The accelerating universe*

Brian Schmidt, the winner of the 2011 Nobel Prize in physics, delivered the Sir C. V. Raman Lecture. He was welcomed and introduced by Anurag Kumar, Director of Indian Institute of Science (IISc), as the 12th Vice-Chancellor of the Australian National University (ANU), a position which he has held since January 2016 and the President and CEO of ANU.

Schmidt shared the 2011 Nobel Prize with Saul Perlmutter and Adam Reiss for their 1998 discovery that the universe is expanding at an ever-increasing rate. He also shared the 2006 Shaw Prize in Astronomy with his colleagues Perlmutter and Reiss.

Before becoming Vice-Chancellor of ANU, Schmidt was a distinguished Professor, Australian Research Council Laureate and astrophysicist at the ANU Mount Stromlo Observatory and Research School of Astronomy and Astrophysics. He received his undergraduate degree in Astronomy and Physics from the University of Arizona in 1989 and Master's degree (1992) and Ph D (1993) from Harvard University. Under his leadership in 1998, the high-Z supernova search team came out with the discovery that the expansion of the universe is actually accelerating.

Schmidt holds a fellowship of the Australian Academy of Science, The United States Academy of Science, and a Fellow of the Royal Society (FRS). In 2013, he was made Companion of the Order of Australia.

In his lecture at IISc, Schmidt initially drew references to the works of Albert Einstein, Arthur Eddington, Edwin Hubble, Alexander Friedman and Georges Lemaître signifying that nearly hundred years of astronomy has culminated in a Nobel Prize and that the winners of this Nobel Prize were lucky to be born at the right time to be part of this great triumph of science. He also talked about the work he carried out while at Harvard and while leading the high-Z supernova search team at Chile.

Schmidt opened his lecture with the well-known fact that the universe is expanding, something that we have known since 1929. Given the age, geometry and composition of the universe, he mentioned that we now know with remarkable precision that the age of the universe is 13.8 billion years, the universe is geometrically flat and is comprised of 69% dark energy, 26% dark matter and 5% atoms, neutrinos and photons. Neutrinos and photons amount to a small fraction of the universe.

Schmidt highlighted the works of some famous astronomers and physicists that led to the discovery of an expanding and accelerating universe as early as 1929. In 1915, Einstein published the theory of general relativity. A year later, he published a paper introducing the cosmological constant into his general theory of relativity, a sort of anti-gravity force that kept the universe from collapsing on itself in his attempt to model the behaviour of the entire universe as a static model. Though Einstein called this idea his 'greatest blunder', in the light of recent discoveries on the accelerating universe and dark energy, the cosmological constant appears extremely relevant. It is the confirmation of Einstein's theory of general relativity by Eddington in 1919 that made Einstein famous amongst the general population. In 1922, Alexander Friedman worked out a series of solutions for the homogeneous and isotropic universe and he discovered a set of traits which involved the notion of the universe being dynamic. Initially Einstein thought the solution by Friedman was erroneous, but later agreed that they were in fact correct. Georges Lemaître, a Belgian monk in his 1927 Ph D thesis, independently derived Friedman's equations. So Lemaître in 1927 discovered the expansion of the universe and discreetly described it, but unfortunately never got the recognition, partly because his work was published in French. In 1929, Edwin Hubble provided his observations on an expanding universe. He observed the brightness of stars and measured their relative distance using the inverse square law. He also measured the red shift – the displacement of the spectral lines caused at the time value. The farther the distance, the more the object was red-shifted. So intuitively, this meant that the universe was expanding.

Schmidt then went on to discuss the origins of the big bang theory. If the universe is expanding, it leads to the question of what might have happened in the past. With everything being closer together, there could have existed an epoch when things were very dense and hot. Hence, the idea of a big bang theory naturally alludes to an expanding universe. Though we do not know what the big bang is, we know that after the big bang the universe emerged hot, dense and expanding. When we look at the cosmic microwave background which is approximately 380,000 years after the big bang, we see a universe that is about 3000 degrees Celsius with a density roughly a billion times higher than today and very high photon content. This is the time the universe went from being ionized to recombined. If we determine the current expansion rate of the universe, we can infer how old the universe is – this essentially is the Hubble constant.

During his stint at Harvard, Schmidt went on to measure the Hubble constant. He worked with Robert Krishner and after 3 years and 11 months, he was able to obtain a value for the expansion rate (Hubble constant) of roughly 73 km/sec/mega parsec which translates into an age of the universe of roughly around 14 billion years. At the same time the ANU was using the Hubble space telescope to make accurate comprehensive measurements of the Hubble constant and the final value they obtained was 72 km/sec/mega parsec.

Schmidt explained how density impacts the expanding universe. Density can be any form of matter or energy, atoms, photons, neutrinos or cosmological constant, essentially anything that has an energy equivalent. This means, if you have a completely empty universe, it does not get affected by the density and continues on the same trajectory that it is on – i.e. the universe is said to be coasting. So the universe gets larger over time. On the other hand if the universe has world matter such as atoms in it, it will slow down over time. Hence the age of the universe is slightly less than the straight curve value of the Hubble constant. If there is enough matter, then the universe will actually be finite – i.e. it will stop expanding and go reverse. In

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the case of a just right universe, the universe has flat geometry.

While leading the high-Z supernova search team at Chile in 1994, Schmidt and his team had the opportunity to carry out an experiment to measure the universe's past owing to an understanding of the type-1a supernova. Type-1a supernovae are the explosions of white dwarfs. Suppose there are two stars born in close proximity. The massive first star will light up owing to a nuclear reaction. Thus, the star instead of collapsing is converted into a white dwarf. The second star lights up owing to a nuclear reaction and starts transferring material to the first white dwarf making it heavier. When the white dwarf is 1.383 times the mass of the sun (critical mass), it becomes unstable. This instability ends up igniting the carbon–oxygen and causes a runway towards detonation along with deflagration, which consumes entire white dwarf in about a second, creating one of the biggest explosions in the universe. They take about 20 days to reach their maximum height, light up and then fade away into oblivion.

This knowledge on supernovae was used by the high-z supernova search team. New technology-digital cameras were installed on the search floor of telescopes that allowed for the first time to observe enough sky to actually find the supernovae. Another technology breakthrough that came about was the TEC telescopes that were actually large enough to take the spectrum of the distant supernovae. The basic idea was to find a supernova by digitally subtracting the images and looking for things that have changed in the image from the past to present. Having carried out this experiment for 3.5 years, Schmidt and his team obtained the data they were looking for at the end of 1997. Based on the data and how it aligned on the diagram, they could see that each supernova provided a measurement of the expansion rate of the universe at that epoch. They found certain uncertainties, i.e. 1 sigma error bars. When they compared the nearby objects to distant objects, the distant objects did not lie in the part of the diagram that they were expecting. Statistical analysis showed that it was 99.9% certain that the data did not lie in the part of the diagram where the universe was slowing down. Rather it was above the line in the area, where the universe was expanding slower in the past and faster in the present. Saul Perlmutter and his team from Berkeley were getting the same results – almost to the same precision. So in 1998, the two teams provided evidence that the universe is accelerating.

Schmidt then went on to explain the accelerating universe from the concept of Einstein's cosmological constant. In terms of modern astronomy, the cosmological constant is a form of energy (similar to dark energy) that is everywhere in the universe, immutable in time and in space. The universe is coasting along or expanding with density dropping over time. So even if this energy constant is 30 orders of magnitude less than the atomic density in the universe, as the universe continues to expand, there is going to be a time when the cosmological constant becomes most important in universe and begins to accelerate the universe. If the universe stops expanding owing to too much density, the cosmological constant will not take over. The early universe was expanding and slowing down due to gravity. 6.5 billion years ago, the density of normal matter and the density of cosmological constant equalled and the cosmological constant took over as accelerating the universe. Unless some other event occurs, the accelerating expansion of the universe will continue into the future such that we eventually lose sight of the rest of the universe. This theory can be tested through a giant redshift survey of galaxies.

Schmidt explained the concept of dark matter normally seen in clusters. When two clusters come together, the dark matter does not interact and goes through the other dark matter. Dark matter is ubiquitous and important relative to the atoms that make up the earth. Even before galaxies were formed, the evidence for dark matter was found in the early universe, by observing small fluctuations in the cosmic microwave background radiation, the radiation that comes to us directly from the Big Bang. An image of the sky in this radiation provides a view of the universe when it was only 380,000 years old without any nonlinear objects, stars and galaxies. There were just weak fluctuations, like sound waves propagating through hot gas. We can figure out the properties of these sound waves and it turns out that they also require dark matter to be present in large quantities, about 6.5 times of ordinary matter such as atoms. Dark matter does not interact with the radiation or the ordinary matter in any way except through gravitational interactions. This shows that dark matter is present in the early universe as well as in today's galaxies and galaxy clusters. These sound waves have a very specific scale and can be used to measure the geometry of the universe. Because the universe acts as a giant magnifying glass if closed, or an inverse magnifying glass if open, we can determine the size of the sound waves and hence measure the geometry of space. We then get a good measurement of curvature based on those sound waves. Having obtained a good measurement of curvature, we can figure out what is happening with the dark energy in the cosmic microwave background. We find that the universe is almost exactly flat by fitting the curves. Thus, from the redshift surveys, we have a flat universe that is made up of 30% gravitationally attractive material. This means there is 70% mystery matter floating around.

Schmidt went onto explain the work that is currently in progress. He mentioned that Adam Reiss in 2016 has published a local value of the Hubble constant that is about 3 standard deviations discord with the Planck measurement. Though there is no problem as such, this hints to us that there might be a problem. Further research is under progress to uncover the reason behind this. So the big questions that remain are – What is dark matter? What is dark energy? Schmidt concluded that we have a law that works very well, but there are still many questions to answer. With this, we see that astronomy is alive and well with many unanswered questions that will be the subjects of further research.

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