Nobel Prize in Physics awarded for research in cosmology and exoplanets

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The latter half of the 20th century and the first decades of the 21st have witnessed an immense growth in humanity's understanding of cosmology and planetary astronomy, shifting them from fields that were based on either speculation or limited data to those that were decisively placed within a rigorously scientific framework. This year's Nobel Prize in Physics honors James Peebles, Michael Mayor and Didier Queloz for their integral roles in understanding the Earth's place in the cosmos.

James Peebles, who was born in Canada in 1935, began his career in cosmological studies while a graduate student, and then professor, at Princeton University. Since 1964, he has focused on what is known as physical cosmology, the study of the large-scale structures and evolutionary dynamics of the universe. His work has spanned the breadth of the field, including predicting the cosmic microwave background, leading the work to understand the structure of galactic clusters, making several contributions on the synthesis of elements just after the Big Bang and working to understand dark matter and dark energy.

Modern cosmology is based on Albert Einstein's theory of general relativity, which unified space and time as a single dynamic entity, spacetime, which is warped by the local presence of mass and energy. Using those equations, Soviet mathematician Alexander Friedman developed a theory for an expanding universe in 1922, which was confirmed by US astronomer Edwin Hubble in 1929. This led to the realization that if the universe is expanding, it must have originated as a single immensely hot and incredibly dense point. We now call this moment the Big Bang.

These early studies led to further developments in the 1940s which attempted to uncover why protons, neutrons and electrons formed into mostly just hydrogen and helium in the early universe and why matter clumps together to form galaxies and galactic clusters. Astronomers realized that these were related, that the primordial energies from which the building blocks of atoms emerged were also the initial conditions for what eventually became the galaxies, though the exact model to describe this process would not be developed for several years.

Peebles came to prominence after the 1964 discovery of the cosmic microwave background radiation, which confirmed predictions he and others made of the overall temperature of the universe. Peebles then realized that the detected temperature is directly related to the initial density of the universe and thus places constraints on how much and what types of matter were created by the Big Bang.

His major breakthrough occurred two decades later as scientists were working to determine how galaxies formed in the first place, because protons, neutrons, electrons and photons (particles of light) were not heavy enough to make matter coalesce in the early universe. Peebles suggested that it was dark matter, a type of invisible and still largely mysterious type of matter which was earlier theorized by Fritz Zwicky and Vera Rubin, and which makes up about a quarter of the universe. He played a critical role in the research that finally developed a model of sound waves in the early universe, known as baryonic acoustic oscillations, that caused the necessary clumping to eventually form galaxies. These theories have since been confirmed by the COBE, WMAP and Planck experiments.

It should be mentioned that cosmology is an immensely social and international field of study, which is not wholly captured by an award which can at most be granted to three individuals. Peebles himself has said, "It was not a single step, some critical discovery that suddenly made cosmology relevant but the field gradually emerged through a number of experimental observations. Clearly one of the most important during my career was the detection of the cosmic microwave background (CMB) radiation that immediately attracted attention ... [from] both experimentalists interested in measuring the properties of this radiation and theorists, who joined in analyzing the implications."

While the origins of the universe were relatively well understood by the mid-1990s, a critical question about the evolution of the universe still remained: Was the development of planets around the Sun a fluke or a common occurrence for most stars?

This was partially answered in 1992, when an exoplanet was first detected around a pulsar using the millisecond radio pulses emitted by the dead star. That technique, however, could not detect planets around Sun-like stars, and so astronomers turned to a method known as radial velocity.

This technique was developed by Otto Struve in 1952, and measures the wobble of a star as it travels through the galaxy caused by an orbiting planet. This is done by looking at slight shifts in the star's color, which becomes red when the star moves away from Earth and blue as it oscillates back toward our planet. These changes, however, are so minute it took four decades until technology was available to make reliable scientific observations.

These developments, primarily the ELODIE spectrograph, allowed Michael Mayor and Didier Queloz to start an observing campaign of 142 stars, a record in the early 1990s. By the fall of 1994, they noted that the star 51 Pegasi had periodic color shifts every four days. More surprisingly, the size of the shifts suggested a Jupiter-sized planet orbiting very close to its star, which had thought to be impossible based on the one data point of planetary formation that then existed, our own Solar System.

That aside, the short orbital period of the planet, dubbed 51 Pegasi b, allowed for many other teams to quickly confirm the discovery, including Geoff Marcy, Paul Butler and numerous others.

A special word should be said about Geoff Marcy, who developed novel experimental techniques that greatly refined our ability to eke out the minute wobbles of star motion caused by their orbiting exoplanets. Marcy and his team confirmed the discovery of 51 Pegasi b along with 70 of the first 100 exoplanets discovered, winning him many awards along with Mayor and Queloz, including the Henry Draper Medal, the Beatrice M. Tinsley Prize and the Shaw Prize, as well as being a contender for the Nobel.

He has, however, largely been ostracized by the astronomical community since 2015, when he was forced to resign from his Berkeley professorship through a Title IX procedure which included several anonymous accusations of sexual harassment. To this day, none of the accusations have been proven, much less presented in a court of law.

The discovery of 51 Pegasi b, unofficially known as Bellerophon (the tamer of Pegasus in Greek mythology), opened up a torrent of further exoplanet candidates and confirmations. In the ensuing five years, astronomers used the radial velocity to find dozens more planets, mainly large gas giants close to their parent star, revitalizing the field of planetary formation.

At the same time, the newly found exoplanets forced researchers to radically change their theories of how solar systems came to be. Every system has proven to be unique and added more difficulties to those attempting to make an overall model showing how so many different types of planets can develop at so many different orbits and around so many different types of stars.

Mayor's and Queloz's work also spurred the development of the Kepler spacecraft, which searched for exoplanets from 2009 to 2018. Instead of watching for shifts in a star's color, Kepler watched for periodic drops in a star's brightness, indicating a planet transiting between its parent star and the telescope. Using this method, Kepler was able to watch hundreds of thousands of stars and discover thousands of exoplanets. It firmly established a now accepted axiom of the universe, that virtually every star has a planetary system.

Moreover, Kepler has narrowed down the search for an Earth-like planet. It has found rocky planets smaller, larger and the same size as Earth, as well as planets at the right distance from their star to harbor liquid water on their surface. Ultimately, the study of exoplanets will not just lead to understanding how planets form. Its final goal is to shed light on how life itself evolves.

2019 Nobel Prize in Chemistry

The Nobel Prize in Chemistry 2019 was awarded to John B. Goodenough, M. Stanley Wittingham and Akira Yoshino for their development of lithium-ion batteries. Their work in the 1970s and 1980s has laid the basis for all modern rechargeable batteries, including those found in laptops, phones, power tools and electric cars, as well as storing electricity generated by wind and solar power.

Ever since Alessandro Volta demonstrated in 1799-1800 that electricity could be generated chemically using his Voltaic pile of zinc and copper, immense efforts have been directed toward making and storing electricity. This was spurred on by the industrial revolution and the electrification of countries which spread widely in the latter half of the 19th century. There have however been few genuine developments in making more efficient ways of extracting electrical energy from chemicals; lead-acid batteries were developed 150 years ago and are still used to start today's gasoline-driven cars.

The research that ultimately led to the development of lithium-ion batteries began in the 1960s when it became apparent that oil is a finite resource and that industries reliant on it, particularly the auto industry, would eventually have to find another source of energy. This drove Exxon to hire, among others, Stanley Wittingham in 1972 to research a variety of non-petroleum-based energy sources. Soon after, Wittingham discovered that tantalum disulphide has a crystal structure within which potassium ions can be placed, creating a very energy-dense material.

Wittingham eventually used lithium in conjunction with titanium disulphide (used to make the battery lighter) to make a battery where electrons would efficiently flow between the negatively charged anode and the positively charged cathode of a battery. Exxon abandoned the research, however, when oil prices fell and Wittingham was unable to stop his batteries from exploding.

This research was picked up by John Goodenough, who through a series of experiments recognized that mixing lithium with cobalt oxide would be twice as efficient at storing electric potential energy as Wittingham's design. Goodenough also found that batteries could be made uncharged, which helped to simplify the manufacturing process.

The decisive step towards commercially available batteries, however, came from Akira Yoshino, who worked at the Asahi Kasei Corporation, one of many companies in Japan looking for lightweight batteries that could power and make cordless phones, cameras and computers practical. Yoshino found that by replacing cobalt oxide with petroleum coke, his batteries were capable of being charged hundreds of times before they began to deteriorate.

Most importantly, Yoshino moved away from using pure lithium to lithium ions, which have one less electron in their atomic structure. The change in chemical structure meant that the batteries no longer exploded upon a shock, such as being dropped, and paved the way for the introduction of lithium ion batteries in 1991 and which have played a central role in all facets of modern electronics.