# Young suns and infant planets: probing the origins of solar systems

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# Summary

How do planetary systems form and evolve? Is our Solar System unique or just one of many others that might even harbor Earth-like planets? And could such Earth-twins perhaps host some forms of life? Questions like these have fascinated humankind for thousands of years, yet we do not have conclusive answers for all of them.

The past 30 years have revolutionized our understanding of planetary systems in our Galaxy. In 1992 the first planet outside our Solar System was discovered: this extra-solar planet (or exoplanet) was a strange world, vastly different from the eight planets that humanity had known before. The star that this planet was found to orbit was markedly different from our Sun. PSR B1257+12, which is the name of this planet hosting star, is a so-called pulsar: a fast-spinning object that marks the endpoint of the evolution of many stars that are more massive than the Sun. But even the first planet that was discovered around a Sun-like star in 1995 is a hostile environment; in fact, it had nothing in common at all with objects that we knew from our Solar System. This exoplanet with the name 51 Peg b is a gas giant like Jupiter, yet located at a much closer separation to its star. With an orbital semi-major axis of merely 5 % of the Earth-Sun distance this planet is even closer to its host star than Mercury is to our Sun. Due to its enormous size and very close orbit, 51 Peg b was the first example of a new class of planetary objects: the so-called hot Jupiters.

From these initial discoveries, an exoplanet revolution emerged in the past decades. Today, we know about 4’500 planets outside our Solar System, and several thousands of new discoveries are predicted for the next few years. Despite this abundance of detected planetary systems, only a small fraction of these planets (about 1 %) could be captured in an image. This small number is due to the major challenges that have to be overcome in order to take such an image. First and foremost, the star is many times brighter than the planet that we want to observe. Second, the separation between both objects as seen on the sky is tiny. An often used analogy is that of a firefly (our model planet) that one wants to image directly next to a giant lighthouse (our star). Naturally, the intensity of the lighthouse outshines the small firefly by several orders of magnitude. Even when just standing a few meters apart, it seems impossible to spot the small firefly with one’s bare eyes right next to this massive source of light. But extra-solar planetary systems are usually at much larger distances of several dozens of light years.[1] For our firefly-lighthouse analogy this corresponds to a separation of more than 500 km from which one wants to distinguish both individual components.

Less than two decades ago, the first image of such a planetary-mass object was collected with the Very Large Telescope (VLT) of the European Southern Observatory (ESO). Major advances in optical instrumentation, observing strategies, and data-processing algorithms facilitated the imaging of giant extra-solar planets that are usually widely separated from their

[1] One light year is approximately $9.4 \times 10^{12}$ km, which is equivalent to 9.4 trillion kilometers.

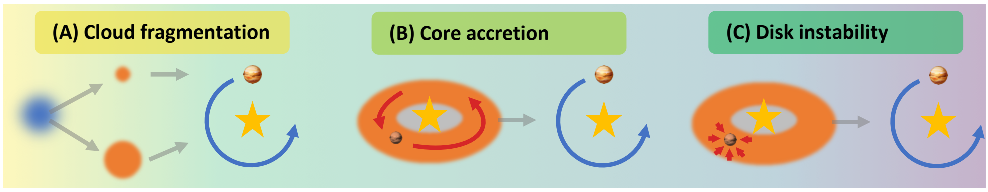


**Figure 1:** Potential formation mechanisms of wide-orbit gas giant planets.

parent stars. Today, about fifty of these Jovian gas giant planets could be imaged. Most of these have orbital separations that are significantly larger than ten Earth-Sun distances and some are even farther separated from their parent stars than all known bodies in our own Solar System are away from the Sun. The formation mechanisms of these wide orbit super-Jupiters are not understood particularly well. As visualized in Figure 1 there exist three competing theories that might explain this phenomenon.

(A) The cloud fragmentation paradigm postulates the formation of planetary mass objects as a byproduct of stellar formation. A collapsing molecular cloud is split up into fragments and some of these fragments might exhibit masses that are too low to fuse Hydrogen or Deuterium.[2] If these these fragments have masses that are smaller than 13 times the mass of Jupiter, these objects have planetary appearances and properties.

(B) The core-accretion mechanism is thought to be responsible for the formation of all Solar System planets. Young stars are usually surrounded by a massive disk that consists of gas and solids that originate from the initially collapsing molecular cloud. In this framework, small dust grains in this disk can coagulate. Via collision processes these grains can grow to kilometer-sized planetesimals. If these protoplanetary objects grow beyond a critical mass, they start accreting a gaseous envelope as we can see it for Jupiter in our Solar System.

(C) The disk instability scenario predicts that dense regions in a circumstellar stellar disk can collapse under their own gravity. This process can directly from gas giant planets that can accrete additional material from the surrounding disk.

All these potential formation mechanisms have characteristic time scales, planet separations, and companion frequencies. To understand the dominant formation pathway of wide-orbit gas giant planets, it is thus common practice to compare simulated planet populations for each of the scenarios to observational results. However, such an analysis has not been conducted for a large and homogeneous sample of young, Sun-like stars. As this category of stellar hosts might resemble the initial conditions that our early Solar System exhibited, a dedicated study of such a sample is quite intriguing and might even reveal insights into the history and evolution of our own planetary system. For this reason, we initiated the Young Suns Exoplanet Survey (YSES), whose preliminary results are reported in this thesis.

## The Young Suns Exoplanet Survey

YSES is observing a unique sample of 70 solar analogs that are located in the Scorpius-Centaurus association. This group of stars is approximately 400 lightyears away from Earth

[2]Planets are objects that cannot produce energy by nuclear fusion in their cores, since their mass is too low to generate the temperatures that are required to ignite this process. Objects that are heavier than approximately 13 times the mass of Jupiter can fuse Deuterium to Helium and are therefore not considered to be planets. Such objects are called brown dwarfs. If the mass of an objects exceeds about 80 times the mass of Jupiter, the internal temperatures get high enough to fuse Hydrogen to Helium, which is the requirement for an objects to be considered a star.

and therefore located in our Galactic neighborhood. All YSES targets are exceptionally young compared to our 4.6-billion-year-old Sun. With an average age of 15 Million years among our sample, we observe these systems just after the phase of planet formation, which is thought to occur within the first few million years of the lifetime of planetary systems. Because planets cool down after their formation, young environments like these are especially well suited to directly detect gas giant companions. We observed all the stars with the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) instrument that is mounted at Unit Telescope 3 of ESO's VLT. This instrument is one of the most advanced devices to obtain images of extrasolar planets. An extreme adaptive optics system corrects for the blurring effect that is caused by the atmosphere of our own Earth. Such a system is required to obtain sharp images from a telescope with a mirror diameter of 8.2 m. Another device that is used by this instrument is a so-called coronagraph. This opaque mask blocks most of the light from the central star and reveals faint planets that were hidden in the much brighter halo around the star (see for instance Figure 3).

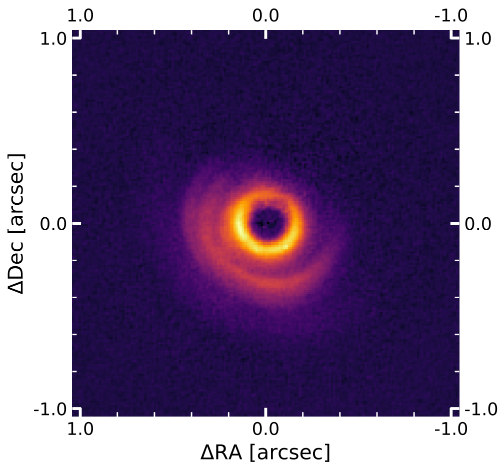


**Figure 2:** A circumstellar disk around Wray 15-788. Only half of the disk is visible. An additional inner disk might cast a shadow onto the upper right parts of the outer ring. The stellar intensity in the image center is attenuated by a coronagraph.

Even though YSES was designed to image new planets, the first result that originated from our survey was the discovery of a circumstellar disk around Wray 15-788. The extent of this disk is huge: the bright outer ring that can be seen in Figure 2 is more than 50 Earth-Sun distances away from its parent star. Moreover, the appearance of the disk is quite peculiar. It looks like the upper right is hidden in darkness. As this effect cannot be explained by the system geometry that we see in the image, we hypothesized that there is an inner disk that is too small to be resolved in our image. This inner disk is misaligned with respect to the structure that we can see, and therefore it is casting a shadow on some parts of the outer disk. In addition, this misalignment might be caused by a planet that is orbiting the star; yet this hypothesized companion has not been detected so far.

The first planetary system that we discovered as part of our survey received the name YSES 1 (see left panel of Figure 3). This star hosts two gas giant planets at very wide orbits, and it was therefore considered to be the first multi-planet system that was imaged around a Sun-like star. The closer planet YSES 1b has a semi-major axis of at least 160 times the Earth-Sun distance and the outer planet YSES 1c is even 320 times farther away from its host star than the Earth is from the Sun. Also in term of mass both planets surpass Solar System standards. Whereas YSES 1c has a mass of six times the mass of Jupiter, YSES 1b is even fourteen times as heavy as this most massive planet in our Solar System. For that reason it is not entirely clear yet, if YSES 1b is actually a planet or rather a brown dwarf companion. Future observations of this intriguing environment should shed light on this open question. Especially, a thorough characterization of both planetary atmospheres might help to distinguish between the most likely formation scenarios for the planets.

The latest discovery from our survey is YSES 2b, a giant planet that is six times as heavy as Jupiter (see right panel of Figure 3). Again, this planet is detected quite far away from its parent star at a separation of more than 110 times the Earth-Sun distance. It is unclear how YSES 2b has formed, as its mass is lower than usually expected from fragmentation

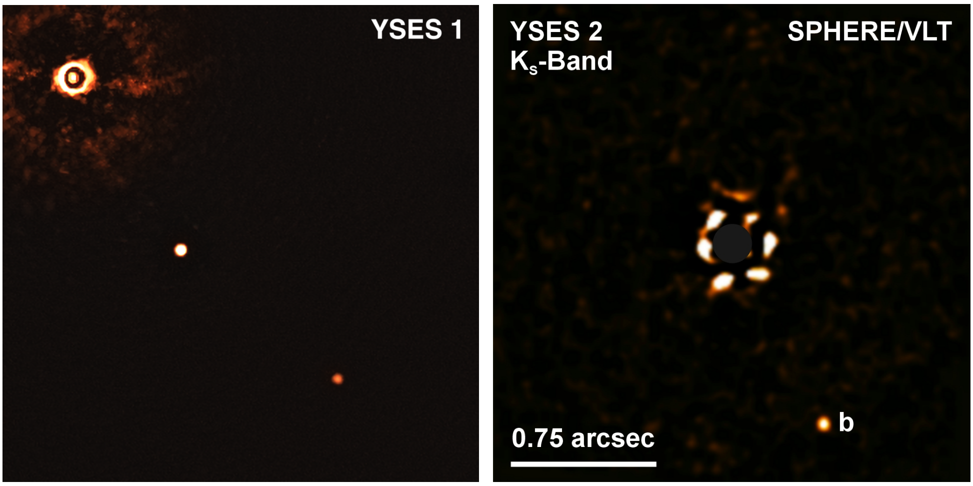


**Figure 3:** The planetary systems around YSES 1 and YSES 2. *Left panel*: The multi-planet system around YSES 1. The star is located in the upper left of the image and obscured by a coronagraphic mask. Two wide-orbit gas giant planets are detected around this solar analog. The inner and outer planet have a weight of six and fourteen times the mass of Jupiter, respectively. Image credit: ESO/Bohn et al. *Right panel*: The gas giant planet YSES 2b. The star is located at the image center and attenuated by a coronagraph.

processes (A) or gravitational instability mechanisms (C). Besides, it cannot have formed via core accretion (B) at such a large distance from the star. A possible explanation might be another as of yet undiscovered planet around YSES 2. This planet could be located closer to the star. Via gravitational interaction it scattered YSES 2b to its current position. Follow-up observations of this system will help to shed light on this potential scenario.

## Future prospects

As some of our YSES observations still need to be carried out, the final statistical analysis of the survey is pending. The occurrence rates of gas giant planets around our target stars will help to constrain the dominant planet formation mechanisms in Sun-like environments. Further atmospheric characterization measurements will provide additional clues regarding the evolutionary history of these solar-like systems. Future observatories such as the James Webb Space Telescope will provide unprecedented insights into the chemical properties of these exoplanet atmospheres, which might be linked to the formation channels of the planets. Especially the new class of giant ground-based observatories such as the Extremely Large Telescope, the Thirty Meter Telescope, and the Giant Magellan Telescope will help to search for additional planets that are located closer to YSES 1, YSES 2, and other stars from our survey sample. These close-in planets are currently out of reach for the present generation of optical telescopes. Driven by the pacey progress in the field of exoplanetary research throughout the last decades that seems to continue for the years to come, we might have a chance to find some answers to the introductory questions – including the detection of life outside our Solar System – perhaps even before the end of this century.