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Astronomers Receive the 2019 Nobel Prize in Physics

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ABSTRACT

The Nobel Prize in Physics of 2019 was awarded to three astronomers – James Peebles for theoretical discoveries in physical cosmology, and Michel Mayor and Didier Queloz for the discovery of an exoplanet orbiting a solar-type star. They revolutionized our view of the universe itself and Earth's place in the cosmos.

INTRODUCTION

Astronomy is an endless attempt to better understand the world surrounding us through observing the universe. Here, I intentionally distinguish between the *universe* (宇宙) and the *world* (世界); I refer to everything observable in space-time as the *universe*, while the *world* is employed for a much more abstract concept than the universe.

I admit that the above statement is merely based on my quite personal interpretation of the words. Nevertheless, it is certainly true that astronomy has played, and will continue to play, a leading role in establishing and improving our worldview.

The Nobel Foundation announced that the Nobel Prize in Physics for 2019 was awarded to three astronomers *for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos*. This is exactly what I have in mind for the unique role of astronomy, as mentioned in the above.

PEEBLES

The original idea of big-bang cosmology was proposed by George Gamow in late 1940's [1,2], which was subsequently developed by him and his students. They predicted not only the presence of cosmic black-body background radiation (now referred to as CMB), but even that its temperature should be around 5 K [3, 4].

The CMB was serendipitously discovered by Penzias and Wilson in 1965 [5], which proved to be tantalizing observational evidence for the big bang. Exactly at the same time, a group led by Bob Dicke in Princeton was attempting to detect the CMB. They published a *companion* paper [6] describing the cosmological significance of the Penzias-Wilson discovery preceding their short report [5] in the same issue of the Astrophysical Journal.

Peebles played a major role in the theoretical paper, and then started to write a series of pioneering fundamental papers in cosmology that connected the initial conditions imprinted in the CMB with the present large-scale structure of galaxies, on the basis of the laws of physics [7-10].

I started to study cosmology in 1983 when I joined a group led by Katsuhiko Sato, one of the pioneers in cosmic inflationary theories [11], at the University of Tokyo. The first textbook that I read as part of a reading class in this group was "The Large-Scale Structure of the Universe" by Peebles [12].

The book was published in 1980 and described almost everything necessary for theoretical research in cosmological structure formation. Amazingly, a substantial fraction of the material presented in the book was pioneered and developed by Peebles himself. In particular, I was so fascinated by an image illustrating the large-scale pattern

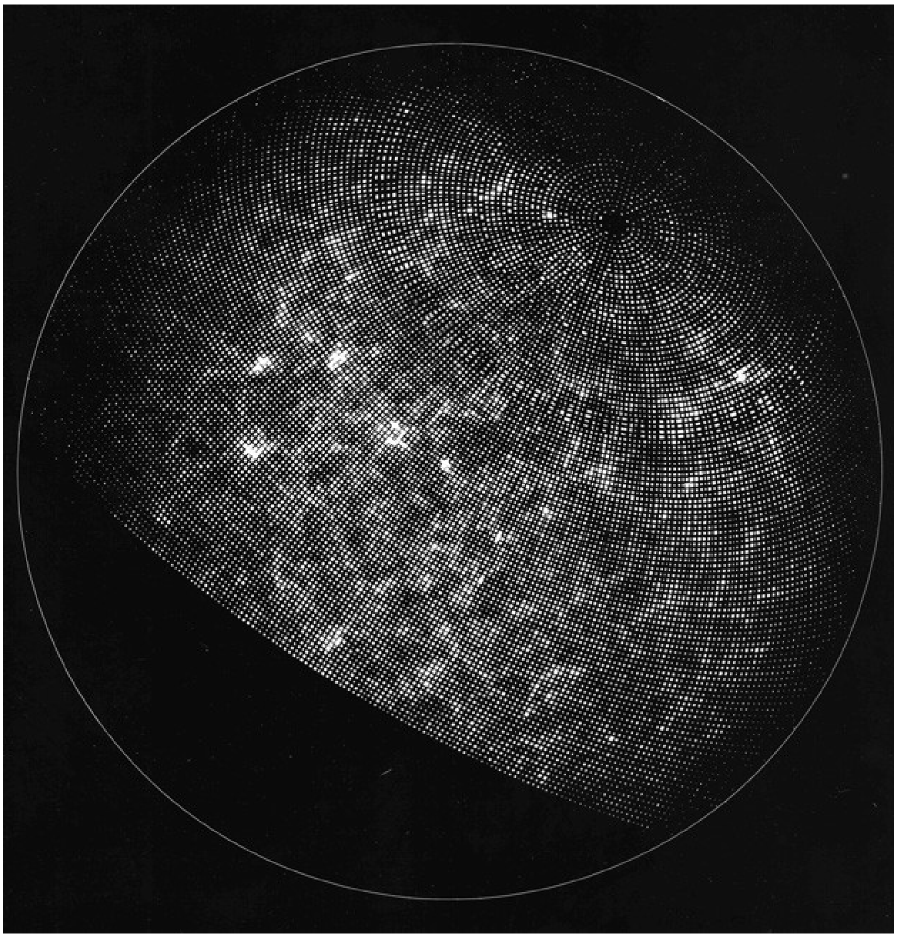

Fig. 1: Large-scale structure constructed from the galaxy number count of the Lick catalog of galaxies. This is a negative image of the figure that Peebles and his collaborators made using a computer to draw the squares and blacking the squares by hand. This plot is reproduced in the frontispiece of his textbook [12], indicating that cosmological information imprinted in the galaxy distribution can be deciphered from physical principles. (reproduced from Annu. Rev. Astron. Astrophys. 2012. 50:1-28)

of galaxy distribution reproduced from the Lick galaxy count (Fig. 1). The image indicated his clear perspective and the goal of *physical* cosmology: understanding the evolution of the universe by deciphering the information imprinted in large-scale structure in terms of fundamental physics. The textbook has continuously fascinated many students all over the world and inspired them to work on cosmology.

The current standard model of cosmology is often referred to as the Λ CDM cosmology. As its name implies, the universe is dominated by two major components: the cosmological constant (Λ) first introduced by Einstein in 1917, and cold dark matter (CDM).

Peebles realized that both Λ and CDM are required to explain several puzzles in cosmology, and published a few seminal papers that were very influential for convincing conservative astronomers at that time to recognize the unexpectedly important roles played by these two components [13-15].

Now, more than thirty years after these papers, all the current observations are explained to a surprisingly high precision by assuming Λ and CDM. This is why (almost) all astronomers are currently convinced of the existence of Λ and CDM, despite the fact that neither has been detected directly yet.

Peebles provided a standard framework for physical cosmology based on fundamental theories of physics so that its predictions could be quantitatively tested against precise observational data. The current standard model of cosmology has been established as a results of his numerous pioneering contributions to theories of cosmic structure formation.

MAYOR AND QUELOZ

Worldviews in ancient Greek cosmology were based on the geo-centric theory. Ptolemy's *Almagest*, for example, presented a world model in which the Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn, and the stars on the celestial sphere are orbiting around the Earth located at the center of the universe. Since the Solar system was supposed to occupy such a unique position in the world model, it should be natural to believe that no other planetary system existed in the universe.

While the presence of exoplanetary systems had merely been a philosophical question for a long time, serious attempts at observational search started only in the 1980's. Their observational strategy, however, assumed that our Solar system should be typical among possible exoplanetary systems.

Jupiter, the largest planet in our Solar system, is fainter by eight orders of magnitude than the Sun. Such a faint planet is almost impossible to detect due to the presence of the bright host star just next to it. A more realistic possibility is to search for a periodic modulation of the stellar radial velocity relative to us due to the barycentric motion of the star.

In order to maximize the detection efficiency of limited telescope time (remember that the orbital period of Jupiter is 12 years), it is reasonable to monitor as many stars as possible while each star is observed once every few months over a decade, for instance. Such a long-term monitoring of something that may not exist at all is likely to be regarded as high-risk and low-return research.

Indeed, there were only a very small number of groups seriously attempting to discover exoplanets. Duquennoy, Mayor and Halbwachs (1991) monitored 291 stars for 13 years starting in 1977, and found no candidate star with a planetary companion [16]. Walker et al. (1995) performed radial-velocity monitoring of 21 bright solar-type stars over 12 years, but found no planetary companion, either [17].

Mayor and Queloz selected 142 stars with no sign of velocity modulation out of the 291 stars and restarted their monitoring using a new spectrograph with much higher resolution in April 1994. In as early as September 1994, they found that a solar-type star, 51Peg, exhibited a significant velocity modulation. From their subsequent monitoring and careful analysis over a year, they concluded the presence of a 0.47 Jupiter mass planet in a 4.2-day orbit around 51Peg. They submitted a paper on August 29, 1995 [18], just after Walker et al. published their negative conclusion in August 1995 [17].

Since their discovery, dubbed a hot Jupiter (a giant gas planet orbiting around a host star in less than a week), was so unexpected from the architecture of our Solar system and inconsistent with the standard model of planet formation, it was received with surprise and skepticism as well. They reported their discovery at a conference on October 6 1995, which was immediately confirmed by one of the participants G.Marcy and his collaborators within a week or so.

This implies that a few groups other than Mayor and Queloz indeed could have achieved the first discovery of an exoplanet, even though nobody at that time, including Mayor and Queloz themselves, had expected the presence of such hot Jupiters before their discovery.

Another milestone is the discovery in 2000 of HD209458b that transits a Sun-like star, simultaneously and independently made by Henry, Marcy, Butler and Vogt [19] and Charbonneau, Brown, Latham and Mayor [20]. Transiting planets can be detected photometrically alone without expensive spectroscopic observations. This is why *Kepler*, a dedicated mission for transiting planets launched in 2009, discovered thousands of transiting planets and revolutionized the field.

I would like to note that 51Peg b is not the first exoplanet ever discovered, but *the first exoplanet discovered around a Sun-like star*. Wolszczan and Frail had discovered two planets orbiting a millisecond pulsar in 1992 [21]. This is also an amazing discovery, but it turned out that such pulsar planets are rare, and thus, unfortunately, did not attract much attention especially among optical astronomers.

In any case, the discovery by Mayor and Queloz suddenly and completely changed the nature of exoplanet research from high-risk and low-return to low-risk and high-return science! Many astronomers decided to seriously join the exciting new field and to explore a variety of exoplanet sciences, such that the number of confirmed planets exceeded 4000 as of November 2019 (Fig. 2). We now know that the presence of exoplanetary systems is universal, but they exhibit amazing diversity that nobody had imagined before the discovery by Mayor and Queloz.

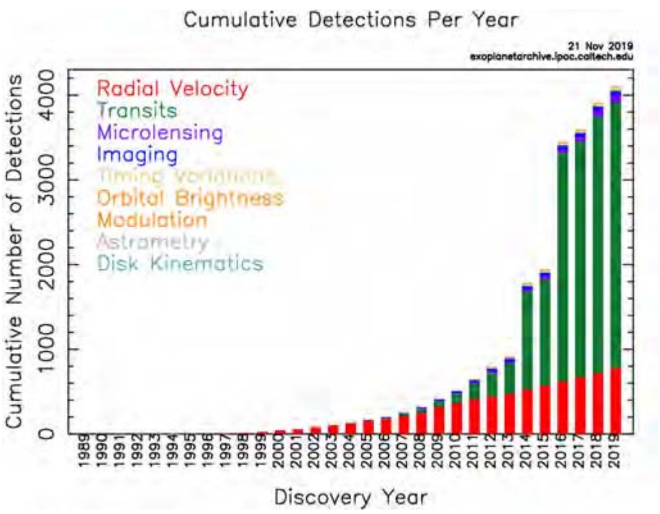

Fig. 2: Cumulative number of detected exoplanets as of November 21, 2019. https://exoplanetarchive.ipac.caltech.edu/exoplanetplots/

CONCLUSION

The Nobel Prize in physics of 2019 was awarded to three astronomers who have revolutionized our worldviews. They have literally shown that *"There are more things in heaven and Earth, Horatio, than are dreamt of in your philosophy"* and *"We did not know at all. We did not know anything"* [22]. Therefore, their discoveries are *not the end. They are not even the beginning of the end, but should be the end of the beginning.*

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