FINDING NEW WORLDS: DIDIER QUELOZ AND MICHEL MAYOR'S NOBEL PRIZE IN PHYSICS 2019

ENCONTRANDO NUEVOS MUNDOS: LOS PREMIOS NOBEL DE FÍSICA 2019 DE DIDIER QUELOZ Y MICHEL MAYOR

R. CÁRDENAS†

Planetary Science Laboratory, Universidad Central "Marta Abreu" de Las Villas, Santa Clara, Cuba; rcardenas@uclv.edu.cu†
† corresponding author

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I. INTRODUCTION

Since ancient times, humans have speculated on the potential existence of other Solar Systems, with planets orbiting a parent star [1, 2]. In 1952 a method based on the measurement of stellar radial velocities was proposed to detect exoplanets [3]. However, formidable technical challenges remained a major obstacle for several decades. In 1992 –40 years later– the first observational detection of exoplanets was reported by astronomers Aleksander Wolszczan and Dale Frail [4]. Using the Arecibo radio telescope, they detected two giant planets orbiting the pulsar PSR B1257+12 in the constellation of Virgo. Many astronomers were surprised, as they expected to find such planets only around main sequence stars.

II. THE METHOD OF STELLAR RADIAL VELOCITIES TO DETECT EXOPLANETS

As mentioned above, the first method to detect exoplanets was based on the measurement of stellar radial velocities. A star and its exoplanet revolve around the centre of mass of the system (the barycenter), as illustrated in Figure 1.

Due to the Doppler effect, an observer on Earth will receive blue-shifted light when the star is moving towards him (or her), and red-shifted light when the star is moving away from him (or her). Including relativistic effects, the redshift z can be calculated as,

$$z = \frac{\lambda_0 - \lambda}{\lambda_s} = \sqrt{\frac{1+\beta}{1-\beta}} - 1, \tag{1}$$

where λ_0 is the wavelength detected by the observer on Earth and λ_s is the wavelength in the reference frame of the star, and the parameter β is defined as:

$$\beta = \frac{V}{c}, \tag{2}$$

where V is the radial velocity of the star relative to the observer on Earth (taken positive if the star is receeding, and negative if it is approaching), and c is the speed of light in vacuum. For the non-relativistic limit, it can be shown that,

$$z \sim \beta = \frac{V}{c}, \tag{3}$$

which is the classical expression for the radial redshift caused by Doppler effect (we note that motion in the transverse direction causes the so called transverse Doppler effect, so far of little or no use for exoplanet detection).

As follows from equations 1 and 2, measuring z would allow calculating V, the velocity of the star. However, this is strictly true only if the stars woobles in the line of sight of the observer on Earth, so the inclination i of the planet's orbit respect to the line perpendicular to the line-of-sight should be considered:

$$V = \frac{V_D}{\sin i}, \tag{4}$$

where V_D is the observed (Doppler) velocity of the star. Also, the period of motion of the star can be determined using Doppler spectroscopy, while its mass is typically determined using the well-known mass-luminosity relationship. Once the stellar properties are determined (radial speed V, period T and mass M), it is possible to determine some properties of the exoplanet.

First we may apply the third Kepler's law (the square of the orbital period T of a planet is directly proportional to the cube of the semi-major axis of its orbit r):

$$r^3 = \frac{GM}{4\pi^2} T^2, \tag{5}$$

where G is the gravitational constant and, as both periods are equal, in 5 it is used the observed period of the star, T. Having determined r, the velocity of the planet v around the star can be calculated using Newton's law of gravitation and the orbit equation:

$$v = \sqrt{\frac{GM}{r}}. \tag{6}$$

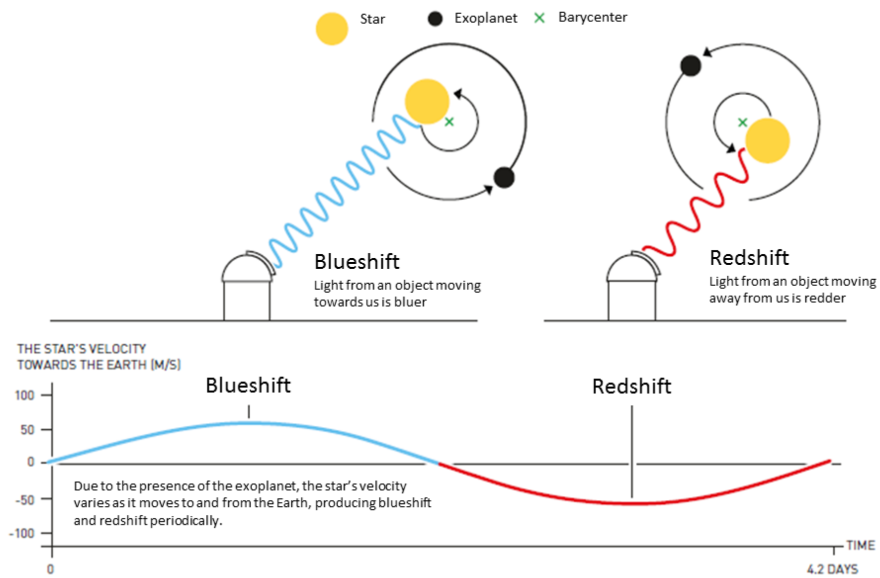

Figure 1. Use of the Doppler effect to estimate the radial velocity of a star, as seen from Earth. Figure modified from [5].

Then, application of the conservation of linear momentum allows determining the mass m of the planet:

$$m = \sqrt{\frac{MV}{v}}. \tag{7}$$

There are other methods to detect exoplanets. For instance, Transit Photometry, which uses the decrease of the intensity of star's light when the planet passes through the line of sight of an observer from Earth. Also Gravitational Lensing and other more recent methods [5].

III. A NEW EPOCH IN EXOPLANET DETECTION

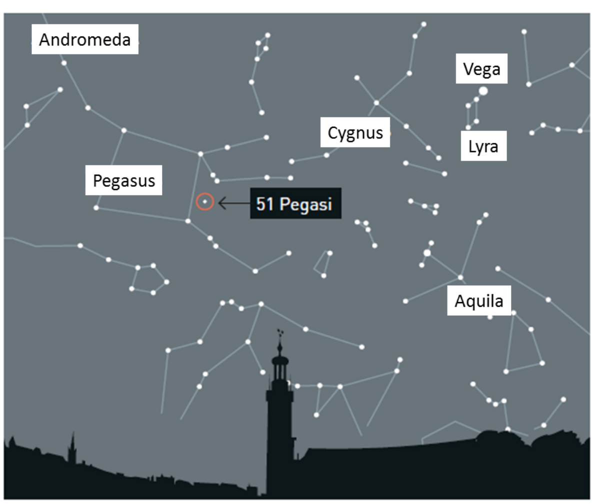

Figure 2. Position of 51 Pegasi b, the first exoplanet detected orbiting a main sequence star. The sketch represents the sky over Stockholm in October. Figure adapted from [5].

Someone monitoring our Solar System would observe a radial velocity change of ± 13 m/s of the Sun over 12 years due to the orbital motion of Jupiter [1]. Of course, this tiny variation imposes a severe challenge from the observational point of view.

Michel Mayor at the University of Geneva, André Baranne from the Marseilles Observatory and collaborators designed a new echelle spectrograph: the ELODIE instrument [6, 7]. Using it on a sample of 142 stars, and surveying around 5000 spectral lines for Doppler spectroscopy, they found that the radial velocity of the star 51 Pegasi (in the Pegasus constellation), had variations with a period of about four days (see Figure 2). In 1995 Didier Queloz and Michel Mayor announced the discovery of 51 Pegasi b, the first detected exoplanet orbiting a main sequence star [8]. Because of this breakthrough discovery, they have been awarded the Nobel Prize in Physics 2019 (shared with Jim Peebles for theoretical findings in Cosmology; see the corresponding article in this issue).

IV. IMPLICATIONS FOR ASTROBIOLOGY

The first announcement of a confirmed exoplanet [4] was taken with caution by the Astrophysics community: several previous claims of discovery had been later rejected because of experimental noise. Additionally, theory predicted only a very small fraction of planets orbiting a pulsar (which has been confirmed late on). Thus, the discovery of Michel Mayor and Didier Queloz of the first exoplanet orbiting a Sun-like star opened a new door in Astrophysics and Astrobiology. Five years after the discovery, when the first review "post–51 Pegasi" appeared, 34 exoplanets had been discovered orbiting

Sun-like stars [1, 2], and as of 7 November 2019, there are 4093 confirmed exoplanets, and more than 3000 expecting for confirmation [9].

An inmediate question arose: are exoplanets habitable? It motivated a closer link between astrobiologists, planetary scientists and environmentalists. It also contributed to further development of the quantification of habitability, with three (complementary) approaches: the astrobiological one, the biogeochemical one and the ecological one. Based on metrics of quantitative habitability, there exists a catalog of potentially habitable exoplanets, maintained by the Laboratory of Planetary Habitability of the University of Puerto Rico at Arecibo [10]. So far, it acknowledges 55 potentially habitable exoplanets using climatological criteria, especially the possibility of having liquid water at the planetary surface [11]. However, it should be noticed that, in our planet, it is estimated that the subsurface biosphere is comparable in mass and volume to the surface one, a fact that multiplies the possibilities of existence of living entities in other planetary bodies. Of special interest is the so-called chemolitoautotrophic life, which uses chemosynthesis instead of photosynthesis to fuel its metabolism, being independent of the availability of sunlight. Therefore, at the Planetary Science Laboratory of Universidad Central "Marta Abreu" (Santa Clara, Cuba), habitability metrics for chemolitoautotrophic life are being developed [12].

V. NAMING EXOPLANETS

The frequent discovery of exoplanets has promoted campaigns to name them [13], led by the International Astronomical Union (IAU). In Cuba, a commission of 5 scientists is working to name the star BD-17 63 (an orange dwarf star) and its exoplanet BD-17 63 b. This system is located at the constellation Cetus (the Whale) and, as ruled by IAU, is visible from Cuba, the naming country.

VI. CONCLUSIONS

The breaktrough Discovery of Didier Queloz and Michel Mayor changed forever our points of views concerning our place in this vast Universe. In particular, the possibility of life in some of these "strange new worlds" has motivated a revolution in Astrophysics and Astrobiology, implying collaborations between astrobiologists and environmentalists [12, 14–16].

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