Dark Energy: The Cosmological Challenge of the Millennium

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Observational cosmology has been making remarkable progress in the last couple of decades. Thanks to advances in technology and large dedicated projects devoted to cosmological problems, we now understand the vital statistics of the universe much better than ever before. These advances have also brought to the forefront a major problem which will probably hold the attention of the theoreticians for the next several decades. In this talk, I shall overview this question and its implications.

The key issue concerns the composition of our universe. Observations have now confirmed that our universe has a fairly wierd composition. To begin with, the mean energy density of the universe which drives its expansion seems to be very close to the critical density, which is the density required to just make the universe collapse again. (The expanding universe is thus similar to a body thrown from the Earth, say, with exactly the escape velocity.) Of this, only about 4 per cent is contributed by normal matter made of baryons, i.e., protons and neutrons. Another 26 per cent or so of the energy density arises from non baryonic particles usually called wimps - which is an acronym for weakly interacting massive particles. These particles - unlike baryons - do not couple to photons and hence do not emit any electromagnetic radiation, which earns them the name *dark matter*. The existence of dark matter is established indirectly through its gravitational effects; observations show that normal galaxies are embedded in much bigger dark matter halos. The evidence for dark matter was mounting over the last two decades and it is generally believed that high energy particle physics models will eventually provide a suitable candidate for the wimp. The really surprising result, which emerged in the last six years or so, concerns the remaining 70 per cent of the energy density. It is made of a very exotic species called *dark energy* which exerts negative pressure. This is more esoteric than anything that has been observationally determined in cosmology in the past and has thrown up a serious challenge.

Considering its importance and the rather strange nature, one might wonder how firm is its observational evidence. The earliest indication that the universe contained something like dark energy came in 1990 in a galaxy survey study led by G. Efsthathiou of Cambridge. The analysis of observational data in 1992 by several groups (including by myself and D. Narasimha of TIFR) led to the same conclusion. A more comprehensive analysis of observations was performed in 1996 by myself, J.S. Bagla and J.V. Narlikar which clearly suggested that the observations demanded nearly 30 per cent of dark matter and 70 per cent dark energy. The key direct evidence, however, came in late ninetees from the analysis of distant supernova data which allowed astronomers to measure the rate of expansion of the universe precisely. This study suggested that the universe is currently accelerating - that is, its rate of expansion itself is increasing with time. It is very simple to show from general relativity that such an accelerated expansion is not possible unless the dominant component in the universe has negative pressure. Thus observations thrusted upon the theoreticians a universe which is dominated by a fluid with negative pressure.

How does one model such a bizzare entity? Normal gaseous systems have positive pressure. If a baloon filled with such a gas expands, its energy content will decrease because the pressure will have to do work in expanding the baloon. If the pressure is negative, a system can expand without its energy density decreasing. Incredibly enough, Einstein himself has suggested decades back a mechanism which has this feature. He postulated — for completely different reasons which are no longer relevant — an extra term in his equations that mimiced a fluid with negative pressure. This term, Λ, called the *cosmological constant* can account for *all* the current observations provided its value is carefully fine tuned. It is possible to form a dimensionless number using Λ and the three fundamental constants in physics $G, \hbar$ and c in the form $\Lambda(G\hbar/c^3)$; observations suggest that this number is close to 10^{-120} !! If the dark energy is indeed cosmological constant, then the theoretical challenge is to understand why this dimensionless number is *so tiny but yet non zero.* (Disturbed by this possibility, people have attempted to model the dark energy by other means like, for example, postulating the existence of certain scalar fields with specific interactions etc. Unfortunately, all these models are ad-hoc and cannot make predictions which are testable by observations.)

One natural — and, in fact, inevitable — contribution to cosmological constant arises from the energy density of quantum vacuum fluctuations. The trouble is, we do not know how to compute the gravitational effects of quantum fluctuations of the vacuum from first principles. Naive estimates suggests that this will give $\Lambda(G\hbar/c^3) \approx 1$ which misses the correct result by 120 orders of magnitude! It is possible to get around this difficulty and get the correct value but only if we are prepared to make some extra assumptions. The appearance of G and $\hbar$ together strongly suggests that the problem of dark energy needs to be addressed by quantum gravity. None of the currently popular models of quantum gravity has anything meaningful to say on this issue (let alone predict its correct value). In fact, explaining the *observed* value of the dark energy is the acid test for any quantum gravity model and all the models currently available flunk this test. There is no doubt that, when we eventually figure this out, it will lead to as drastic a revolution in our conceptual understanding as relativity and quantum theory did.