Einstein's cosmological equations, my then postdocs Parampreet Singh, Tomasz Pawlowski and I have shown that, in place of a classical big bang, there is in fact a quantum bounce (Figure 3). We were so surprised by the finding that there is another classical, pre-big bang universe that we repeated the simulations with different parameter values over several months, but found that the big bounce scenario is robust. The crucial point to remember is that this emerges naturally from the quantum version of Einstein's equations without having to put in anything by hand or extra boundary conditions. So, this leads us to the scenario that a pre-big bang universe shrunk to a very high density and curvature, and then bounced to form the expanding universe that we are in now.

What were the initial reactions from physics academia regarding your new approach?

The reactions were very warm. The few criticisms were constructive in nature and only helped us to go further in our work. By now there are several thousand papers on LQC that are based on the quantum bounce calculations.

Indian LIGO (IndIGO) project and opinions

Laser Interferometer Gravitational-wave Observatory (LIGO) is a grand international scientific project with advanced experimental facilities to detect gravitational waves. One of the centres is coming up in India, which will carry Indian science to greater heights. Ashtekar is playing a crucial role non-publicly in making this grand feat a reality.

What is your contribution to the Indian LIGO project?

Though I am not working in that field myself, I have been pushing it forward because it carries a promise to significantly advance several areas of physical sciences. Some of the younger leaders of the project are my past students. The LIGO scientific collaboration has three major groups and all these groups were chaired by my students at one stage. Providing a pool of talented researchers is my key contribution to LIGO. In terms of pushing India forward, I have been the

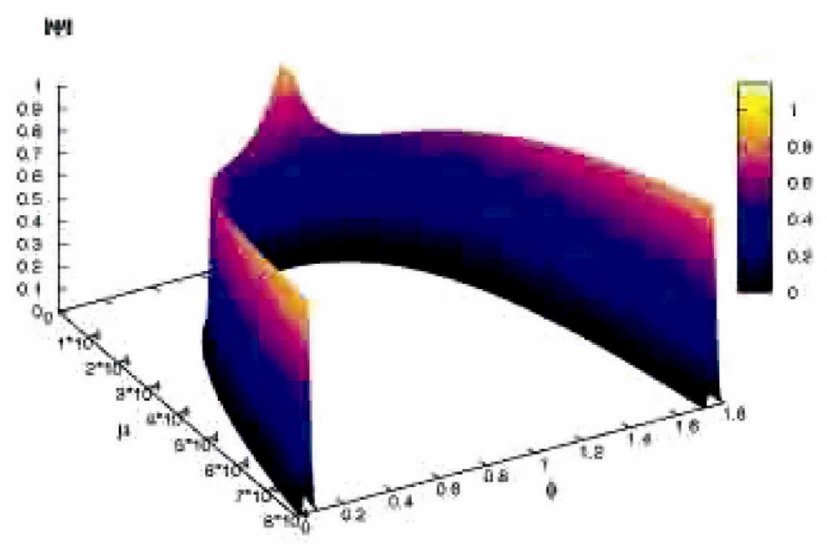

Figure 3. Big bounce replacing the big bang. μ axis refers to space, φ is the time and ψ is the wavefunction. The point where space (μ) goes to zero is the big bang singularity.

Chair of the 'International Advisory Committee' for the Indian LIGO (IndIGO). In that capacity, I serve as a primary liaison for LIGO India between researchers and administrators in India and those in the US. There are differences at the level of the governments as well as institutions. At times, these differences can cause real tension. Since I happen to know both cultures, I have often been able to use informal channels to make things run more smoothly than they might otherwise have.

Any incident you would like to share in particular?

Well, a few years ago, I was in India and there were critical sensitive issues that had to be ironed out because things were quite murky. So over a span of three or four days, I met various people separately and sorted it out. At the end, David Reitze, the Director of LIGO lab in Caltech, said to me jokingly, 'your next mission should be to go to Middle East to make peace!'. I owe both to science and to India. I feel obliged to do my bit for international science as well as India and if people who can talk across borders do not invest time and energy to help, then who will? But it is really a tough job. It takes time, energy and patience, and I would rather spend it doing research. But I want to do my bit for both science and for India. This is the kind of moral compass that you inherit from people like Chandra.

Opinions

You have read the Gita. What aspects of it do you like?

I like Karmayoga. In essence, it says do your duty/dharma and leave all fruits to somebody else. In the *Gita*, Krishna says leave it to me, but that 'me' could be the Guru, the supreme in the non-dualistic sense of Advaita. In the 18th chapter of the *Gita*, Krishna advises Arjuna that it is the *rightful action* for him to wage the war. It is really nice to follow this advice from the *Gita* to do your duty and not be concerned by the rest.

Opinion on the Indian education system...

There are several distinct points I could make. First, when I was young, there was this hierarchy between students and professors, and an unspoken rule that students should not challenge their professors. This had to change and I think it has already changed. For instance, Jayant Narlikar had his own ideas regarding the steady-state universe but did not make that a doctrine requiring others to follow it. He actively encouraged diversity. Second, I hear a lot about the entrance exams in India. I should say right away that I am not very well informed about what these are, as my interaction with Indian students is limited. But what I have heard is pretty bad. Emphasis on preparation for exams, as opposed to gaining real understanding, is something that needs to be rectified speedily. Developing a culture of bad traditions such as this could be the worst thing a society can do to young minds. Third, I get letters from students in India regularly, complaining that they want to pursue their intellectual passion but are unfortunately strongly discouraged by families. But I don't know how to advice them because the general environment for them is so rigid that the pursuit of their dream may leave them stranded in a no man's land. I hope that there will be more freedom for students to pursue deep intellectual interests. The entrance exam culture, when exaggerated, tends to kill this intellectual curiosity.

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G. V. Punyakoti
e-mail: punyakoti.gv@gmail.com