Thousands of planets

Andrzej Niedzielski[1]

1. Institute of Astronomy, Nicolaus Copernicus University, Gagarina 11, 87–100 Toruń, Poland

Searches for planets around other stars than the Sun (exoplanets) are currently one of the fastest developing area of astronomy. They extend significantly our knowledge, and foster development of more sophisticated observational instruments and techniques. New results of such projects are also very much welcome by the general audience as they appear spectacular but easily comprehended. As such planet searches results hold a specific role not only in science but also in the general culture.

1 Introduction

The idea that the Universe is populated and that the stars are homes to other worlds is not a new one. Already Domocrates (460 – 370 BC) and Epicurus (341 – 270 BC) presented such opinions. However, even more contemporary to us Giordano Bruno (1548 – 1600), who shared this view, was not able to phrase it in a physical way. The nature of planets and stars was very vogue back then, and the other worlds were just a philosophical concept.

It was Copernicus (Copernicus, 1543) who presented the first planetary system, a star with planets on orbits around it, the Solar System. The idea was not completely new, already Aristarchus of Samos (310 – 230 BC) is told to introduce it, but presented in more detail was a subject to future successful observational confirmations and elaborated. The Earth became a planet, and although the concept of a planet was still not well constrained the general idea was clear: a star, and planets on orbits around it form a planetary system. We live on a planet.

What remained to be proved was that the stars are physical objects like our Sun, and possible hosts of other planetary systems. That goal was achieved much later, due to affords of numerous researchers including Joseph Ritter von Fraunhofer (1787 – 1826) – who identified the solar absorption spectrum for the first time (1814), Angelo Secchi (1818 – 1878) who found the same lines in spectra of other stars, as well as Friedrich Wilhelm Bessel (1784 – 1846) who measured a distance to another star for the first time (Bessel, 1838).

Philosophically astronomers were ready to look for another Earth but the observational techniques were not mature enough even to search for such massive planets as Jupiter. In addition according to planet formation scenario (Safronov, 1969) gas giants were expected to reside far from their host stars, at several astronomical units, beyond the snow line (Hayashi, 1981) where they form. Estimates of Jupiter analog signal proved that detection of planets around other stars in photometric signal, either in reflected light or during eclipses (transits) is highly unlikely. For radial velocity detection for exoplanets a jump in precision by two orders of magnitude was necessary, not to mention a long term approach, that appeared to be obvious.

Fortunately, another type of low-mass objects, brown dwarfs (Kumar, 1963), became a target of radial velocity searches for low-mass companions to stars. These,

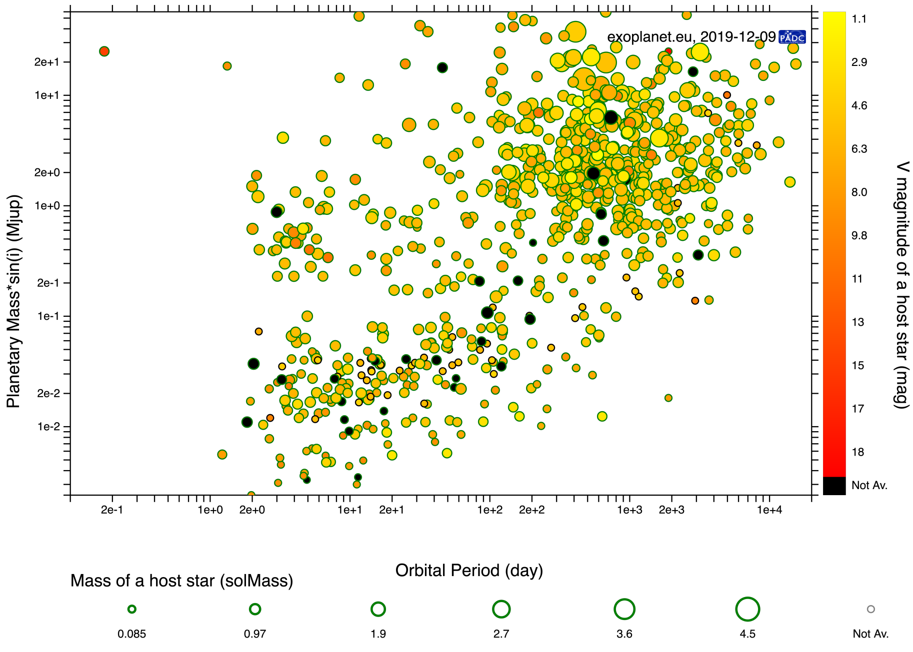

Fig. 1: Planetary minimum mass versus orbital period relation for 840 confirmed planets detected with precise radial velocity measurements (data from exoplanet.eu). Gas giants around stars of various masses and up to distant orbits are present. Hot Jupiters are common. The lowest mass planets are preferentially found around low-mass stars.

were legitimate targets of newly elaborated new generation of stellar radial velocity measuring instruments like Geneva Observatory Coravel (Mayor, 1977; Baranne et al., 1979) or Harvard-Smithsonian Center for Astrophysics speedometers (Campbell & Walker, 1979). One of such projects (Campbell et al., 1988) presented radial velocity variations of $25\,\mathrm{m\,s^{-1}}$ and period of 2.7 yr due to a probable third body in evolved star γ Cep binary system, much later identified as a planet (Hatzes et al., 2003). The same year, quite unexpectedly, PSR B1957+20 was found (Fruchter et al., 1988) to have an eclipsing companion of (currently) BD mass, apparently of stellar origin, though. Only a year later a probable brown dwarf companion to HD 114762, a radial velocity standard (!), was found by Latham et al. (1989).

The first exoplanets came as a surprise, detected by Wolszczan & Frail (1992) on orbit around an old millisecond pulsar PSR1257 + 12. Three planets of that system formed probably in a way similar to planets around young stars but after the supernova explosion. Specific conditions required to form planets in such circumstances make pulsar planet rare (Martin et al., 2016).

The first exoplanet around a solar-type star 51 Peg (Mayor & Queloz, 1995) brought another surprise. Giant planets may reside in very tight orbits making the probability of photometric detection of transits two orders of magnitude higher. A hunt for *hot Jupiters* through transits was launched. A new era of exoplanet searches started.

2 Thousands of planets

Historically the radial velocity technique was the first efficient way to search for exoplanets. It delivered 858 planets in 638 systems, of which 150 host more than one planet up to now (after exoplanet.eu, September 2019). After successful detection of the transit of HD 209458 planet by Charbonneau et al. (2000), first transiting exoplanets came from OGLE data (Udalski et al., 2002), starting with OGLE Tr 56 b (Konacki et al., 2003). Many ground-based project devoted to transit searches were initiated then, including TrES (Alonso et al., 2004), HATNet (Bakos et al., 2004) or WASP (Pollacco et al., 2006). The potential of space observations of planetary transits was quickly recognised and the CoRoT mission presented first candidates – (Barge et al., 2008; Alonso et al., 2008). Starting from 2010 Kepler space mission (Borucki et al., 2010) took over the field and delivered over 2600 exoplanets. Transit searches, both from space and from the ground delivered 2954 exoplanets in 2219 systems, 481 of them multi-planetary (after exoplanet.eu, September 2019). Transiting exoplanets, although represent a population of systems with a specific geometric orientation for terrestrial observers, represent these days the most abundant source of data on exoplanets.

It is important to realise, that these two main techniques operate on different samples of stars and deliver different planets preferentially. Radial velocity searches typically focus on relatively bright stars of spectral types F-M, where numerous narrow absorption lines allow for high precision. They typically avoid binary stars. Detectability of radial velocity signal is limited by instrumental precision, and orbital periods by the length of a project. Technically Jupiter mass planets are easily detectable today but Earth-mass planets can only be detected around very low-mass stars where the Doppler signal is large enough.

Vast majority of transit planets known so far come from Kepler, a relatively large telescope in space that operates on rather faint targets. Multiple observations of photometric transit signal of unknown period require continuous monitoring therefore short period systems are much easier to detect.

A comparison of populations of exoplanets delivered by radial velocity and transit searches is presented in Fig. 1 (for radial velocity searches) and Fig. 2 (for transits). The hot Jupiter planets are present in both cases, but longer period gas giants are missing in transit searches. The population of low-mass planets orbiting low-mass stars (red dwarfs) seems to be the common ground, where mutual observations lead to new results. Transit observations deliver planetary radii, radial velocities – masses, together they allow for studies of physics of exoplanets. Additional spectroscopic observations open another new area of exoplanet atmospheres studies, biomarkers search and possibly life.

The population of faint exoplanet hosts from Kepler is now being extended to brighter stars, where spectroscopic follow-up is more successful, no surprise then that next leap in exoplanet searches and characterisation is expected from space missions like TESS (Ricker et al., 2014, 2015), PLATO (Catala, 2009; Rauer et al., 2014), CHEOPS (Broeg et al., 2013; Fortier et al., 2014) that will deliver thousands of new transiting planets around brighter stars. On the other hand large telescopes like the ESO ELT armed with high resolution spectrographs (cf. Marconi et al. 2016) are expected to resolve planet light outside transits and deliver more data on exoplanet atmospheres reflected light. Certainly we are only the beginning of the real harvest.

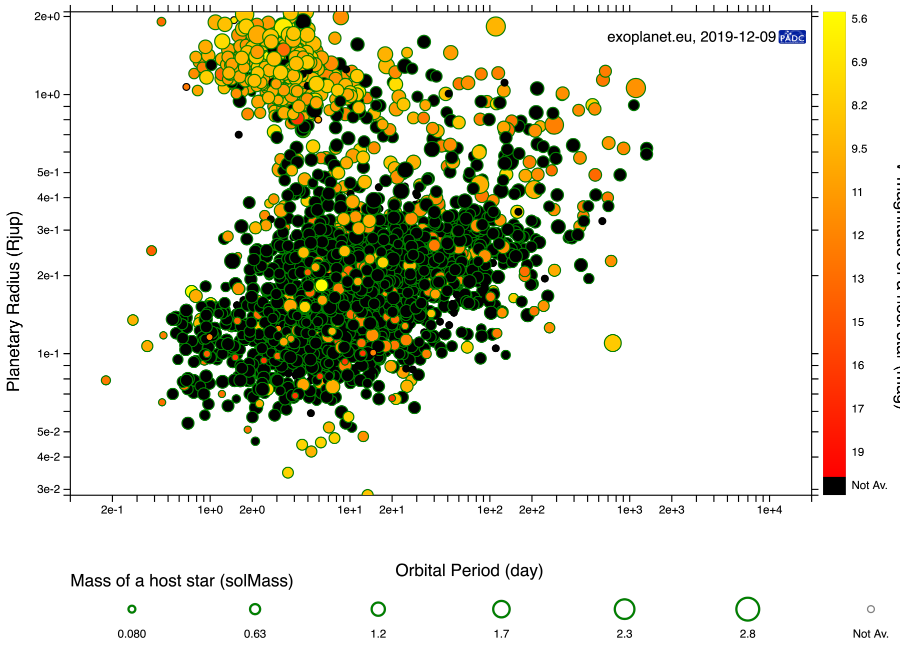

Fig. 2: Planetary radius – orbital period relation for 2953 confirmed transiting planets (data from exoplanet.eu). Short period planets prevail. Hot Jupiters are very common. Low-radius planets dominate.

Given the population of over 4000 exoplanets known so far a legitimate question is: do all stars have planets? The answer to that question depends on what star do we have in mind. When it comes to solar-type, solar-mass ($0.5-1.2\,\mathrm{M}_{\odot}$) stars about 10 % of them appear to have massive, planetary-mass ($0.3-10\,M_{\mathrm{J}}$) companions with periods between 2 and 2000 days (Wittenmyer et al., 2016; Mayor et al., 2011; Santerne et al., 2016). Hot Jupiters, with periods of $1-10$ days, so numerous in both transit and radial velocity searches appear around $0.5-1$% of stars. Their observed overpopulation is due to simplicity in detection only. Jupiter analogs, gas giants of $0.3-13\,M_{\mathrm{J}}$ at $3-7$ AU orbits appear around about 6% of stars (Wittenmyer et al., 2016) and long period giants on $5-20$ AU orbits are estimate to be present around ≈50% of stars (Wittenmyer et al., 2016). Lower-mass planetary companions ($3-30\,M_{\mathrm{E}}$) with period periods shorter than 50 days are found around ≈27 % of stars (Mayor et al., 2011).

Lower mass stars ($0.1-0.5\,\mathrm{M}_{\odot}$), red dwarfs are of special interest as they appear ideal targets for searches of Earth-type planets through radial velocity measurements. Gas giants on orbits with periods shorter than 5.5 yr of such stars are not common, estimates show that they are $3-10$ less common than around solar type stars. On the contrary, lower-mass, Earth-type are much more common than around solar type stars. On average an M dwarf may have 2 planets of Earth to Neptune size (Gaidos et al., 2016).

Planets are quite common.

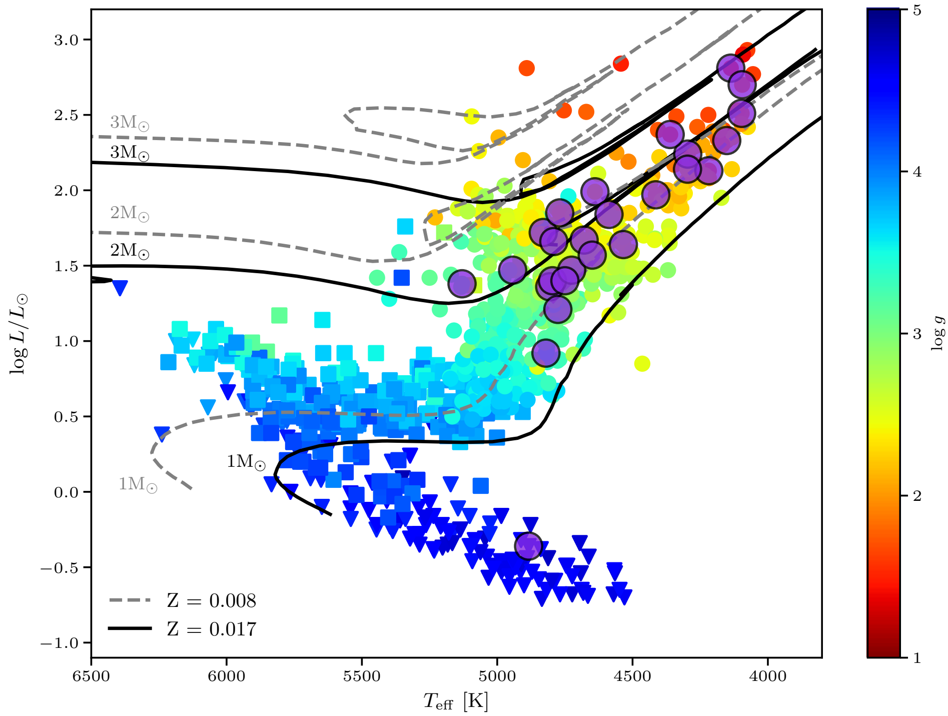

Fig. 3: The Hertzsprung-Russell diagram for the complete sample of 885 Pennsylvania-Toruń Planet Search stars for which detailed atmospheric and physical parameters were determined together. All hosts of planetary systems already detected within our projects are indicated as well (large dots). Virtually all planetary systems detected in PTPS are hosted by evolved giants, located above the horizontal branch in many occasions. The only exception is BD + 14 4559, a dwarf hosting a gas giant.

3 Solaris and Pirx, i.e. BD+14 4559 and its companion.

One of massive radial velocity searches for exoplanets is Pennsylvania-Toruń Planet Search, a project aiming at detection and characterisation of planetary mass companions to evolved stars Niedzielski & Wolszczan (2008). The project was launched in 2004 and designed to use the Hobby-Eberly Telescope (Tull, 1998) and its High Resolution Spectrograph (Ramsey et al., 1998). The first detection of a gas giant orbiting a red giant star was presented in Niedzielski et al. (2007). Starting from 2015 observations are gathered with the Harps-N spectrograph (Cosentino et al., 2012) on Telescopio Nazionale Galileo as well.

In Fig. 3 the Hertzsprung-Russell Diagram with the complete sample of 885 stars studied in detail within this project, for which parameters were obtained in a series of papers (Zieliński et al. 2012; Niedzielski et al. 2016a; Adamczyk et al. 2016; Deka-Szymankiewicz et al. 2018) is presented. Stars with planets already detected are marked as well. Almost all planetary systems detected in the sample so far orbit evolved stars on the red giant branch.

Of the most interesting ones let us recall: the multiple planetary system around an evolved solar-mass star, a K2 giant TYC 1422-614-1 (Niedzielski et al., 2015); the most massive, 1.9 $M_\odot$, red giant star hosting a warm Jupiter TYC 3667-1280-1 (Niedzielski et al., 2016b) or BD + 48 740 - a Li overabundant giant star with a planet which possibly represents a case of recent engulfment - Adamów et al. (2012).

Of specific interest is BD + 14 4559 b, an 1.5 M_J gas giant revolving on a=0.78 au and e=0.29 orbit an 0.9 $M_\odot$ dwarf, discovered within the Pennsylvania-Toruń Planet Search in 2009 (Niedzielski et al., 2009). This planet and its host were chosen by the International Astronomical Union on the occasion of its 100th anniversary to name by polish national poll within the ExoWorlds project, and were assigned names Solaris and Pirx to honor the famous Polish science-fiction writer Stanislaw Lem. Solaris, aka BD + 14 4559 is a V=9.63 star in Pegasus, best spotted by a binocular in polish late summer sky.

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