Nobel Prize in Physics 2011

Dark Lords of the Universe: How exploding stars unlocked the past and the fate of the Universe

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▲ **FIG. 1:** The three Nobel prize laureates, at the occasion at which they received the Shaw Prize for astronomy in 2006. From left to right: Saul Perlmutter, Adam Riess and Brian Schmidt.

The Nobel prize of Physics 2011 has been awarded to the three researchers responsible for one of the most startling scientific discoveries of the past decades. Saul Perlmutter, Adam Riess and Brian Schmidt (figure 1) receive the prize for the discovery of the accelerated expansion of the Universe and for revealing the presence of a mysterious dark energy dominating the dynamics and the fate of the Universe.

In 1998, the Supernova Cosmology Project (SCP), led by Saul Perlmutter (Lawrence Berkeley National Laboratory, UC Berkeley), and the High-z Supernova Search Team (HZSNS), led by Brian Schmidt (ANU, Mount Stromlo Observatory, Australia) and Adam Riess (JHU & STScI, Baltimore), almost simultaneously published the findings of their supernova monitoring campaigns. They themselves were startled to discover that the cosmic expansion is accelerating, instead of the deceleration that was anticipated by the prevailing standard cosmology. Their observations revealed that since the last 6-7 billion years, the dynamics and fate of the Universe have been dominated by a mysterious medium causing gravitational repulsion. Observations since have established that dark energy - the general name now in use, coined by Michael Turner in 1999 - represents no less than 73% of the energy budget of nature.

The repercussions of this discovery are far reaching and represent a historic paradigm shift in our view of the world and the cosmos. It has dramatic ramifications for the ultimate - bleak - fate of the Universe. Moreover, it may have profound consequences for our understanding of gravity at energies occurring at the very first moments of the Big Bang. Ever since, the nature of the dark energy has remained the greatest enigma of 21st century physics. It did not come as a surprise that in 1998 Science magazine branded it the year's scientific breakthrough.

Over the year running up to their discovery the two teams, independently, had been monitoring around 50 supernovae, specifically the type called Supernova Ia (Figure 2). These rare and catastrophic explosions are violent thermonuclear deflagrations or detonations of white dwarf stars, and may reach a brightness comparable to that of an entire galaxy like our own Milky Way. Their enormous brightness allows type Ia supernovae to be detected over vast cosmological distances, currently reaching out to supernovae which exploded a mere 3 Gigayears after the Big Bang, or more than 10 billion years ago. The seminal importance of supernovae Ia is that they are one of the few astronomical objects whose intrinsic luminosity is quite accurately known. Both factors make them an ideal standard candle for measuring the distances over cosmologically significant depths.

Supernovae

Amongst supernovae two major types are distinguished, Supernovae I and Supernovae II. Of interest for the Nobel prize winning discovery is the subclass of Supernovae Ia. These represent rare events that occur

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only a few times per millennium in a galaxy like the Milky Way. Tycho's supernova in 1572 was one, and probably also SN1006. The latter first appeared on the sky between April 30 and May 1 of the year 1006 and is the brightest stellar event in recorded history. Type Ia supernovae are the result of the violent thermonuclear explosion of a white dwarf star. A white dwarf is the remnant of a star that completed its normal life cycle when the energy supply from nuclear fusion ceased. It is limited in mass to 1.38 solar masses, the Chandrasekhar mass, beyond which electron degeneracy pressure can no longer support the star. When the star is part of a binary system and is gradually accreting mass from its binary companion, it will start to collapse once it surpasses this limit. When it concerns a carbon-oxygen white dwarf, a rather common type, the carbon and oxygen ignite nuclear fusion as the core is heating up to temperatures in excess of billions of degrees. A few seconds later, the nuclear fusion reactions proliferate throughout a major fraction of the star in a runaway deflagration. Recent research suggests that some of the Supernovae Ia may have a different origin and are the result of the merging of two white dwarfs. In both situations, the vast amounts of energy that are released completely unravel the star in the subsequent violent supernova explosion. The light curve of a supernova Ia, i.e., the evolution of its brightness as a function of time, is marked by a characteristic peak shortly after the explosion and a gradually fading tail in the following months, powered by the radioactive decay of Nickel and Cobalt.

Three important developments paved the road for the groundbreaking discovery by the Nobel laureates. The first was the introduction of large mosaic charge-coupled device (CCD) cameras on 4-meter class telescopes, enabling the systematic search of thousands of galaxies over large areas of the sky for the rare supernova events. It was crucial to find the supernova at least before or around it would reach peak brightness. A second major development was the dramatic increase in computing power in the 1980s, enabling the vast amount of data processing necessary for an automated search of supernovae amongst the millions of galaxies that were monitored. The most important breakthrough was the finding that Supernovae Ia can actually be used as accurate cosmic standard candles. The discovery was made possible by the high quality supernova light curves and spectra obtained by the Calan/Tololo Supernova Search, led by Mario Hamuy. This enabled Mark Phillips in 1993 to find a tight correlation between the rate at which the luminosity of a type Ia supernova declines after the explosion and its absolute brightness. The luminosity distance of the supernovae is determined by relating the observed brightness to the inferred intrinsic brightness.

Redshift and Expansion

Driven and inspired by these important advances, the competing SCP team of Perlmutter and HZSNS team of Schmidt & Riess set out to measure the expansion history of the Universe. To infer the expansion history of the Universe, the distances to supernovae are measured as a function of their cosmic redshift. In cosmology, redshift is a direct manifestation of the expansion of the Universe: a source that has a redshift z emitted its light when the Universe was (1+z) smaller. In a strongly decelerating Universe, the physical distance of a supernova with a given redshift would be less than that in a weakly decelerating (or accelerating) Universe. At that redshift, it would translate into an object whose observed brightness would be higher in the strongly decelerating Universe. One may only imagine the surprise when it turned out they were even fainter, by ~0.25 mag, than they would be in an empty freely expanding Universe, indicating that the expansion has been speeding up for the past 6-7 billion years.

To reach and solidify this surprising finding, the SCP and HZSNS teams had to deal with a range of major practical and scientific challenges. On the practical side, there was the overwhelming logistic and political challenge of assuring vast amounts of (strongly contested) observing time on a range of telescopes, including 4 meter-class ones for probing the high redshift universe. Various astronomical effects might render the measurement of any subtle cosmological effect insignificant, and had to be corrected for. One major influence is that of dust, affecting the observed brightness of supernovae. Another major uncertainty was the poorly understood influence of heavy chemical elements on the supernova light curves. Such effects are sufficiently worrisome to have cast considerable doubt on the perplexing findings of the supernova teams. Their results remained intact, even after putting their results under heavy scrutiny through a large range of tests dealing with each imaginable pitfall or artefact. Of crucial importance was that independently the other competing team reached the same conclusion. Almost overnight, our view of the Universe underwent a major paradigm shift.

Paradigm Shift

To fully appreciate the significance of their discovery, we need to step back in time and assess the situation in cosmology in the late 1980s and 1990s. With hindsight, we can best characterize it as a brewing crisis. On the one hand, there was a successful "standard" cosmology. The Friedmann-Robertson-Walker (FRW) Big Bang universe had been augmented by an inflationary phase that should have taken place in the very early Universe. It offered a natural explanation of several of the remarkable fine-tunings of the FRW universe models. One

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of the firm predictions of inflation is that the universe should have a flat geometry. This means that the energy density of the Universe should be equal to the critical density (~2×10^{-29} g cm^{-3}), the density at which the Universe would have a flat geometry. It would imply that it is filled with vast amounts of undetected dark matter. However, by 1995 a range of astronomical observations had indicated that the total amount of dark and baryonic matter could not exceed 30% of the critical density. Perhaps the clearest mark of the impending crisis was the finding by the APM galaxy survey that the clustering of galaxies on Megaparsec scales differed significantly from the prevailing 'standard cold dark matter' cosmology. It led George Efstathiou, Steve Maddox and collaborators to remark that only the presence of a cosmological constant could make sense of these results. Equally pressing were the questions concerning the age of the oldest stars. Stars with ages of 13-15 billion years had been found in globular clusters. Even after this estimate got tuned down, they remained billions of years older than the implied age of the cold dark matter dominated Universe: an unacceptable situation.

In the previous decades there had been occasional speculations about the return of the cosmological constant as a major factor in the cosmological power game between the various cosmic constituents. Dismissed by Einstein himself after Hubble's discovery of the expansion of the Universe, as his "biggest blunder", the cosmological constant Λ would be the first suggestive source of a cosmic acceleration. In an attempt to estimate its natural magnitude on the basis of a quantum-mechanical interpretation as the energy of the vacuum, Yakov Zel'dovich in the late 1960s and Steven Weinberg in the mid 1980s argued that it should be no less than 120 orders of magnitude larger than suggested by observations. At an estimated 73% of the critical density, the dark energy content of the Universe falls "somewhat" short of Zel'dovich's estimate and underlines our total lack of understanding with respect to the nature of the dark energy.

▼ **FIG. 2:** Type Ia supernova SN2011fe is clearly visible as the bright, bluish star in the upper, right portion of spiral galaxy M101. The image was obtained on 18 September 2011 with the Mayall 4-meter telescope at Kitt Peak National Observatory. Image courtesy: T.A. Rector (University of Alaska Anchorage), H. Schweiker & S. Pakzad

In this situation of crisis, the discovery by the Nobel Laureates instantly settled the doubts and discussions. This may explain why their astonishing conclusion got almost instantly accepted and overnight changed the standard view of the Universe. In a sense it was a classic example of Kuhnian scientific revolution.

Consequences

What is the harvest of this seminal discovery? Vast, and even superseding that of Brian Schmidt's Australian vineyard, despite the fine wines he produces. Dark energy appeared to the fore as dominant dynamical influence in the Universe. The acceleration implies that the age of the Universe is substantially higher than previously assumed and the present age estimate of 13.7 Gyr solves the stellar age problem completely. With the exception of a few remaining issues, the current concordant ΛCDM Universe model appears to agree with an amazingly large and ever growing range of astronomical observations. Nonetheless, the fate of the Universe looks bleak, our fate lonely. Long before it will reach a near empty Dark Era, some 10^{100} years in the future, we will have lost contact with all surrounding galaxies as the accelerated cosmic expansion will have moved them out of view: the end of Cosmology. Inspired by the far-reaching ramifications of an accelerating Universe, a fast growing train of ever more extensive and costly research projects in astronomy, cosmology and physics is setting out to unravel the mystery of the dark energy. At the moment, not one of the hundreds of proposed theories has been able to unravel its nature. A large number of new profound questions have emerged, and a sense of thrill has taken hold of the astronomy and physics communities. The key to the dark lord of the world may very well be the key to our existence. It was in 1998 that the lock was detected, by the 2011 Nobel laureates. ■

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