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Memorie della

Exoplanets

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Abstract. A brief introduction to Exoplanetology, a relatively new branch of astrophysics, is object of this presentation. We depart for a journey out of the boundaries of our Solar System: we take off from the discovery of the first extra-solar planet, sail through the techniques to search and characterize planets around other Stars, and land on the state-of-the-art space observatories that will heavily contribute with new data to exoplanetary science in the next future. ESA's CHEOPS, PLATO and ARIEL are those new frontier missions to which ASI is providing massive contributions.

Key words. Astrobology – Exoplanets – CHEOPS – PLATO – ARIEL

1. Introduction to Exoplanets

It's been about 25 years, since Michel Mayor and Didier Queloz did discover the first planet to orbit a Star other than our Sun (Mayor & Queloz 1995), that scientists have been able to hunt for exoplanets of so large a variety to challenge our imagination. It can be stated that every Star we can observe in the night sky, starting from those forming our galaxy, is orbited by at least one planet.

1.1. The hunt has begun

The ideal method to spot an exoplanet is to take a direct image of its recognizable shape while it's orbiting its parent Star. Let's imagine being outside our solar system and look at Jupiter - the biggest planet in our solar system - from afar: the planet would be a dim dot next to a very bright Star. To actually see Jupiter it is not at all a simple task: its outer atmosphere reflects only one part out one-hundred-million of the light coming from the Sun. Here we see an example observed with the Very Large Telescope in Chile. It is a hot planet in its youth, quite far from its Star clearly visible in this image that was acquired through the use of a coronagraph to block out the direct light from the Star.

1.2. Stellar radial velocities

Let's observe Jupiter from great distances once more: it could be appreciated that the Sun, as a result of the revolution of Jupiter around it, moves by an appreciable quantity every 12 years (Jupiter's orbital period): the two in fact revolve around a common center of mass. This shift can be seen in the light coming from the Sun as a Doppler shift of the wavelengths of its spectrum. One part in 10 million: a fraction that we can measure. Thus, using Doppler spectroscopy, exoplanets can be identified as Mayor and Queloz did in 1995. The two researchers developed a high resolution spectrograph capable of measuring the shifts of the

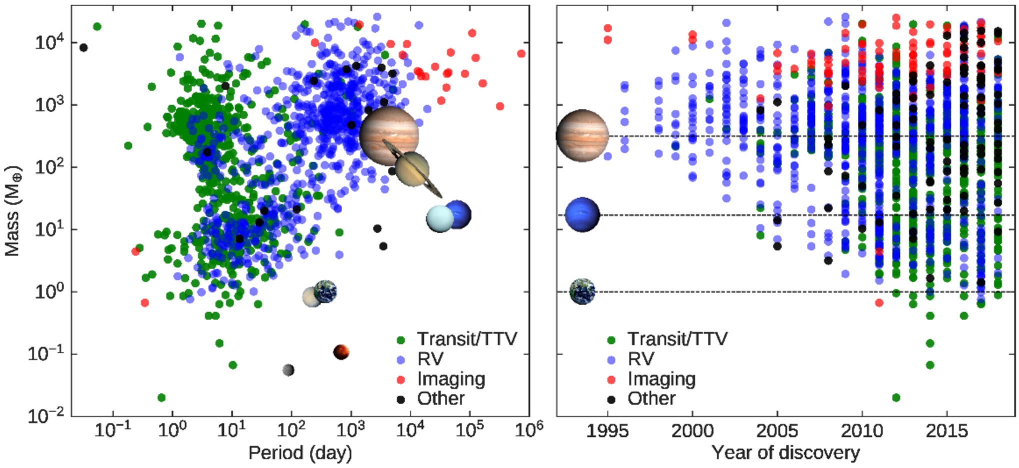

Fig. 1. Planets' mass and period distribution Vs. year of discovey (credit: exoplanet.eu).

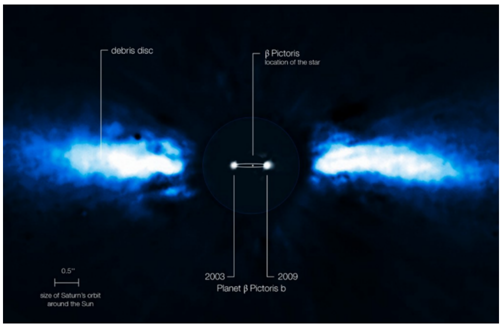

Fig. 2. Beta Pictoris b (credit: ESO/A.-M. Lagrange)

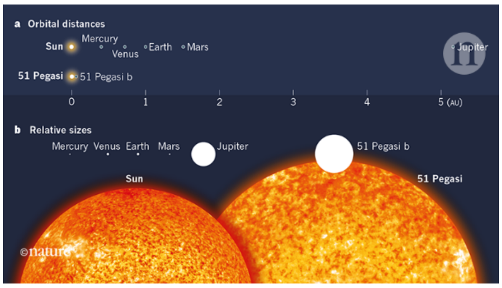

Fig. 3. The planetary systems of the Sun and of 51 Pegasi (credit: Nature)

spectrum of the starlight, dividing it into 67 bands: each of those moved towards "red" or towards "blue" because of the motion of the Star away from or towards the observer, respectively. While observing the Star 51 Pegasi, a yellow dwarf similar to our Sun, Mayor and Queloz in fact discovered a Jupiter-type planet, with a mass equal to about half Jupiter's mass, which rotated once every 4 days at a distance 20 times smaller than Mercury from the Sun: a so-called hot Jupiter.

This method allows to calculate the mass and period of rotation of the planet, once the characteristics of the parent Star are well known. A fundamental datum to continue in the characterization of an exoplanet is its size. Once known the size and mass of the planet, it is then possible to calculate the density of the planet.

1.3. Transit Photometry (and Spectroscopy)

In order to determine the size of the planet the transit photometry method can be used. A good precision photometer can measure the brightness of a Star and how it varies due to the transit of a planet in front of the stellar disk: such instrument can return extremely precise "light curves" of the Star during the transit. In this way, only the exoplanets that are in its line of sight with the Star can be observed: it is a necessary condition to witness a transit. When a planet transits in front of its Star it causes an eclipse (see the case of Venus with our Sun): it can be seen how the light coming from the Star is dimmed by the shadow of the planet. The larger the planet, the bigger the dip (the "transit depth") in the starlight measured: the "depth" of the transit is related directly to the size of the planet relative to the Star. From its analysis a measure of the radius of the planet will be obtained: Jupiter passing in front of the Sun causes a decrease in brightness of 1%, while the Earth of 0.01%. Larger bodies are certainly easier to detect. Once known the size and mass

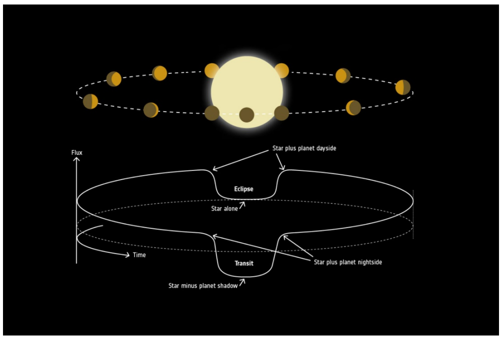

Fig. 4. Light and phase curve of a transiting planet (credit: ESA)

of the planet, it is then possible to calculate its density. The density of a planet allows to speculate on its internal structure: gaseous, largely rocky, largely metallic, covered with oceans, or ice or lava, with a thick or dim atmosphere. The "radial velocities" and "transits" methods are particularly effective in finding large planets and very close to their Stars. Transit's light and phase curves carry more information than that: if investigated with a spectrometer, atmospheric features of exoplanets can be detected.

1.4. Circumstellar discs

There is another method to search for exoplanets that may be of particular interest for astrobiology. Direct observation of circumstellar disks around young Stars (1My of age) are a clear hint that a planet is forming: rings of hot debris can be distinguished, and in particular the gaps between them testify the presence of a growing planet. ALMA is an example of how interferometry can be used to simulate telescopes of apertures that are not physically feasible: using 60 antennas, operating at mm-wavelengths, arranged on large surfaces up to cover a distance of 16 km, it is possible to reach resolutions higher than those of HST (0.13 arcseconds). Through this method, giant planets at

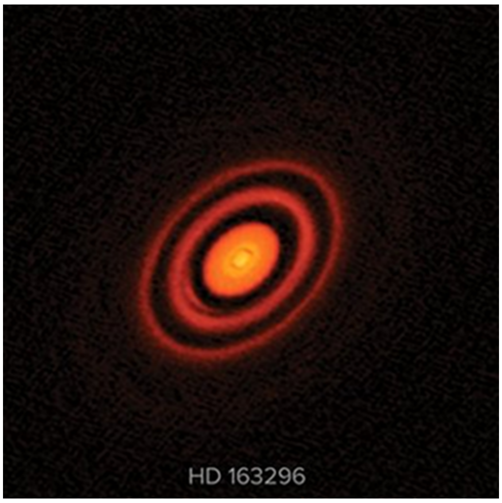

Fig. 5. HD 163296, a forming planetary system (credit: Nrao/Aui/Nsf, S. Dagnello)

great distances from their Stars can be found; information about the composition of the dust (sand grains, the size of mm) can be gained, thus contributing to a better understanding of the formation, origin and evolution of those planets and - in general - of Star systems, including ours.

2. Exoplanets Missions

To date, the most effective method in searching new exoplanets is certainly the transit method: more than 70% of the more than 4000 known planets have been discovered with this method. Yet, it is evident that only a very small fraction of the existing planets can be discovered in this way. NASA's famous Kepler mission used this method to discover new planets: it had pointed its 1m-aperture telescope to the

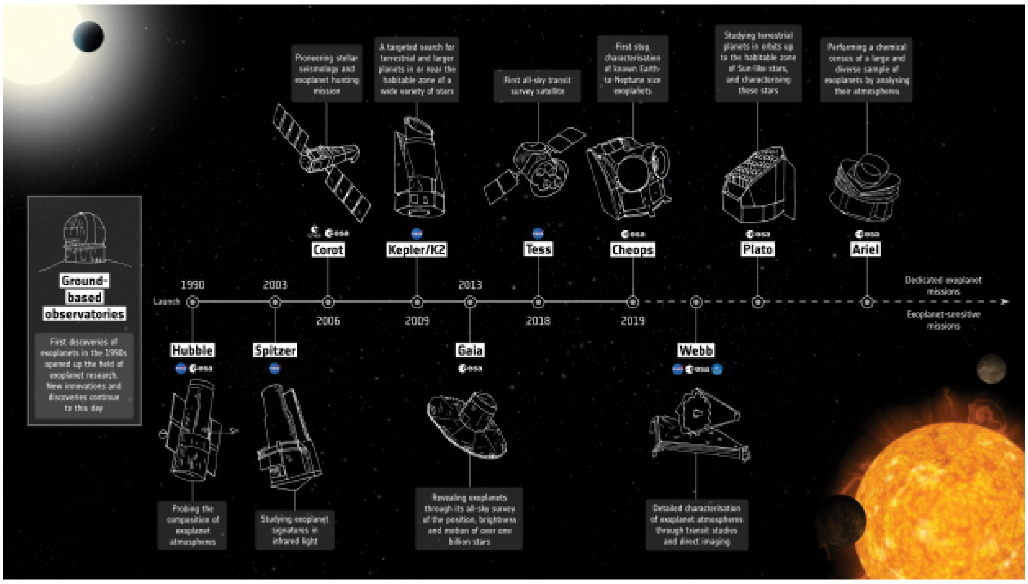

Fig. 6. Exoplanet mission timeline (credit: ESA)

Swan Constellation (only 1/400 of the sky) - out of the Milky Way disk, at a distance of 1000 LY from us - for 4 years, looking for Earth-like planets in the habitable zone. Kepler did find some bizarre planets, some already foreseen by science fiction, super-Earths and mini-Neptunes very close to their host Stars. Unfortunately, due to their large distance from us, it is not possible to obtain information on their masses: the method of radial velocities and the Doppler spectroscopes available on Earth require bright Stars to resolve a measurable mass. NASA's TESS, Transiting Exoplanet Survey Satellite, is the successor of Kepler: it employs four 10cm-aperture telescopes with a wider field of view, each 6 times Kepler's. It has scanned 90% of the sky divided into 26 sectors, each observed for one month. TESS focuses on planets that orbit quickly (¡a month) around red dwarfs, Stars that are much more frequent in our galaxy and that often proved to host a planet: here it is easier to identify rocky planets in the habitable zone, with the advantage that they are closer to thus possible subject of investigation by other missions. Planets like the Earth around Stars like the Sun will be waiting for other missions capable to hunt them. Kepler 186 is an example of a planet in the habitable zone of its Star - that is, the zone in which, in principle, it is possible to have liquid water on the surface of a planet. The habitable zone is located at different distances depending on size and luminosity of the host Star.

2.1. ESA's Exoplanets Missions

ESA has adopted three missions dedicated to the study of exoplanets. Italy, through ASI, is significantly involved in all the missions selected by ESA in its mandatory scientific program (Cosmic Vision). Furthermore, ASI is playing a major role in the development of the scientific instruments on board of those missions. The first one is the S-Class mission **CHEOPS** (Benz et al. 2021), launched in December 2019. The other two are M-Class missions, **PLATO** (Rauer et al. 2014) and **Ariel** (Edwards et al. 2019), planned to be launched in 2026 and in 2029, respectively. In December 2019, ESA launched the first of these missions: CHaracterizing ExOPlanetS, **CHEOPS**. It is the first small mission (S-Class) within ESA's Cosmic Vision Program.

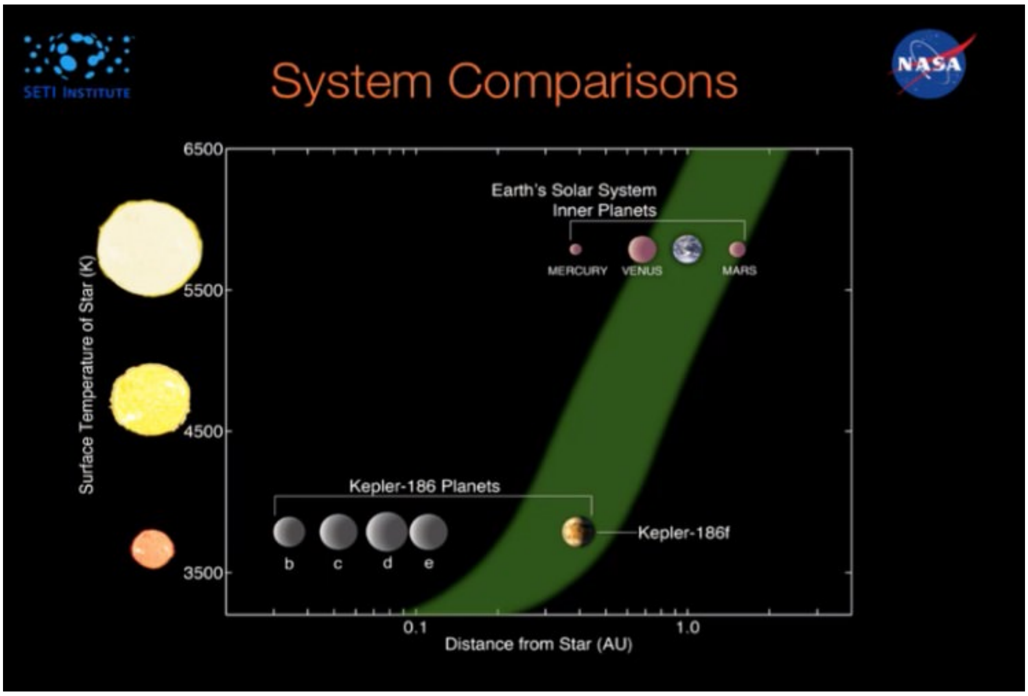

Fig. 7. A comparison of the Kepler 186 and Solar systems (Credit:NASA/Ames)

As such, the compact spacecraft (roughly a 1,5 m long cube) - which orbits the Earth at an altitude of 800 km on a Sun-synchronous orbit - hosts one only scientific experiment, a photometer, that has a very specific objective: collect and measure the light coming from a Star known to be orbited by a planet, while that same planet is transiting in front of its disk. Italians scientists from the Institute for Astrophysics (INAF) developed a particularly clever compact optical design for the telescope (300 mm by 300 mm) that the Italian Space Agency took the responsibility to develop and produce. CHEOPS is a follow-up mission: it won't be looking for new planets, it will rather look at some among the more than 4.000 already known, to characterize them in an unprecedented way. Most of the exoplanet discoveries have been made using the radial velocity method: thus, the mass of the planet has been measured with a good precision. CHEOPS is observing bright, nearby Stars that are orbited by one or more planets with size ranging from Earth's to Neptune's, and an orbital period of 50 days or less. CHEOPS will observe each transit more than once during the lifetime of the mission, thus improving the accuracy of the measurement of the planet's diameter: in this way, this measure is estimated with an accuracy of up to 5 times higher than what was best done before. This was the case of the first exoplanet characterized by CHEOPS during the in-orbit commissioning: KELT-11b, a puffy gaseous planet about 30% larger in size than Jupiter, is orbiting its parent Star (a subgiant yellow Star located 320 light-years away) in 8-hour at a distance to the Star that is much closer than Mercury to the Sun. The diameter of the planet was determined to be 181,600 km, with an uncertainty just under 4300 km. When the mass and size of the planet are known with good precision then the measure of its density will be too: it will be possible to speculate on the composition and structure of the planet. Particular attention will be given to those planets which can be assumed

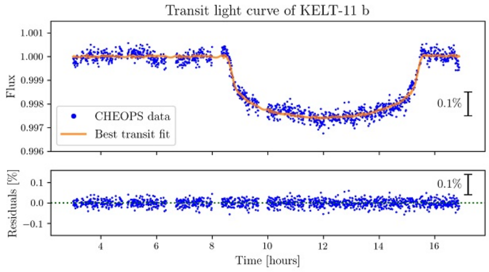

Fig. 8. Transit light curve of KELT-11b (credit: CHEOPS mission consortium)

to have an atmosphere worthy of subsequent spectroscopic analysis. CHEOPS can also discover other planets in the same Star system it is observing, as well as other hidden peculiarities in the light curve it measures: planetary rings, moons, etc.

PLATO (PLAnetary Transits and Oscillations of stars) will put ESA at the forefront of exoplanet research: it will employ transit photometry to discover rocky planets in orbits up to the habitable zone around Sun-like Stars. It will also investigate seismic activity in Stars gaining better understanding on the planet's host Star in terms of its age and thus the age of the Star system. It will be launched in 2026 to an orbit around the Lagrangian point L2 of the Earth-Sun system. Its payload consists of 26 small telescopes (the optical section is called Telescope Optical Unit, TOU) each with a diameter of 12 cm, with a total field of view equivalent to the human eye. PLATO will focus on bright and

Fig. 9. PLATO FOV (credit: INAF)

nearby Stars. It will therefore be easy to characterize the exoplanet in terms of its mass through the method of radial velocities (bright Stars), and also to observe its atmosphere with future ground and space missions. In addition, PLATO will be so sensitive as to detect variations in brightness associated with the oscillations of the parent Star (asteroseismology): Stars ripple forming waves similar to earthquakes, their study allows to investigate the internal structure of the Star, its density, its composition. It will then be possible to tell when the fusion of hydrogen into helium began and study the evolution of its planetary system on a cosmic scale. The optics of the telescope are being developed under the supervision of ASI and the scientific support of INAF. The same Italian industries which developed the telescope for CHEOPS are at the forefront of the development of the TOUs, their integration and alignment. ASI is also responsible of the procurement of the Instrument Control Unit (ICU). **ARIEL** (Atmospheric Remote-sensing

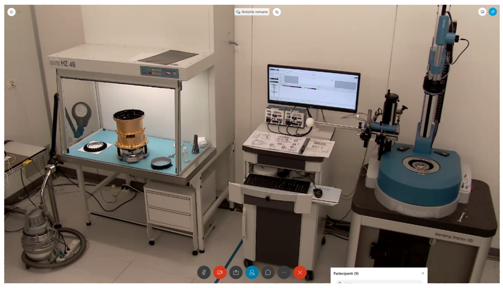

Fig. 10. TOU EM after successful alignment of its 6 lenses (credit: ASI)

Infrared Exoplanet Large-survey) will use transit spectroscopy to analyze the atmospheres of the planets and build a statistic of the chemical composition of the surfaces and / or atmospheres of the planets. This will enable the study of exoplanets both as individuals and, importantly, as populations, in greater detail than ever. Like PLATO It will be launched with an Ariane 6 towards the Lagrangian point L2 of the Earth-Sun system and will scan the sky for 4 years. To derive composition and temperature of atmospheres in an unambiguous way ARIEL observe planets in a wide

Fig. 11. Ariel Spacecraft (credit: Ariel consosrtium)

electromagnetic band that includes both the visible and the near infrared. It will do this by means of a VIS IR spectrometer, IARS, and also by exploiting the instrument for fine guidance, which is equipped with channels with sprectrocopic capacity. ARIEL will study the atmospheres of at least one thousand planets orbiting nearby Stars, with the aim of determining their chemical composition and physical conditions, enabling the diversity of properties of both individual planets as well as within populations to be assessed. Taking into accounts populations of planets in various regimes of mass and temperature it will be possible to understand the common principles in the processes of planetary formation. ASI is responsible for the development of the metre-class Telescope, and is also providing the AIRS Instrument Control Unit and a part of the warm electronics of the FGS Control Unit. At that point in time, considering also the synergy with other past and future missions such as ESA's Gaia and NASA/ESA JWST, a clearer view of how planets are formed and how they evolve together with their host Stars will be available. Whether we will be able to answer to questions related to life and its emergence elsewhere in the Universe is difficult to predict today, but all those missions are necessary steps towards that higher goal.

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