From the margins to the mainstream: Nobel celebrates exoplanets!

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Abstract

This year's Physics Nobel Prize was jointly awarded to three scientists. Phillip James Peebles from Princeton University, USA, received one half of the prize for his seminal work on physical cosmology, and other half was shared by Swiss scientists Michel Mayor and Didier Queloz for the discovery of an exoplanet around a solar-type star 51 Peg. While James Peeble's contribution helped us understand the structure and evolution of the Universe at large scale, the exoplanet discovery was a watershed moment in humanity's quest to seek answers to fundamental questions about the existence of planets and life elsewhere in the Universe. Exoplanet research, once a marginal field, has now become a principal area of research in Astronomy and Astrophysics. In the context of exoplanetary search, we will trace the historical development of the subject and how new ideas and technological innovations paved the way for the rapidly expanding field of exoplanets.

Introduction

One half of the Nobel Prize for physics for the year 2019 was awarded to Michel Mayor and Didier Queloz (see Figure 1) for their discovery of the first exoplanet orbiting a sun-like star. Exoplanets are planets orbiting stars other than the sun. Although their existence was speculated for a long time and various attempts were made to detect them starting from the 1980s, it was Mayor and Queloz who achieved the first firm detection of an exoplanet around the main sequence star 51 Peg in 1995. Their discovery ignited the field of exoplanets, and paved the way for several dedicated missions – both ground-based and space-based – to detect exoplanets, resulting in an explosion in our knowledge and understanding of extra-solar planetary systems in the last two decades. While we knew only of one planetary system around a sun-like star until 1995, that number has crossed the 4000 mark now.

Why was the Nobel Prize awarded to this discovery? It is not so much for the new physics that this discovery has brought to the fore, but primarily for overcoming the enormous technical challenges involved in detecting exoplanets. Also, for the profound impact this discovery had on the scientific field and on the public imagination. In this article, we will first discuss the physics, the techniques and the history of the detection, and then provide a brief overview of the current status of the field by summarising what we have learned so far about exoplanetary systems, and how it is challenging our long held notions about the formation and evolution of planetary systems.

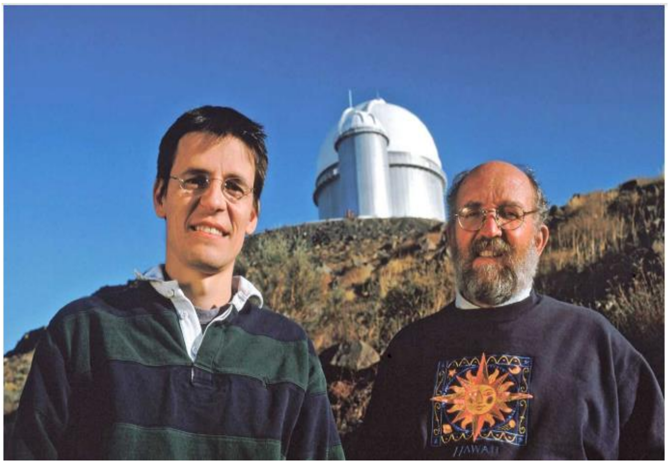

*Figure 1***:** *Winners of 2019 Physics Nobel Prize, Didier Queloz and Michel Mayor at La Silla Observatory in Chile (Credit: L. Weinstein/Ciel et Espace Photos)*

From the margins to the mainstream

Early days of exoplanet research were subject to extreme scepticism. So intense was this scepticism and disbelief that it destroyed the careers of some of the pioneers who were instrumental in developing the technique that would later become one of the most successful search method for exoplanets. Bruce Campbell, one of the Canadian astronomers, who pioneered this technique, had to quit astronomy in frustration.

In the words of the Nobel winner Didier Queloz, the early days were hard: "*Back then, exoplanet research was a very small field. I think there were about fifty of us and we were seen as weirdos. Now there are probably over a thousand people working in the field."* Sara Seager, another pioneer in exoplanetary atmospheres, who is a professor at MIT agrees: *"To see a field go from obscure, fringe and laughable to Nobel-worthy is a huge tribute to people all around the world making exoplanets real. In exoplanets, the line between what is considered completely crazy and what is considered mainstream science is constantly shifting. The Nobel award is a cataclysmic shift in the right direction."* Martin Rees, Astronomer Royal and an Emeritus Professor at the University of Cambridge concurs in his response to the news of exoplanet discovery winning the Nobel prize: *"The study of exoplanets is perhaps the most vibrant field of astronomy."*

The field of exoplanet research has come a long way. It has emerged as a principal area in astronomy now. More than 10% of the scientific sessions in all the major international astronomy & astrophysics meetings and about 25% of the science cases for all major existing and upcoming astronomical facilities are on exoplanets now.

The technique: challenges and solutions

From stars to planets

In the modern era, the physical motivation for planet search came from a renowned astronomer Otto Struve in 1952. Struve had measured the rotational velocity of the main sequence stars and showed that stars of spectral type F5 and later have very low rotational velocities. If stars are formed by gravitational contraction of interstellar gas and dust cloud then they should have high rotation rates. How do you explain this angular momentum deficit in majority of the main sequence stars? Struve argued that stars lose their angular momentum to the rotating disc where planets are eventually formed. So the slow rotating main-sequence stars, according to Struve, were perfect targets for the planet search programme. Not only Struve gave physical basis for the existence of planets around stars but also proposed techniques to detect them. Two most successful methods used today for planet detections, namely the radial velocity and the transit method, were originally proposed by Otto Struve. However, the lack of suitable technology in the 1950s was a major bottleneck. Even if planets were common, the expected transit or Doppler signal was way too small to be detected. The existing instruments at that time were not sensitive enough to tease out tiny signatures of planets from the starlight.

Radial velocity (RV) method

The RV method is based on the principle of Doppler shift caused by the relative motion of a star along the observer's line of sight. Due to mutual gravitational force the star-planet pair revolves around a common center-of-mass which is often very close to the center of the star. Since a distant observer cannot see the planet directly, its presence has to be inferred indirectly from the reflex motion of the star and the effect it has on the starlight. The electromagnetic radiation emitted by a typical sun-like star has thousands of characteristic absorption lines superimposed on a blackbody continuum. Apart from revealing the chemical composition and prevailing physical conditions (e.g. temperature, pressure, density etc) on the surface of the star, the stellar absorption lines are excellent proxy for detecting planet induced motion of the star via Doppler method.

A near-edge on configuration of a star and its planetary companion is illustrated in Figure 2. From an observer's view point, the orbital motion of the star at any instant can be resolved into radial part -also called the line-of-sight component, and the transverse part. Clearly, the star has largest radial velocity component at location B and D and accordingly the spectral lines will show maximum blue and red-shift. On the other hand, transverse component dominating at location A and C renders no wavelength shift. It is necessary to take multiple observations of the stars to derive complete information about its orbital parameters. Notably, the planetary mass ($m\times\sin i$) derived using RV method depends on the angle of inclination i.

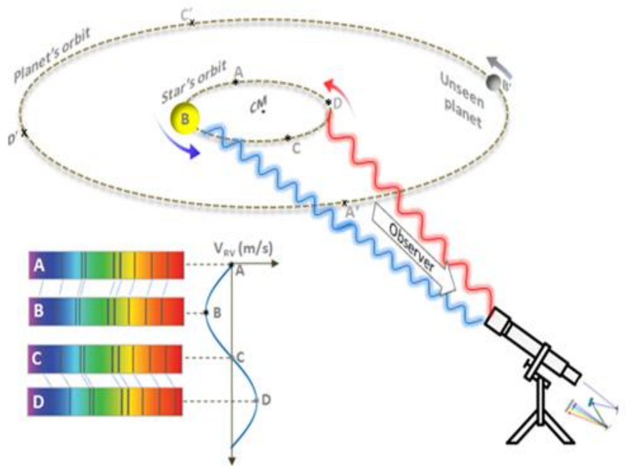

Figure 2: A star and a planet revolve around a common center of mass (CM). For a distant observer, the line-of-sight velocity component of the star appears to vary during its orbital motion. The starlight collected by a telescope is analyzed by a high-resolution spectrograph. Spectral lines are blue-shifted when the star's motion is towards the observer (location B) and red- shifted when it is away from the observer (location D). No line shift is expected at location A and C. A complete RV phase curve of the star can be obtained by observing the star at multiple epochs in its orbit.

The technical challenge: RV precision

In the non-relativistic limit, the radial velocity of the star V_{RV} can be determined from the Doppler formula as:

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda_{obs} - \lambda_{res}}{\lambda_{res}} = \frac{V_{RV}}{c} \qquad (1)$$

where $\Delta\lambda$ the wavelength shift, c is the speed of light, λ_{obs} and λ_{res} observed and rest frame wavelengths.

For a given star, the RV amplitude is larger for high mass planet and small orbital distance, while the opposite is true for when the planet mass is low and orbital distance is large. If we consider the example of our solar system, the gravitational tug of Jupiter orbiting at 5AU distance would cause the Sun to move at a speed of 12 m/s. Using Eqs (1) this translates to a wavelength shift of 10^{-14} m (10^{-5} nm) in the visible light spectrum.

In astronomical spectrographs, starlight is split by a dispersing element such as a grating/prism before the spectrum is digitally recorded on a CCD detector array. For a typical resolution ($R = \Delta\lambda/\lambda \sim 50{,}000$) of the astronomical spectrographs at optical wavelengths, we get the resolution width as $\Delta\lambda \sim 0.1$Å. For Nyquist sampling, $\Delta\lambda$ should be registered at least on 2 pixels, giving a spectrograph dispersion of 0.05 Å/pixel. In velocity units, this corresponds to 2-3 km/s per pixel element. Clearly, the RV induced spectral shift (12 m/s) by a Jupiter-mass planet is a tiny fraction (~10^{-3}) of the pixel unit. Furthermore, the Doppler wobble induced on Sun by Earth from 1 AU distance is merely 10 cm/s, making the detection of Earth analogues a formidable task from ground even with the current technology.

For planet detection, the real challenge is to keep the spectrum of the star stable on the CCD pixel array at sub-nm level! However, various sources of instrument noise cause the spectral lines to move on the detector plane. The noise induced motion of spectral lines directly translates to RV errors that are several orders of magnitude larger than the actual Doppler signal that we intend to measure.

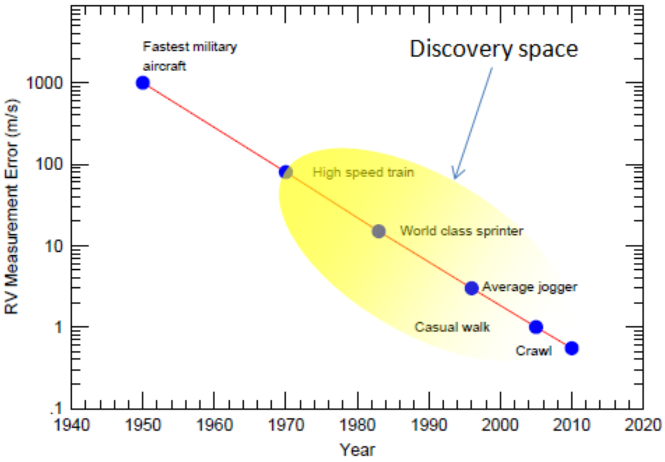

Figure 3: A chronology of improvement in RV precision over time (A. P. Hatzes, Chapter 1 in "Methods of Detecting Exoplanets", Springer 2016).

During normal observations both telescope and spectrograph are exposed to environmental and technical perturbations of varying severity. A telescope forms the star image at a specific focal plane where the spectrograph is attached. The stellar spectrum is taken by keeping the stellar image fixed on the entrance slit of the spectrograph. However, the stellar image moves randomly because of several factors such as changing atmospheric seeing conditions, slow thermal and gravity loading of the mechanical structure and imperfect guiding and tracking of the telescope. Likewise, the inaccuracies in the wavelength calibration source lead to RV errors of the same order.

RV precision: solutions

Efforts spanning several decades were just devoted to overcome the difficulties outlined in the previous section. Teams interested in planet search programmes had taken two different approaches to solve the RV problems as discussed below.

1. *Stabilized spectrographs*

After the sources of RV errors were correctly identified, many remedial steps were taken by different groups to mitigate them. A significant change came from spatially decoupling the spectrograph from the telescope. A desired stability was achieved by installing the spectrograph on a vibration-free platform housed inside a temperature and pressure controlled room. The light from telescope to spectrograph was transported by optical fibers. The scrambling property of the fiber ensured that slit illumination was stable all the time.

A simultaneous reference scheme was developed to take the star and Th-Ar wavelength calibration spectra at the same time. This was helpful in tracking zero-point drifts of the spectrograph during star's observation. The radial velocities of the stars were derived by performing simple cross-correlation between the observed spectra and the numerical template of the star. New technology (high quantum efficiency CCDs, double scrambler made with hexagonal fiber, white pupil design, cross-dispersed high resolution echelle gratings etc) was incorporated to further improve the spectrograph performance. By early 1990s these efforts brought down the RV errors down by a factor exceeding 1000.

2. *Absorption cell spectroscopy*

The self-calibrated absorption cell technique was pioneered by Bruce Campbell and Gordon Walker in the 1980s. They used a hydrogen-fluoride (HF) cell in the telescope beam path and achieved a remarkable precision about 15 m/s (1979). The long path length (~ 1m) of the cell and high toxicity of the HF gas turned out to be a major operational hurdle. Later, Butler and Marcy used Iodine gas cell which has strong absorption lines from 500-630 nm, making it an ideal substitute for the HF cell. The Iodine cell is heated to 60-70^o C temperature where molecular iodine exists in the vapour form. During the stellar exposure, Iodine absorption features are superimposed on the star spectra. Unlike stabilized spectrograph, absorption cell technique does not attempt to eliminate the noise. Instead, the instrumental noise becomes common to stellar and Iodine lines. Using a powerful forward modelling code, it can track and calibrate all changes in a spectrograph, even if it is unstable.

After several years' hard work, 3m/s Doppler precision was achieved with Iodine cell in 1996. The price paid for the high precision was large computational time and the complexity of the code. The attractive feature of Iodine technique is that it works on any general purpose spectrograph without the need for additional design changes and stabilization. This way the exoplanet field became more accessible to a larger community of astronomers worldwide.

A gradual evolution of radial velocity precision is shown in Figure 3. With these trends still holding, the next generation of ultra-stable spectrograph equipped with new calibration technologies such as laser frequency combs will bring the RV precision to a few cm/s level.

The history: the pioneers who made the discovery possible

(i) Roger F. Griffin (1967-)

Roger Griffin at Cambridge, UK built the first cross-correlation spectrograph reaching 100 m/s precision on bright targets (1967). Major source of RV errors were identified by Griffin, which eventually led to the development of stabilized spectrographs. He also showed that telluric lines can be used as a stable wavelength reference (1973). This idea was the basis for the later advancements of the absorption cell spectroscopy developed by Campbell and Walker and perfected by Marcy and Butler.

(ii) Campbell & Walker (1981-1988)

The first systematic radial velocity search for substellar companion orbiting a sun-like star was carried out by the Canadian team led by Gordon Walker and Bruce Campbell. Using the Canada-French Hawaii telescope on Mauna Kea, Hawaii, they started their ambitious survey in 1981. They pioneered the absorption cell technique for robust wavelength calibration and employed an absorption cell of Hydrogen Fluoride (HF) to achieve an RV precision of 10 - 15 m/s. They, in fact, reported the detection of 1.7 Jupiter mass (M_J) planet with an orbital period of 2.7 years around the star γ Cep, but later retracted the result. Eleven years later, the existence of this planet would be reconfirmed.

(iii) Latham et al. (1984-1990)

David Latham and his team were the first to use stabilised spectrographs fed by optical fibers in radial velocity work. They serendipitously discovered a 13 M_J companion (orbital period 84 days) to the F-type star HD 114762. Although the mass was too high to be considered a planet at that time, this was the first firm detection of a substellar object beyond the solar system.

(vi) Marcy & Butler (1992 -)

Geoffrey Marcey and Paul Butler of San Francisco State University carried out one of the largest radial velocity survey of 70 nearby stars searching for exoplanets using the Hamilton spectrograph at Lick Observatory. They used iodine absorption cell to obtain a RV precision of 25 m/s in 1992. They were the first to model variable instrumental profile as a function of wavelength, and were able to achieve a high RV precision of 3 m/s by 1996. Unsurprisingly, they detected about half of the exoplanets discovered during the next 15 years.

(v) Hatzes & Cochran (1993 -)

Hatzes & Cochran from Texas (US) demonstrated that they achieve a RV precision of 10-20 m/s by making use of telluric O_2 bands for calibration. They tentatively reported the detection of a 3 M_J planet around the bright K giant star Pollux (β Gem).

(vi) Mayor & Queloz (1994 -)

Mayor and Queloz used newly built fiber-fed echelle spectrograph ELODIE (shown in Figure 4) to observe a selected sample of stars between 1994-95. They found a strong RV signal (see Figure 5) from 51 Peg, indicating a definitive presence of planetary companion. This Nobel prize winning work was published in November 1995 issue of *Nature*. Earlier Mayor had built Correlation Radial Velocity (CORAVEL, RV precision 300 m/s) spectrograph that was used to conduct a large survey of solar-type stars and binary systems. In 1989, observations taken by Mayor with CORAVEL and by Latham at Oak Ridge observatory had indicated a 13 M_J companion around HD 114762. Subsequently, Mayor was also involved in the development of several other successful spectrographs such as CORALIE, SOPHIE and HARPS. Together, the Swiss group led by him has discovered over 300 planets using the RV method.

Figure 4: The 1.9m telescope at Haute-Provence Observatory in Southern France (Left panel). The ELODIE spectrograph credited with the discovery of 1st exoplanet was located in a separate room below the observatory floor (right panel). Fiber-pick up and calibration assembly attached to the Cassegrain focus of the telescope can be seen in the inset. (Image from: www.obs-hp.fr)

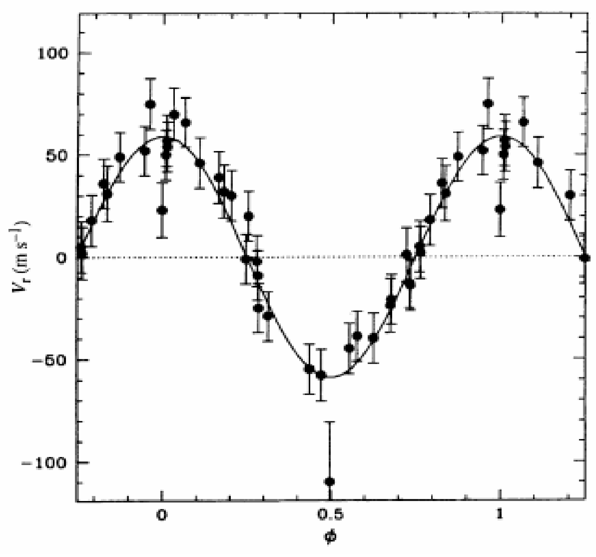

*Figure 5: The RV phase curve of 51 Peg as reported in the discovery paper (Mayor and Queloz, Nature **378**, 355, 1995).*

Current Status

We have come a long way since the discovery of the first exoplanet. We now know of more than 4000 confirmed exoplanets, and the number is likely to increase manyfold with the next generation of exoplanet missions. Previous space-based exoplanet missions like Kepler and CoRoT along with ground-based facilities such as HARPS, WASP, HIRES and KELT have shown us that exoplanets are ubiquitous.

What have we learned so far about exoplanetary systems?

(i) There are more planets than stars in the Universe!

One of the major findings of the Kepler mission is the fact that exoplanets are extremely common. By modeling and characterizing both the planets in the Kepler field as well as the Kepler telescope's detection efficiency, it is possible to calculate the average number of planets around a star. It appears that every star in the Kepler field has about 1.5 planets around it. This means that almost every star hosts more than one planet, and that there are more planets in the Universe than stars.

(ii) Our solar system is not an archetypal planetary system!

Up until the end of the last millennium, it was generally thought that our solar system is a model planetary system. Our understanding of how planetary systems formed was primarily based on our solar system. However, from the observed properties and the architecture of known exoplanetary systems, it is becoming increasingly clear that our solar system perhaps is not a representative planetary system.

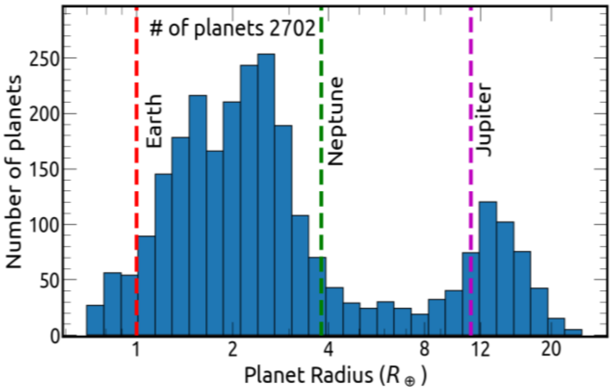

Figure 6: The radius distribution of all known exoplanets in units of Earth radius ($R_\oplus$). The coloured dashed lines are marked to show the radius of Earth, Neptune and Jupiter.

The radius/mass distribution of all the known exoplanets show that most planets have radius/mass between that of the Earth and Neptune (see Figure 6). Planets with sizes between Earth and Neptune appear to be the most common in our galaxy. Interestingly, there is no such planet in our solar system! Also, small planets are more common than Jupiter-size gas giants. Only less than 7% of the stars have Jupiter-like planets. Further, the period distribution of exoplanets is very different from planets in our Solar System. Most exoplanets have a period of less than 30 days (see Figure 7). This means that they are almost 10 times closer to their parent star than Earth is to the Sun, orbiting well inside the orbit of Mercury (orbital period ~ 88 days). The results quoted above are valid even when corrected for observational biases and selection effects, indicating that solar system is, perhaps, not an archetypal planetary system.

(iii) Know the star, know the planet

One of the important results that is becoming increasingly evident is the strong dependence of the planet properties on their host star properties. It is as though the planets know what star it is born around! For example, it is found that stars hosting gas giant like Jupiter have high iron (Fe) content than stars that do not host giant planets. Further, cooler low-mass stars seem to host more planets than hotter massive stars: stars that are cooler than the Sun (M dwarf stars), on average, have 2 planets per star while stars hotter than the Sun (F type) have about 0.7 planets per star. Sun-like (G & K type) stars tend to have about 1.5 planets per star. It is also found, however, that sun-like stars, on average, host more giant planets than cooler low-mass stars.

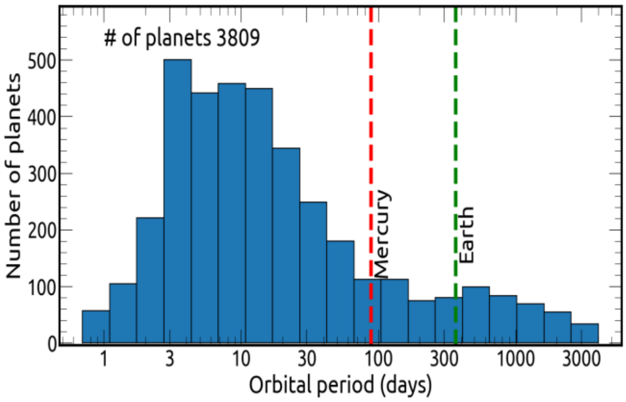

Figure 7: The period (in days) distribution of all known exoplanets. The colored dashed lines are marked to show the period of Earth, Neptune and Jupiter.

Future frontiers

The award of the Nobel Prize has recognized the emergence of exoplanetology from the margins to the mainstream of astrophysics research. Coming years will see more exciting discoveries and rapid growth of the field. With a suite of space telescopes scheduled to be launched and several large-aperture (30 meter class) ground-based telescopes becoming operational in the next two decades, one can expect to come closer to finding a “second Earth", while at the same time adding more exotic and unexpected planets to the ever growing number. Continuing our tryst with exoplanets we have learned “*of infinite worlds to exist beside this our earth*” as Giordano Bruno had insightfully speculated in the sixteenth century. We have found planets around dead stars and planets around stars that are being born. We have also found planets that are so close to their stars that they are a hellish landscape, but haven’t yet found a habitable planet like our Earth. The search for another pale blue dot, a lonely speck somewhere in the great enveloping cosmic dark, is on.