Prof.dr. M. Fridlund

Exoplanets and space research

Universiteit Leiden

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Exoplanets and space research

Inaugural lecture by

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A small boy sees a moving light in the sky and the world changes - for him but more important for the world.

Almost 56 years ago, outside the city of Stockholm, Sweden, I was brought out in the evening on a clear night by my father and grandfather. They proceeded to show me the constellations. Then they told me to watch the horizon and I was going to see something new and remarkable.
Suddenly a relatively bright star appeared at the horizon and started to ascend towards zenith. I will never forget the impact of that first moving light. It was clear that it was not an airplane. It was just a single white light moving so slowly that it looked just otherworldly. But Sputnik 1 that had been launched only 48h before by the Soviet Union was now mankind's first spacecraft in Earth orbit. It augured in the era of space research that has changed among many other things our perception of the Universe in a multitude of ways.

Space research, in the form of observations carried out by descendants of that first Sputnik, has today led us to know that our world is not alone but only one among a multitude of planets orbiting other stars. We are on the threshold of understanding the context within both our own Earth and all the life on it exist and evolve. We will do this by studying these exoplanets as they are usually referred too, in detail. This research consist one of the fastest growing sub-disciplines of modern astronomy. But it is a young science. Essentially everything important in the field has happened in the last 25 years, and most of the progress can be dated from 1995.

I have been privileged to be able to work in this field and following this incredible progress for most of my career. I have seen the topic change from when only a few enthusiasts were pursuing actual research to the status today when young budding scientists are eager to get in and "make a difference". We have learnt a lot during this period, but much, much more remain to be discovered.

But this story begins much earlier. In ancient times, our early ancestors studied the heavens and first noted the stars. It must have been very early that they discovered moving objects. Our planet is blessed with a large Moon, and its presence plays a part in our story. In ancient times its path across the sky must have been the first observable of what was to become the science of the movement of bodies in space, *celestial mechanics* - and therefore the root of all astronomy and astronautics.

The relatively bright star-like objects, that took part not only in the diurnal movement of the sky, but also followed their own slower paths, across the sky were named after Gods, but it is known that already 2500 years ago or more philosophers had identified them as worlds in their own right. They were the planets, the wanderers, and they were different from the fixed stars that did not appear to move.

Incidentally, it could be noted, that the most fundamental difference between planets and stars - that the stars shine because they generate fusion energy internally and becomes extremely hot on the surface, while the planets only shines with the reflected light, from the stars, since they do not generate any significant energy themselves was a discovery that would have to wait another two millennia.

Detailing how the ancients developed their picture of the Universe would, however, take us to far from today's topic. But we would like to mention that already 2500 years ago philosophers in Greece were convinced that some of the lights in the sky were inhabited. Since then, these issues, about life elsewhere in the Universe, have never disappeared from the thoughts of man.

Suffice it to say that after about half a millennium, a picture of the Solar system had emerged. There was our world, our planet, The Earth. Then there were the other planets, our Moon and the Sun. As is usual in science, there were a few competing theories, mainly regarding the placement of our own Earth in the Universe, whether the celestial worlds were inhabited, and what the stars were and where they were located. But movement based on the principle of the circle and circles moving on circles (epicycles) were considered a true description of the cosmos. And most people were certain that the Earth and man were in the very center of the Universe.

The dark ages that followed the fall of the Western Roman Empire in about the 5:th century A.D. led to a break in the progress. We do not know how many times the knowledge of antiquity was re-discovered during this period, but slowly the old picture re-emerged. The cultural explosion taking place during the renaissance coincide with the modern view of the Universe emerging with the work of scientists like Copernicus, Brahe, Galileo and Kepler who brought us ahead of the ancients. It now became known that the Sun and not our own world was the center of the Solar System, with the planets, including our own, revolving around it - and in ellipses - not circles around circles around circles.

Modern astronomy was moving ahead indeed. Christian Huygens manufactured a metal plate with a number of differently sized holes in it. Through these holes he regarded the Sun. Then remembering his photometric observations he waited for the star Sirius to emerge in the evening. By comparing the flux from the star with what he remembered from his daytime observation of the Sun, he calculated the distance to Sirius to be what we today would call ½ light year. He had assumed that Sirius was another object like the Sun, not knowing that Sirius in reality is 25 times brighter which would have given him a more or less correct answer (of 9 light years). The more or less simultaneous determination of the speed of light made by Roemer in Paris helped in proving that the system of the 'fixed' stars was significantly larger than the Solar System. The scale of the Universe was becoming apparent. It was also taken as fact that it would be impossible to see other planets orbiting around other stars. They were much to far away.

And we were learning how to measure the movements of the 'fixed' stars. By the 18:th century it was clear that they were not fixed but moved and the very long times - hundreds or thousands of years needed to observe the displacements with the naked eye or with the simple instruments available at the time were due to these large distances. Stars were other Suns at distances requiring many years for the light to traverse the empty space between them and us. In contrast we already then knew that light make the trip from the planet Jupiter in about ½ hour, from the sun in 8 minutes and from our Moon in 1 1/4s.

Progress was being made. During the 19:th century, the technique of analyzing starlight by passing it through a prism (spectroscopy) was developed and Christian Doppler could demonstrate that a change in the velocity of astronomical objects cause a change in color of these. When such an object is moving towards us the light waves from it get bunched together and the wavelength shorter - then the light gets bluer. As they move away from us, the waves get stretched out and the light then gets redder. Superposed onto the colors we see hundreds of thousands of thin black lines caused by atoms and molecules in the stellar atmospheres absorbing the light of specific colors (or wavelengths). The movement of these lines of the spectrum could be used to discern the velocity of the star, along the line of sight.

As the 20:th century dawned, a ray of hope (no pun intended) was seen as this technique - what we astronomers call the radial velocity effect - was refined more and more. We could now measure how stars moved along the line of sight. When telescopes became bigger and better we could also measure the movements of stars across the sky with increasing precision. We were beginning to build a three-dimensional picture of the movement of the heavens.

The key to these observations and calculations were the celestial mechanics which now had incorporated Kepler's and Newton's laws. Applying these laws specifically to our Solar

System, it was clear that the planets of our Solar System were not moving around the Suns geometrical centrum but rather around the center of mass of the whole Solar System. The Sun contains more than 99% of the total mass of our system so the center of mass is located either inside the Sun or just outside depending on whether Jupiter and Saturn happen to be on the same or opposite sides of it.
But the Sun of course also rotates around this center of mass. What this means is that the Suns velocity relative to a distant star - *Let us here assume for a brief moment that there are some astronomers orbiting this distant star and who happen to be as curious as we are* - changes as the Sun and the planets of the Solar System revolve around this center of mass. And the change in the solar velocity during each revolution is measurable through the Doppler effect. This is the good news. The bad news is that the velocity changes with about 15 m/s - plus or minus - over 12 years (this is mainly caused by Jupiter which has the largest effect). During the early 20:th century astronomers were lucky if they could measure changes of 50 km/s. By the middle of the century this had improved to about 50 to 100 m/s but was still not quite enough.

For long period planets like Jupiter and the 30-year orbit Saturn, the effect would be long lasting, however, and would cause the Sun to move, to "wobble" - off the intended orbit around the center of the Milky Way Galaxy. One would have to follow a stars path across the sky for decades, but several attempts to measure such a "wobble" of nearby stars were attempted during the period between 1910 and 1950 and success was reported in a number of cases. The estimated mass of the perturbing body in those cases was typically 5-10 times the mass of Jupiter. None of these experiments were, repeatable, however.

Here is where things stood in the year of 1952.
In that year, the famous Russian-American astronomer, Otto Struve, published a 2-page paper in magazine "The Observatory", with the un-remarkable title:
"Proposal for a project of high-precision radial velocity stellar work".

The paper is, however, very remarkable. In it He points out the following:

1. The frequency of planet-like bodies in the galaxy which belongs to stars other than the Sun is a burning question for Astronomy
2. Recent discoveries of such planets by Strand, Deitch, Van de Kamp, Reuyl and Holmberg stimulate the interest in this problem (None of these assumed planets found through the wobble I just mentioned, do actually exist)
3. The absence of rapidly rotating G and K stars indicate that these stars have converted their original angular momentum - presumably into the angular momenta of systems of planets

Struve concluded that there might be many planet-like objects in the Galaxy, but how to detect them? The methods current in the 1950's would not suffice to detect the objects found in our Solar System since they were too small or too distant from the Sun. Even Jupiter will only change our Suns velocity by about 15 m/s, which is not much more than the velocity that Usain Bolt reaches in a 100m race. As was stated above, this was not detectable with the instruments then available. But Struve pointed out something based on his knowledge about binary stars. Assuming that planets and stars form in similar ways, there was nothing that prohibited the existence of large planets being very much closer to their host star, and under such circumstances the effect of the planet on the star would be detectable - even in 1952. If we assume we have a planet of roughly Jupiter's size, orbiting around a solar-like star at a distance of about 3-4 million km instead of the 780 million km that our Jupiter is from the Sun, then, under those circumstances the effect on the Sun would be that it would change its velocity along the line of sight back and forth with 200 m/s every day or two which was detectable in Struve's day. Then there would be eclipses. The random orientation of the orbit of such a close in planet would be so that in more than 5% of the cases, the planet would regularly transit its star as seen from the Earth resulting in a drop of the stellar light intensity of about 2% - something easily detectable with the new (in 1952) photoelectric detector.

Struve, in 1952, in principle, set out the modern methods of searching for exoplanets and today when reading his short paper one wonders why it would take until 1995 before the first results according to these suggestions were reported?

I think it was a combination of two things. The implementation of such a program would be much harder than what Struve suggested it to be. Photographic glass plates were the detector of choice in those days, for following large number of stars. Such plates had a low efficiency, as well as being non-linear which made it difficult to calibrate them precisely. But I think, more important was a general understanding that most Solar Systems had to look exactly like our own system, with no planets (and particularly no gas giants like Jupiter) very near to the host star. Under those circumstances a program such as that suggested by Struve would require a very large effort but was likely to produce a non-result.

Simultaneous with Struve's paper, however, our knowledge of stellar physics and of the processes through which stars are born began to move forward. The likely sites of star formation began to be identified during the 1950:ties and 60:ties through among other things the discovery of Herbig-Haro objects. These are small emission nebula pre-dominantly discovered on the surface of the dark patches, that are themselves found superposed onto the Milky Way band in the sky. What was highly interesting with the Herbig-Haro objects were that they changed their shapes and intensities on time scales of only a few years. Apparently some very energetic process was taking place.

The development of infrared detectors, during the same period, made it possible to penetrate the dark clouds, behind the Herbig-Haro objects and here we found the forming stars in abundance. The Herbig-Haro's themselves were gas that lit up when outflows or jets of material from the forming star hit dense blobs of ambient gas.

Today, we know that the dark patches are clouds, usually called "molecular clouds" because of being pre-dominantly composed of molecular hydrogen, but with plenty of other - rather complex and most often organic - molecules in the mix. A few % of the mass of the clouds consist, however, of micrometer sized dust- and ice-grains. It is from this mélange that stars and planets are formed. Studying infrared- and microwave radiation emanating from the depth of the molecular clouds has allowed a picture to emerge where a part of the cloud suddenly collapses. Over some thousands or tens of thousands of years, the molecular gas falls freely towards the center where a star builds up from the material. Since the collapsing cloud is rotating, the angular momentum has to be conserved and a rotating disk forms around the nascent star. It is from structures in this disk that we believe planets, asteroids and comets form. Of course, the region closest to the star gets successively hotter and hotter and it is believed that a large void exist in the inner parts of the forming planetary system. This is especially so since as have been observed, the youngest phases of a star tend to be violent, with massive outflows of ionized gas and significant eruptions during maybe the first million years of its existence. This is when we expect the planets to form from the left over material in the disk. Further, the expected temperature structure in the disk should automatically lead to a diversification of planets with rocky, Earth- or Mercury like worlds forming from refractory dust-grains in the inner parts. Refractory grains have a mineral composition allowing them to survive at higher temperatures. Then lower density planets with an increasing mix of ice and volatile grains are found as we progress outwards in the system, and finally gas giants furthest out, formed where the molecular gas has been relatively undisturbed by the forming star, and has been able to accrete onto a rocky core.

This emerging model of how stars and planets form is probably what led astronomers to disregard Struve's project, and actually postpone the search for exoplanets. All large planets would be in the outer parts of their systems, far from the host sun in orbits taking more than 10 years to carry out one revolution around the primary, something that would lead to astronomers spending their whole career looking for just one detection!

What most astronomers had forgotten and what had led Struve to make his bold proposal is that there exist systems with two or more stars orbiting each other in a much tighter arrangement.

One of the first variable stars to be discovered was Beta Persei - Algol - a relatively bright star in the constellation of Perseus. Every 3 days, regular like clockwork, this second magnitude star begins to grow fainter. After about 4 hours it is less than 3 times as bright than as it started out and after a few hours it then begins to brighten again. A total of 10 hours after the phenomena began it is back to normal. These changes were known by the ancients. The name Algol means Ghoul in Arabic. In Greek it was called the Gorgon which has a similar meaning. A calendar made 3200 years ago in Egypt may refer to the periodicity of Algol to determine the difference between "lucky" and "un-lucky" days. It was not until 1783, however, that John Goodricke announced a study of the star to the Royal Society in England that offered an explanation. His proposed model consisted of two stars, one of them less luminous than the other, where the former passed in front of the latter every 3 days.

This model was unambiguously confirmed in the 1880:ties when Edward Pickering and Carl Vogler found a double set of spectral lines in Algol and also measured the periodic Doppler effect, the movement of these spectral lines with time, thus finding the velocities of the two stars.

Algol was only the first of these so-called spectroscopic binary stars. Many were found successively and these objects took on a very large importance during the 20:th century, since by analyzing the movements of the stellar components one can determine the mass of the individual stars. The study of spectroscopic binaries thus became a linchpin in our understanding of stars. Interest in these objects led to the construction of better spectrographs, and here and there, researchers started to look also for the signature of planets. It is no surprise, then, that the handful of astronomers who were equipped with the tools to study binaries and peculiar stars in detail were the first to eventually pick up something.

In 1988 the Canadian astronomers Campbell, Walker, and Yang published a paper reporting the radial velocity observations of a few dozens of solar type stars and claiming the "indication" of Jupiter mass companions in 7 of these stars. Most astronomers, however, ignored this "indication" since all the detections were marginal. The planet orbiting gamma Cephei, was the only one eventually confirmed in 2003.

It did not make an impact either when Dave Latham at Harvard published a paper titled "The unseen companion of HD114762 - A probable brown dwarf" in May 1989. An object with 11 Jupiter masses were orbiting a solar type star every 84 days. In the abstract, Latham writes: "This leads to the suggestion that the companion is probably a brown dwarf star, and may even be a giant planet."

At the time, astronomers made a distinction - purely based on theoretical considerations - that an object with a mass larger than 13 solar masses is a star of the type "Brown Dwarf" since it presumably generates energy from some kind of nuclear reactions. A smaller object would be a planet, since it would not generate any significant energy internally. We note here that the radial velocity method does only provide a minimum mass of any orbiting body, since by itself it does not tell us what the inclination of the system is and therefore how much of the true space velocity of the planet is along the line of sight. It turns out that Latham's object HD114762b really has a small inclination and thus a mass of 11 Jupiter masses and it is thus, together with Gamma Cephei b the first exoplanets discovered.

Something was in the air, or actually happening out in space.

On 21 April 1992, radio astronomers Wolszczan and Frail announced the discovery of two planets orbiting the pulsar PSR 1257+12.

Pulsars are compact remnants of Supernova explosions. Such an explosion take place towards the end of the life of a very massive star. The star collapses in a gigantic explosion and part of the star form a very compact object - maybe only about 10 km in diameter and spinning very rapidly. The rotation period is of order milliseconds, and the very strong magnetic field that has been preserved and concentrated in the collapse, generate radio pulses also with these very short and precise periods. It was thought that any planets orbiting such stars would be destroyed in the explosion. It was a great surprise when timing analysis of the signals demonstrated that there were Earth-size bodies in orbit around the pulsar. This discovery was confirmed, and is generally considered to be the first definitive detection of exoplanets. These pulsar planets are now believed to have formed from the remnants of the supernova that produced the pulsar, in a second round of planet formation, or else to be the remaining rocky cores of gas giants that somehow survived the supernova and then decayed into their current orbits.

Today about 5 such planets are known with a possible 5 more awaiting confirmation

On 6 October 1995, the Swiss astronomers Michel Mayor and Didier Queloz announced the first definitive detection of an exoplanet orbiting a nearby solar type star, the G-type star 51 Pegasi. The discovery, made using a spectrograph called Elodie at the Observatoire du Haute Provence in France ushered in the modern era of exoplanetary discovery. Technological advances, most notably in high-resolution spectroscopy, and driven by this discovery, led to the rapid detection of many new exoplanets. For the first few years and using the radial velocity method astronomers continued to detect exoplanets indirectly. Of course, in the beginning of this new era, the searches were biased towards large planets in short orbits. The first confirmed planet, 51 Pegasus b orbits its solar type star, once every 4.23 days. And the planet is supposed to be half as massive as Jupiter!

Several astronomers queried the observation, however, and assumed that the observation was the result of tracking sunspots on the stellar surface instead. Astronomers, however, rapidly picked up more planet candidates. The two US astronomers Geoff Marcy and Paul Butler reported large planets around two stars, 47 Ursae Majoris and 70 Virginis. The latter were almost 7 Jupiter masses but what was more surprising was that it has an eccentricity of 0.43. We'll, planets are supposed to orbit their primaries in elliptical orbits with the primary in one of the foci but this was getting to be a bit ridiculous. The orbit looked more like that of a comet. As Marcy put it in the discovery paper: "The formation of such giant planets in eccentric orbits is not explained by current theory". To make matters worse, the next exoplanet to be discovered, 16 Cyg b has an eccentricity of 0.69

So, initially, most exoplanets found were massive planets that orbited very close to their parent stars. Many astronomers were surprised by these "hot Jupiters", since the theories of planetary formation had indicated that giant planets should only form at large distances from stars. Only old Otto Struve was probably smiling in his grave.

The discovery of the first few planets allowed for more astronomers to begin searching for exoplanets, as well as providing funding for more and more sophisticated spectrographs. The two High Accuracy Radial Velocity Planet Searchers or HARPS

- North in the La Palma observatory in the Canary Islands and South at the European Southern Observatory's La Silla Observatory in Chile - are now the "gold standard" in this area of exoplanet searches. For brighter stars, they can measure velocity changes of less than 1 m/s. This is required since if you would want to look for the Earth in this way you would need to have a precision of 10 cm/s in your measurements.

Planets with larger distances from their primary, as well as smaller and much smaller masses have been found as the methods and instruments have become better and better. The prevalence of "hot Jupiters" among the first exoplanets was clearly an effect of them being easier to find. Nevertheless it remains to be explained what the origin of these bodies is and any theory for the formation of planets have to include their presence.

In 1999, Upsilon Andromedae became the first solar-type star known to have multiple planets. Other multiple planetary systems were found subsequently. But there is something peculiar with these systems. In the case of Upsilon Andromedae, we have 4 planets. First there is "b", a "hot Jupiter" of ½ the mass of Jupiter in a 4 ½ day circular orbit. Then, roughly where Venus is in the Solar System, we find planet "c" possibly a brown dwarf of 15 Jupiter masses and a 241 day highly eccentric orbit. Somewhere around where Mars should be we have planet d of 10 Jupiter masses, again in a highly eccentric orbit. Then, at the same distance from Upsilon Andromedae as our Jupiter is from our Sun, we find "e", a one Jupiter mass planet in a circular 10.5 year orbit.
The latter object, "e", is finally, something we recognize from our own Solar System. The problem is only that the rest of the system is strange. I do not think one can claim that we have found a solar system analogue. The presence of these large, massive planets - some of them penetrating into the habitable zone of this star - thus where liquid water and life as we know it could possibly exist - would definitely destroy the chance of finding small rocky planets in stable orbits. They would be ejected from the system or merged, "eaten" by the large planets.

As mentioned before, the chance of seeing an exoplanet transit across its host star's surface is very low - certainly less than 10% for very close in planets and dropping below 0.5% for something in an orbit resembling that of the Earth. In the year 1999, the number of known exoplanets had risen to around 100, and this second breakthrough in exoplanetology took place in 2000, just on schedule as it appears. Dave Charbonneau and co-workers including Dave Latham and Geoff Marcy detected the variation in a Sun-like star's apparent luminosity as an orbiting planet passed in front of it. Since they at the same time had the radial velocity data they could now determine the real mass of the planet, as well as its diameter and thus its density, surface gravity and escape velocity. This discovery turns out to be one of the most important since we found the first confirmed exoplanet in 1995. It means that we are able to study the physics of the exoplanets. Since the year 2000, many networks of telescopes searching for such transiting planets have been deployed around the world, but in parallel with the developments on the ground, something had begun to happen relating to instruments in space.

In the beginning of the 1990:ties, before the first confirmed exoplanets were reported, both the European Space Agency and its US counterpart, NASA set up several study groups with the objective to determine what would be required to detect the equivalent of our own Earth, orbiting a solar type star, *and* to determine if such an Earth analogue could and would be hosting life as we know it. This led to the large and comprehensive studies that are known under the names of Darwin (the European one) and Terrestrial Planet Finder, or TPF (at NASA).

I had the privilege of leading the Darwin study from its beginning in 1996 until it was placed on hold in 2007. This I count as one of the most exciting and important tasks I have performed in my professional life.

With strong and mostly positive collaboration between ESA and NASA, we in a few years designed a large space interferometer, that could carry out this task. The interferometer thus consist of several telescopes that would each be on its own spacecraft flying freely in space, and in formation. They would each observe the same star and send their individual light beams to a separate spacecraft where the beams would be made to interfere with each other in an appropriate way. This would make the array the equivalent of a telescope with the diameter equal to the distance between the outmost telescopes that could be as much as ½ to one kilometer. Working in the Infrared wavelength region the array would be able to obtain a spectrum of the Earth showing so-called biomarkers at a distance of more than 100 light years.

The most interesting thing about this study was to figure out what a biomarker would be. A biomarker would have to be detectable at interstellar distances and it should only indicate the presence of life and not produce false positives. It also had to be unambiguous in order not to require sophisticated modeling with too many free parameters in order to be interpreted. It turns out such biomarkers do exist.
It has been found that on the Earth, today, essentially all its Oxygen in the form of molecular free oxygen, as well as the Ozone in our atmosphere have been created by life. Cyanobacteria also called blue green algae started this process in archean times and today plants contain chloroplasts which are symbiotic cyanobacteria that have become incorporated in plant cells. These microorganisms carry out photosynthesis and releases free oxygen to the atmosphere. While the mechanism doing this is known to have operated for 2.8 billion years we still are not quite clear of exactly how it works today and why the atmospheric content is what it is namely 21% and not 14% or 7%. What is clear, however, is that the origins of all oxygen in the Earth's atmosphere derive from one thing: life. If we removed all living things on the Earth, the free oxygen would disappear in a geologically very short time becoming bound in different oxides.

At the same time the strong spectral signatures of free molecular oxygen and ozone would disappear from a spectrum of our Earth. This thus become our bio-marker.

The free Oxygen has only been there for about half of the time the Earth has existed. There were other molecules produced by the predecessors of the blue-green algae. For unknown eons before the rise of the cyanobacteria, so-called anaerobic bacteria and similar microorganisms were using sulfur for their energy needs and releasing methane into the atmosphere.

The point being, is that then as today our atmosphere was out of chemical equilibrium. And this is our biomarker. By analyzing the spectrum of a terrestrial exoplanet, if we find a molecular signature that demonstrates such an dis-equilibrium we could be reasonably certain not only that the planet was hosting life – we would also be able to tell in what stage it were.

For the first few years after 2000, things looked quite hopeful for Darwin and its US counterpart. Very large amounts of money was made available in order to develop the technology required. But at the same time the political climate for large technologically driven experiments changed. As time went on, the study effort that went into Darwin and its US counterpart was shrinking rapidly. It was becoming clear that such a complex spacecraft would require more resources than was available. Several large projects on both sides of the Atlantic have been cancelled over the last decade. And Darwin/TPF was one of them. Another way of progressing than the mighty hammer blow that Darwin/TPF could have been had to be found.

It was clear that a more stepwise approach must be taken. Each step could be addressed separately and leading to the next in a fairly obvious way. Luckily enough, in both Europe and the US plans were afoot to do this. In Europe the multinational, French-led CoRoT and in the US the Kepler space missions were being developed. Both of these were designed to search among hundreds of thousands of stars for transiting

exoplanets and determine their orbits and diameters. A ground based program would then determine the masses with 'classical' radial velocity measurements. This would find the number of stars having planets and of the number of different types of planets per star.
CoRoT was launched into space in 2006, and Kepler in 2009. Both have worked beautifully as intended and again, nature tend to be a bit different than what we were expecting. Designed so that one could detect planets of the same size as the Earth, both spacecraft have carried out their missions. But, they have also demonstrated unknown things. Completely new classes of planets have been discovered by both spacecraft.

In 2009, CoRoT discovered the planet CoRoT-7b. It is clearly a 'rocky world' made out of the same types of rock and metals as the Earth is. It is 50% larger than our planet but what is really remarkable is that it orbits its host once every 20.2h - less than an Earth day. The host is of solar type and about 80% the size of the Sun as well as about 400 degrees cooler. Half of the sky on this planet is covered by its star and the temperature on its surface is high enough to melt iron, gold and nickel.
This planet first was classified as 'abnormal' - whatever this is when it comes to the first object discovered of anything? But it was not 'abnormal' for very long. A year and ½ later, The Kepler space craft discovered the planet Kepler-10b. This is an identical planet in orbit around an identical star. Recently the stars 55 Cancri and Alpha Centauri B - that are of the same type as the stars CoRoT-7 and Kepler-10 have been found to possess more or less identical planets in more or less identical orbits. We are thus talking about a new class of objects that could be designated 'hot Super-Earths'
But CoRoT has also found CoRoT-9b. This is a Jupiter size planet in an almost circular orbit, around another solar type star. It is located at a distance that could be beneficial to life, but it is a gas giant located where we not expected it. There could of course be a largish moon around it that could host life. We do not know yet but many scientists are looking.

Recently CoRoT found another planet that may be among its most important discoveries. CoRoT-32b is the youngest planet found so far. It is a gas giant in a 'hot' orbit. Or at least a 'warm' orbit. Since its host star - unusually enough - can be aged-determined with high precision and is very young, it is a unique object and will be a laboratory for examining all models for planet formation with respect to their time scales.

CoRoT in total have identified and confirmed about 35 new transiting planets in 33 systems. A further more than 200 candidates remain to be followed up and mass determined. NASA's Kepler mission have identified 2,321 candidates and confirmed 115 planets. The three latest Kepler-finds are all of the super-Earth category but located within the habitable zone of their respective systems.

As of today, a total of 872 confirmed exoplanets are listed in the Exoplanet.eu database, including a few that are confirmations of the claims from the late 1980s. That count includes 683 planetary systems. There are many systems where there is more than one star, and at least one system, Kepler-16 where the planet orbits around both components of a binary star system. In my opinion, one of the most interesting facts that slowly have emerged during the last decade is the enormous diversity among the exoplanets. It is almost like they all were individually designed to a specific classification. There are individual classes like 'hot Jupiters' or 'hot super Earths' there are also 'Jupiters in Earth or Venus like orbits', there are 'Jupiters and super Earth's in warm orbits, and cold orbits, etc.

What we have *not found* so far is a single system that looks like ours. Ok, the exact analogue is still maybe beyond our technical grasp, but the problem is that we find so many different systems that there is less and less stars around where a system like ours could be hiding. Does this means that our type of system is very rare? Nature must be trying to tell us something - probably about the formation process. Although the star and planetary formation process appear simple and at first governed only by the law of gravitation and of conservation of angular momentum other aspect soon come in posing questions like:

- What is the importance of magnetic fields?
- What is the importance of the gas and dust mixes?
- Is settling of dust increasing the dust to gas ratio in the disks important?

Etc, etc, etc.
All such aspects need to be investigated and put into context. We may indeed wonder about the star-planet interactions both as what concerns the formation and evolution of planets and the possible emergence of life.

Of course this brings us finally to the issue about life. What can we say at the moment about this topic. I am afraid not very much. There is a small number of planets - less than 5 - that are located within what has come to be called the Habitable Zone or even the "Goldilocks zone"- The latter term being invented by the Americans of course. Not to warm, not to cold but just quite right.
Slowly, by repeating these phrases enough times it has come to mean that if we find a planet within any of these zones there HAS to be life there!
Nothing could be further from the truth. The "Goldilocks zone" just means that the direct incoming radiation from the host star in question provides roughly a temperature that neither does not freeze water, nor does it boil it - and that's it! There could be literally dozens of dozens of parameters that go into the formation of a solar system like ours and dozens of dozens of free parameters that go into the emergence of life - and we do not even know how it happened on this planet.

I will finish with some very personal thoughts about something that I have learned from exoplanetary research. When I was that little boy and saw Sputnik 1 and decided on what I wanted to do for the rest of my life I started on a process of learning. Very early during this learning I was taught the following: We are ordinary beings living on an ordinary planet orbiting a very ordinary star in an average galaxy,…. It was essentially in every book – and this was in the 50:ties and 60:ties when we had no exoplanets, had calculated about three stellar 1-dimensional models and still believed that our Galaxy was a normal spiral. So there was very little observational facts.

Today…. We'll I don't know about ordinary beings. The Milky Way is not a normal spiral and it is an unusually large such galaxy.... And the Sun is among the 10% most massive stars in the galaxy... and it is among the 25% most metal rich stars in the Galaxy (metals in astronomy is all elements except Hydrogen and Helium).
And…. From CoRoT and Kepler data it appears that the Sun is among the 5-10% least active stars in the Galaxy. This will already make the Sun as 1 in about 1000. And that is just the beginning. There are strange things in the isotopical ratio in the Solar system indicating that the proto-solar nebula was exposed to the ejecta of at least one and possibly two supernova from exactly the right distance, namely between 0.7 and 1.0 light year. Too close and the Solar nebula blows away and thus no planets. Too far away and we do not get the isotopes we have.

Does this mean that we are special and a rarity in the Galaxy? Are all these factors important for the formation of planets like the Earth, and the emergence and evolution of life. I don't know and we do not know. What I do know is that the TV-series "The X-files" is absolutely, positively right - The truth is out there

In the near time perspective, new spacecraft and large installations on the ground like the ELT and its non-european cousins will provide some answers to these questions and of course pose new questions - after all - We do live in extra-ordinary and exciting times.

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1980-1982	Astronomer on Balloon borne Infra Red Astronomy Platform (Univ. of Groningen, Univ. of Stockholm, Caltech)
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2007-2013	ESA Study Scientist PLATO mission
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Written chapters in several books on astrobiology and exoplanets intended for graduate and under-graduate studies

Space research, in the form of observations carried out by descendants of the first Sputnik in 1957, has today helped us to know that our world is not alone but only one among a multitude of planets orbiting other stars. We are on the threshold of, using space facilities, to understand the context within where both our own Earth and all the life on it exist and evolve. This will be done by studying such exoplanets -- as planetary objects orbiting stars other than our Sun are usually referred too -- in detail. This research consist one of the fastest growing sub-disciplines of modern astronomy and is a very young science. Essentially everything important in the field has happened in the last 25 years, and most of the progress can be dated from 1995.

It has been a privilege to be able to work in this field and to follow this incredible progress. The topic has changed from when only a few enthusiasts were pursuing actual research to the status today when new data is published on more or less a daily basis. We have learnt a lot during this period, but much, much more remain to be discovered.

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