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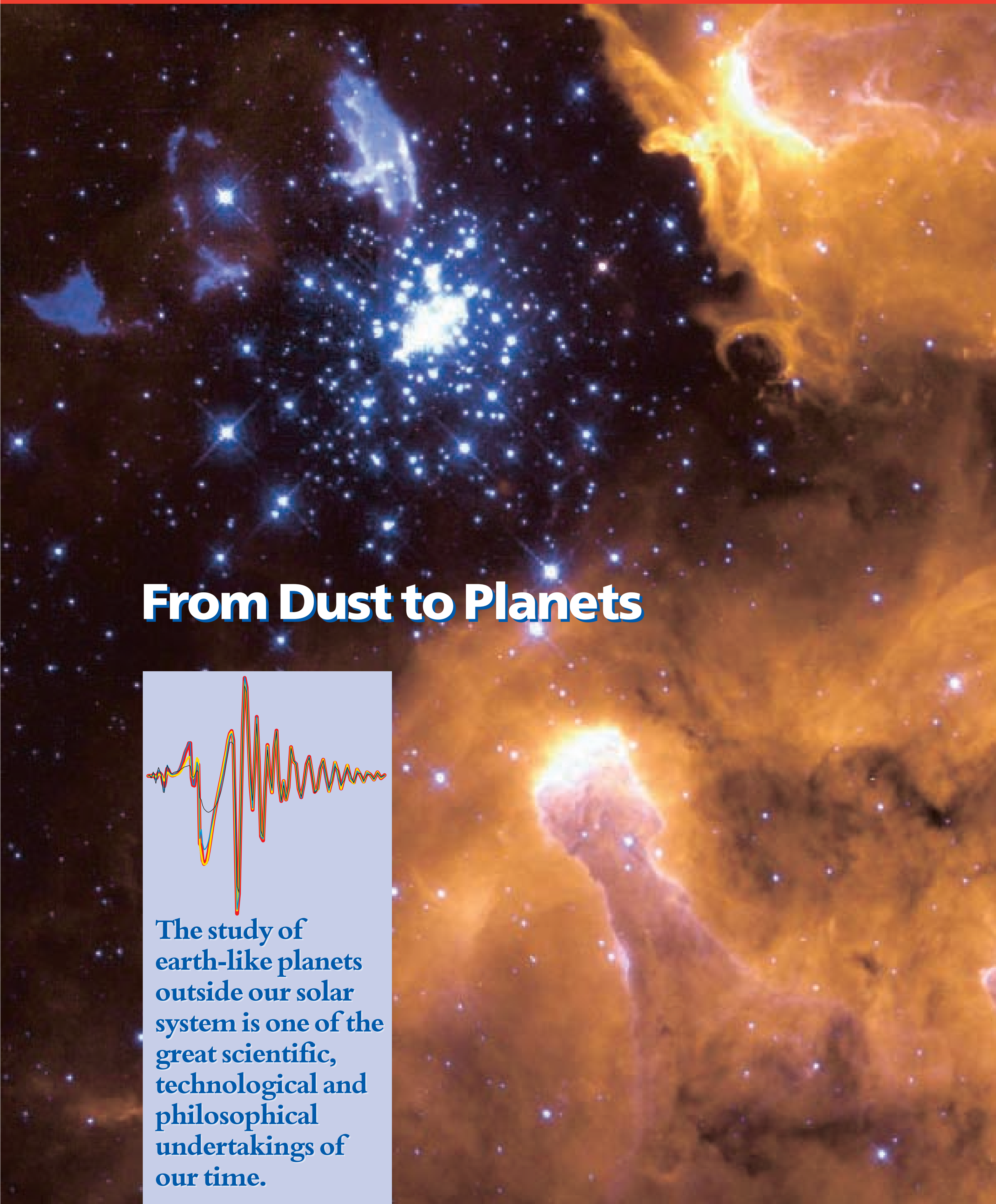

From Dust to Planets

The study of earth-like planets outside our solar system is one of the great scientific, technological and philosophical undertakings of our time.

Editorial

Chance or necessity? Careful observation of our world provides us a fascinating picture where chance and necessity play the key role. Weather evolution may be one of the most prominent examples in our daily life: While short-term forecasts have become fairly precise, thanks to a wealth of data gathered by spacecraft and ground-based stations and powerful computers processing these data, long-term forecasts remain a dream, because non-linear, chaotic processes become dominant. Interestingly, teachers at every level tend to carefully avoid the topic of chaos, perhaps because they prefer the rigour of order to the freedom of chaos… But order is only half of the truth, as we should have learnt in the last 150 or so years since the publication of the "On the Origin of Species" by Charles Darwin.

The orbits of planets around a central star are another example of a short term deterministic and long term chaotic process. While it is possible to predict for example the orbit of Saturn and its moon Titan over a decade – which is of crucial importance for the common ESA/NASA mission Huygens/Cassini, which is currently on its seven years journey to Saturn and Titan – it is not possible to investigate the formation process of our solar system simply by extrapolating back over billions of years to the era when our sun began to shine.

In recent years, it has become possible to observe – at least indirectly – planets circling around other stars. M. Mayor and D. Queloz of the Observatory of Geneva were the first to announce such a spectacular finding. Observing and comparing solar systems yields a new picture of the star and planet formation process, which itself is the product of interaction between chaos and necessity. It is this topic to which the present issue of SPATIUM is devoted. Prof. Willy Benz of the Physikalisches Institut of the University of Bern gave the members of our association a fascinating lecture on the subject of planet formation. We are pleased to submit herewith the revised version of his lecture to our readers.

Bern, October 2000
Hansjörg Schlaepfer

Impressum

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Phone ++41 31 631 48 96
Fax ++41 31 631 48 97

President
Prof. Hermann Debrunner,
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Birth and death of stars in the NGC 3603 nebula (W. Brander/JPL/IPAC, E.K. Grebel/U. Wash., You-Hua Chu/UIUC, HST/NASA)

From Dust to Planets *)

Willy Benz, Institute for Physics, University of Bern

Introduction

While the search for planets and life outside the solar system has been going on for decades, the discovery in 1995 of the first extra-solar giant planet by Geneva Observatory astronomers Michel Mayor and Didier Queloz followed within months by the discovery of 2 new giant planets by Geoffrey Marcy and Paul Butler of Lick Observatory (USA) has sparked a real revolution. Five years later, over 50 such giant planets have been found **(Figure 1)**. implying that at least 3–5% of all sun-like stars have giant planets.

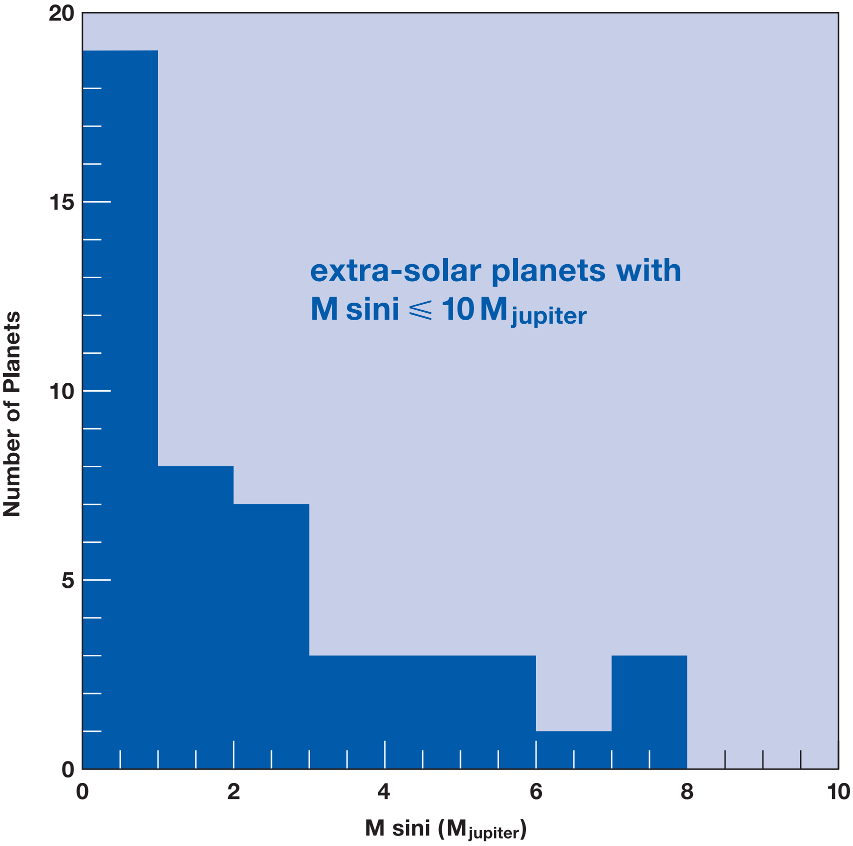

Figure 1
Mass of the extra-solar giant planets discovered thus far. Since more massive planets are easier to detect, the paucity of massive objects indicates that jupiter-sized (or smaller) objects are by far the most abundant ones.

Since this represents only the fraction of stars having planets that could be detected with current instruments, we must conclude that planet formation is not an extraordinary event but rather quite common occurrence.

Our solar system forms the basis for most of our information about how planetary systems must develop. However, the degree to which it is actually representative of all planetary systems is unclear. It now appears to be very different from all those discovered thus far. Indeed, contrary to the giant planets in our own system (Jupiter, Saturn, Uranus, Neptune), the newly discovered planets have much smaller orbits many with sizeable eccentricities. Although there is clearly a strong observational bias against detecting distant and/or small planets, it is significant that none of these newly discovered objects should have existed according to conventional formation theory!

Does this mean that our solar system is unusual or maybe even unique or have we simply not yet been able to detect the right kind of systems elsewhere? To answer this central question requires getting a full measure of the possible diversity between existing systems as well as a much better understanding of the physical processes underlying planet formation and evolution.

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*) Pro ISSI lecture, Bern, 3rd November 1999

Planet formation: The conventional picture

Planets are likely nothing else than a by-product of star formation stemming from the necessity of conserving angular momentum. Indeed, stars form through the gravitational collapse of interstellar matter over more than 8 orders of magnitude in size. In the presence of rotation and/or magnetic field, the collapse must results in a star/disk structure with the star having most of the mass and the disk most of the angular momentum. Thanks to the incredible resolution of the Hubble Space Telescope (HST), a few of these disks orbiting nearby young stars could even be imaged **(Figure 2)**.

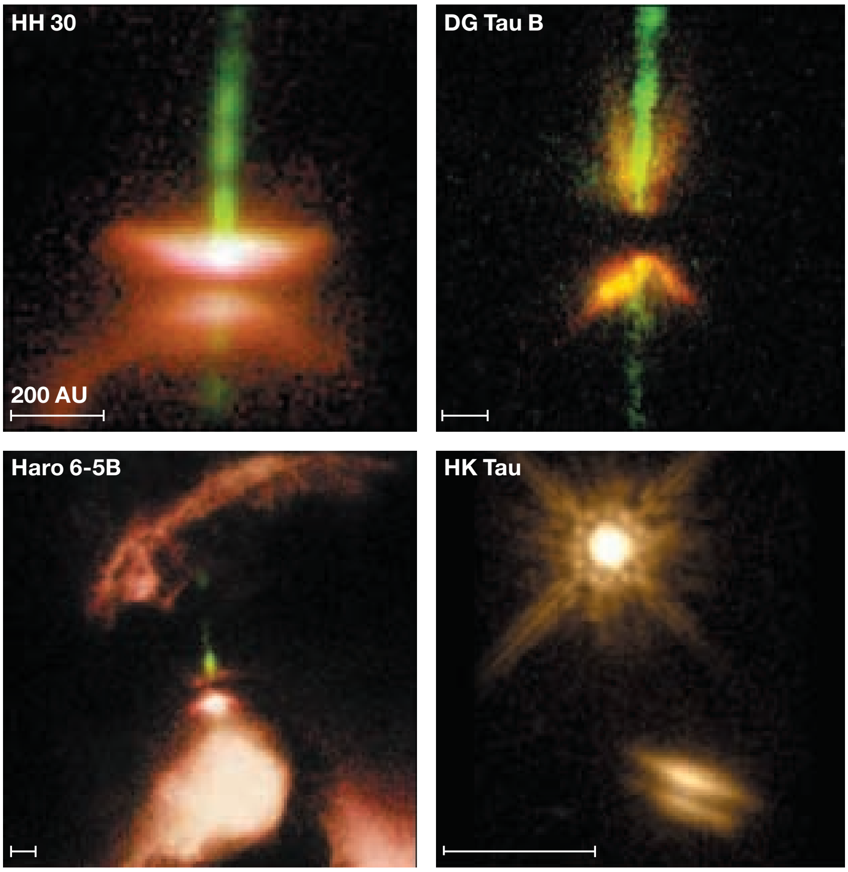


Figure 2
Images of circumstellar disks around a few nearby young stars imaged by HST. Note the the bipolar jets emerging on either side of the disk.

In the case of the solar system, the disk is generally taken to have a mass of a few percent of a solar mass and to be less than 100 AU (1 AU is the distance between the Earth and the sun) in size.

Planets subsequently form in this disk probably mostly through collisions at first between dust grains and as time goes by between larger and larger bodies. Earlier theories in which planets form through the gravitational collapse of patches in the disk have grown out of favor. The flow diagram in **Figure 3** illustrates these concepts.

This picture provides a simple explanation why all planets in our solar system not only orbit the sun nearly in the same plane but also in the same direction. The nearly coeval formation of the planets and other small bodies and the sun is actually supported by comparing the ages of the oldest Moon rocks and the sun.

The basic challenge of planet formation consists therefore of assembling in a disk orbiting a central star micron-sized or smaller dust grains in bodies with over 10^4 km in diameter **(Figure 4)**, a growth by nearly a factor 10^{13} in size or 10^{40} in mass! Since giant planets are mainly gaseous planets, their formation must take place while gas supply lasts. From studies of disks around other young stars, it is believed that typical lifetime of disks are of order a few million years. Hence, as paradoxical as it sounds, giant planets must be formed in less than ten million years while forming terrestrial planets may take much longer.

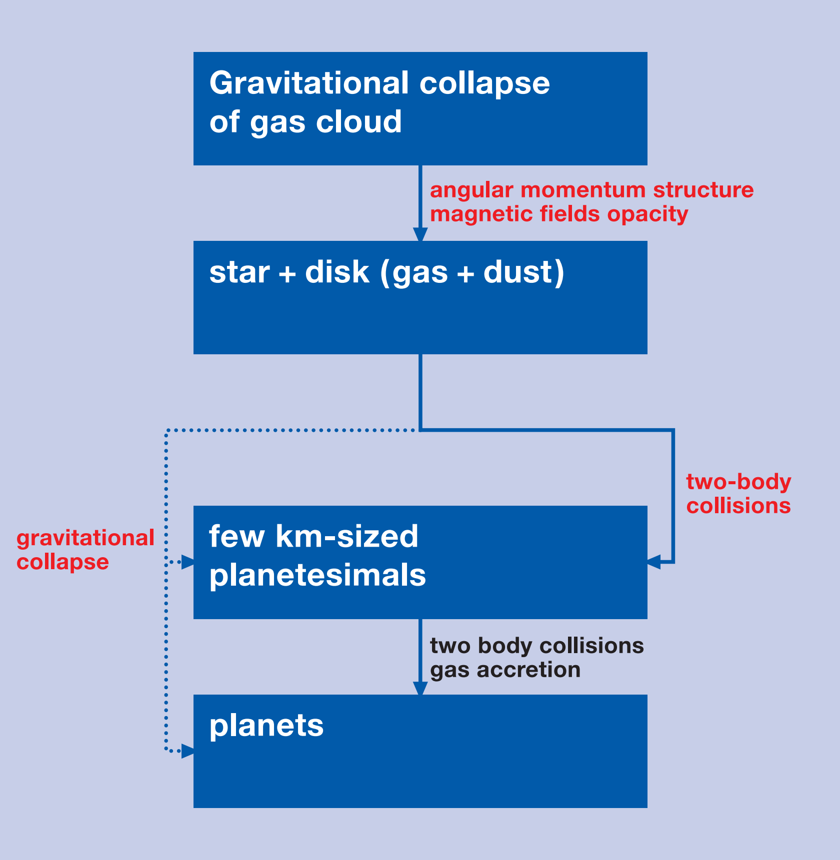
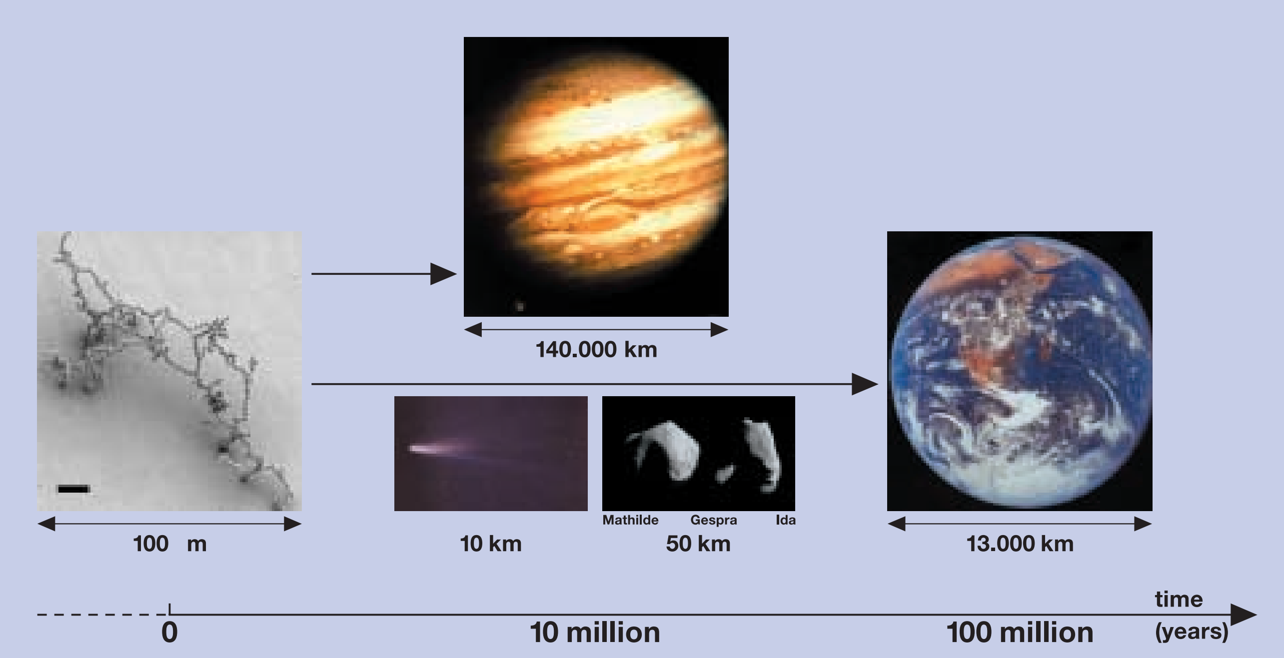


Figure 3
Planetary formation as a by-product of star formation. In the standard model, the planets form entirely through collisions (solid line) while in other models gravitational collapse is invoked at various stages of the formation process. The main physical processes at play are shown in red.

Figure 4
The challenge of planetary formation: Assembling micro-meter dust grains in planets through collisions in an amazingly short timescale.



On their path to becoming a planet, dust grains reach the size of comets and asteroids which, if they can avoid being incorporated in a larger object, are left behind like crumbs on a table after a good meal.

The early phases: The first million year

The growth of planet-sized bodies in this disk is thought to occur essentially through collisions. Earlier models relied on gravitational instabilities in the dust layer to rapidly grow objects several kilometers in size (dotted line in **Figure 3**). However, it has been pointed out that the velocity shear between the dust and the gas will stir up the dust sufficiently to make instabilities impossible. While the extend of this turbulence of the dust layer is still debated, collisional growth from the smallest sizes on has become the favorite scenario.

At first, dust grains collide at relatively gentle velocities which are determined by size and shape dependent gas drag. As bodies grow larger, the importance of gas drag diminishes to vanish completely by the time bodies reach several tens of meters in size. With subsequent increase in mass, the collisional cross section of these planetesimals increases due to gravitational focusing yielding to the so-called runaway growth phase during which the larger bodies sweep-up all the smaller ones within their gravitational reach.

This phase is not without problems. Laboratory experiments have shown that at the very small scale dust aggregates readily **(Figure 5)**.

On the very large scales, various impact simulations have shown that self-gravity will ensure growth. However, the situation is much less clear for objects ranging in size from a centimeters to kilometers since in this size range no real “sticking” mechanism has yet been found. Indeed, at this size, the forces operating at the micron size level are no longer effective and gravity is still much too weak.

The escape velocity of a 1 meter-sized rock is of order 1 mm/s while the typical collisional velcity between these objects is of order 100 m/s. Hence, for sticking the bodies involved have to be able to dissipate all but 10^{-10} of the incoming kinetic energy. Whether this can be achieved by purely mechanical structures or requires the presence of a “glue” whith special visco-elastic properties remains to be seen.

Figure 6 summarizes the main three stages of growth, the relevant physical mechanism operating and the main study tools.

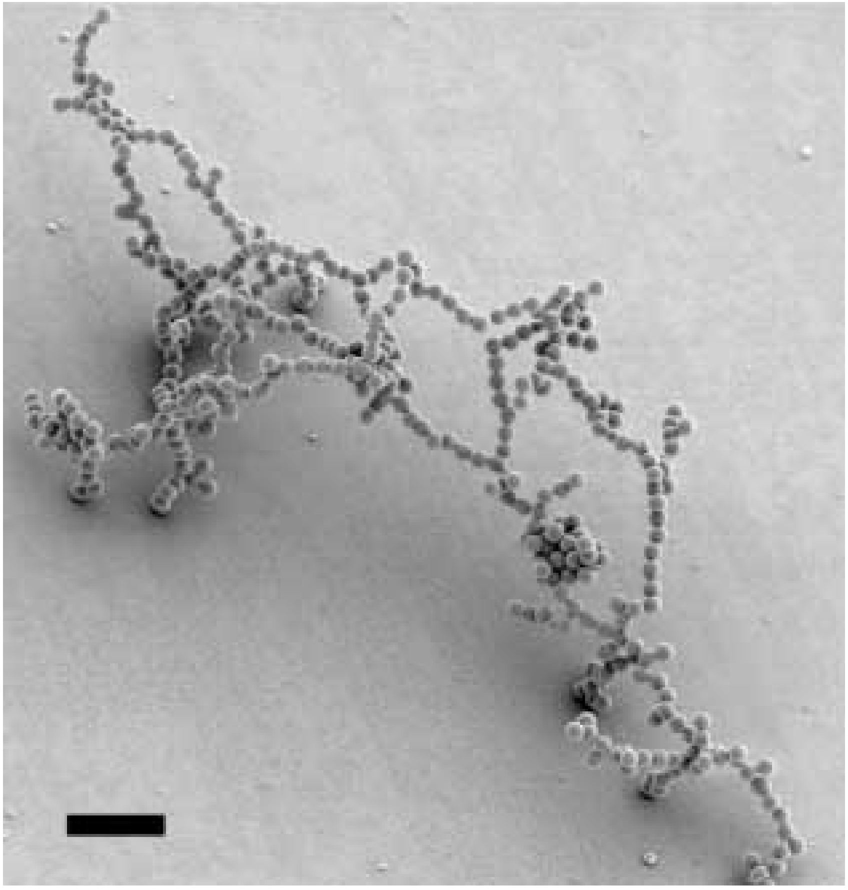


Figure 5
Aggregate obtained in laboratory dust coagulation experiments by J. Blum and collaborators. The scale is given by the 10 µm black line.

The late phases: 100 million years

This early planetary accretion phase was, over a few million years, replaced by an even more violent period when growing bodies encountered one another at increasingly high velocities boosted by mutual gravitational interactions. This phase last for another 100 to 200 million years until all remaining bodies have been swept up by the planets. Collisions occur in a random fashion involving objects of different masses, structures, composition and moving at different speeds. Thus, this phase of planet formation must not be viewed as a monotonic process by which material is incrementally added to a growing planet. Instead, accretion must be viewed as a long chain of stochastic events in which non-disruptive infall exceeds, over time, violent dispersal.

The so-called giant impacts in which proto-planets of comparable size collide represent the ultimate in violence during planetary accretion. While they can lead to the total destruction of the planets involved they can also leave scares arguably the best evidences remaining today of such a violent past. The Earth's Moon, for example, is believed to originate from the debris ejected after such a giant impact and subsequently re-accreted in Earth's orbit **(Figure 7)**.

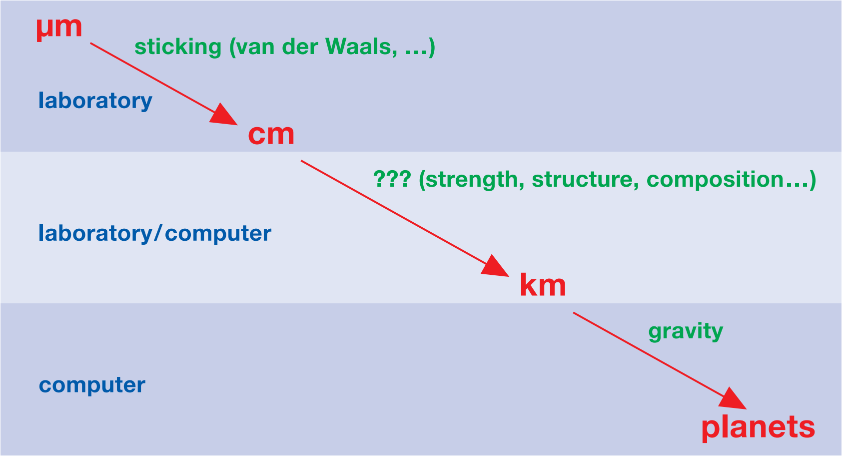


Figure 6
Planetary growth stages. In green the main physical mechanism ensuring growth and in blue the main tool used to study these phases. Note that the growth mechanism in the meter size range is still unknown.

Figure 7
The Moon may have originated from the debris ejected in orbit following a giant impact of the sort depicted in this painting by W. Hartmann.

Simulations of both impact and re-accumulation have not only shown that such a scenario is possible but have made it today's favorite theory of lunar origin. Studies of lead and tungsten isotopic composition of the silicate Earth have even allowed to date the giant impact to about 50 million years after the start of the solar system!

Mercury's anomalous composition can also be explained in terms of a giant impact which ejected most of the mantle of the planet leaving behind essentially the iron core. A similar event could have caused the large obliquity of Uranus. Giant impacts, by explaining many individual planetary characteristics as outcome of a general process rather than the result of unique and ad hoc local conditions, have undoubtedly become a central characteristic of the modern paradigm of planetary formation.

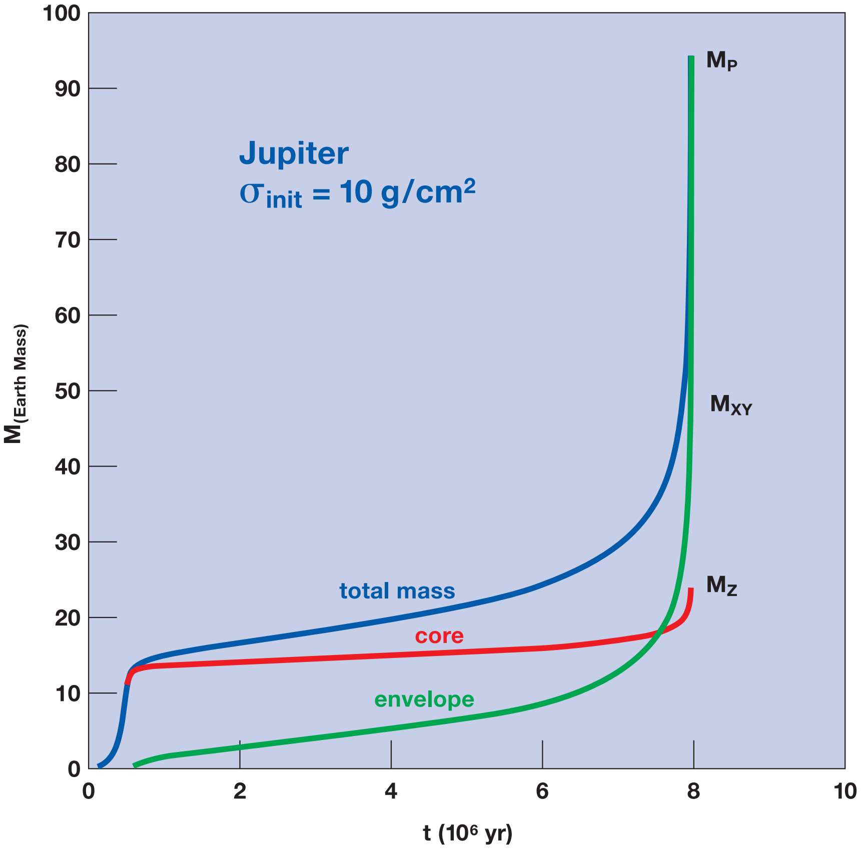


Figure 8
Accretion history of Jupiter. Note the rapid accretion of the gaseous envelope (green) onto the core (red) once the system has reached the critical state. (adapted from Pollack et. al 1996). With the surface density adopted here ($10\ g/cm^2$), Jupiter reaches its final mass in about 8 million years.

Giant planets

If a body grows beyond a critical mass of about 10 times the Earth's mass while still embedded in a gaseous disk, it will be able to accrete dynamically a considerable amount of surrounding gas eventually becoming a giant gaseous planet such as Jupiter or Saturn **(Figure 8)**.

In comparison to terrestrial planets, giant planets formation must proceed very rapidly since observations of many young stars as well as some theoretical considerations imply that circumstellar disks have lifetimes ranging from one to ten million years. The time available is therefore relatively short especially since the envelope accretion begins rather slowly at first **(Figure 8)**. It is therefore important that the seed body reaches critical mass rapidly hence relatively high surface densities of solids are required. This explains why giant planets were believed to form only sufficiently far away from the star where ices and not just silicates are present.

Planet formation: The problem

With the discovery of the first extra-solar giant planet, we have learned that some stars have giant planets orbiting at distances up to 10 times closer to their star than Mercury to the sun. While not all are that close, a significant number of them orbit within 0.1 AU of their star! In addition, except for these very close planets for which tides circularize the orbit, the eccentricity of all extra-solar planets is rather large. To illustrate to what extend these systems differ for our own solar system, we have plotted in **Figure 9** the eccentricity of all extra-solar giant planets as well as solar system planets as a function of their semi-major axis.

The presence of these giant planets at close orbital distances requires significant modifications and/or extensions to the standard formation model outlined above for two major reasons. First, the mass of typical proto-planetary disk within the orbit of the closest objects observed would not amount to a jupiter mass by a large factor even assuming 100% efficiency in collecting the matter. Second, even if there was sufficient mass available, the young 51 Peg B for example would be torn apart by the star's gravitational forces at its current location.

To reconcile theory and observations different mechanisms have been considered which essentially allow planets to migrate from their birth place to where they are observed today. This planetary migration is not a new idea, but it was never considered before as an essential ingredient in planet formation.

Most migration scenarii consider the gravitational interactions between the growing planet and the gaseous disk. When a massive objects orbits inside a gaseous disk, gravitational interactions between the two give rise to significant perturbations in the disk. In particular, if the planet is massive enough a gap in the disk opens while density perturbations extend further inwards and outwards **(Figure 10)**.

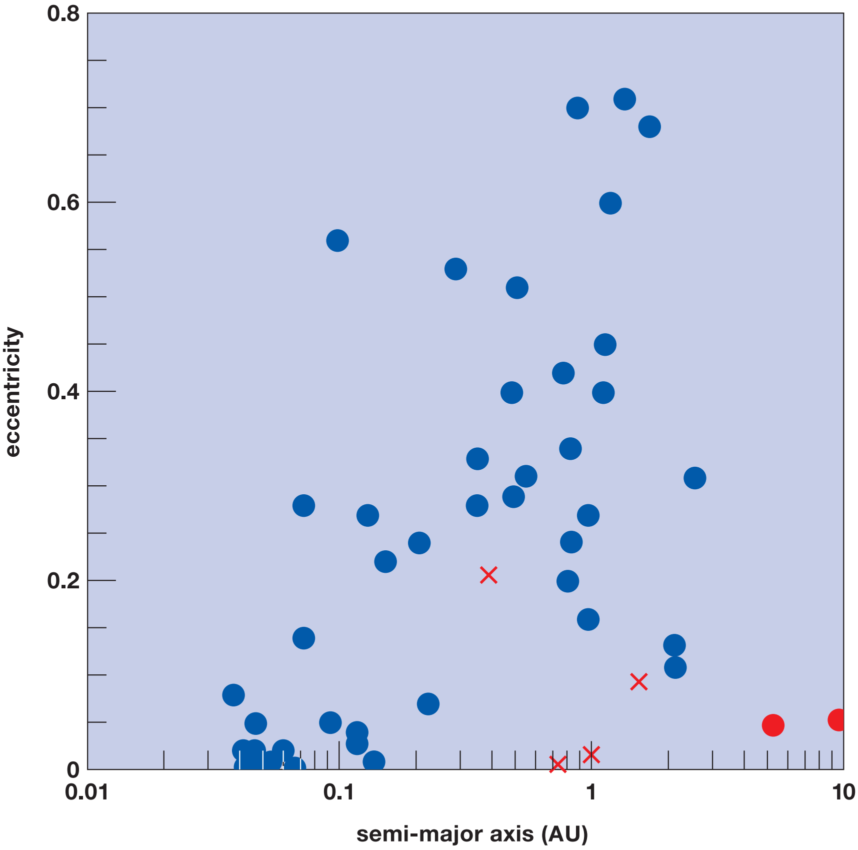


Figure 9
Eccentricity as a function of semi-major axis for giant extra-solar planets (blue dots), giant (red dots) and terrestrial planets (red crosses) of our own solar system. Note the difference in orbital parameters of giant planets in and outside our own planetary system. The absence of extra-solar giant planets beyond 3 AU is due to observational biases.

The tides raised in the disk by the planet result in a non-axisymmetric density distribution which in turn exerts a torque on the planet. The magnitude as well as the sign of the net torque is determined in a relatively complicated manner by the overall structure of the disk itself. Sophisticated multi-dimensional numerical simulations are required to actually compute this torque. **Figure 11** displays an example the torque exerted on a planet from the different regions of the disk.

The result is a transfer of angular momentum from the disk inside the planet's orbit to the planet as well as a transfer from the planet to the disk outside its orbit. As a result of this transfer, the planet opens a gap in the disk and spirals slowly inwards.

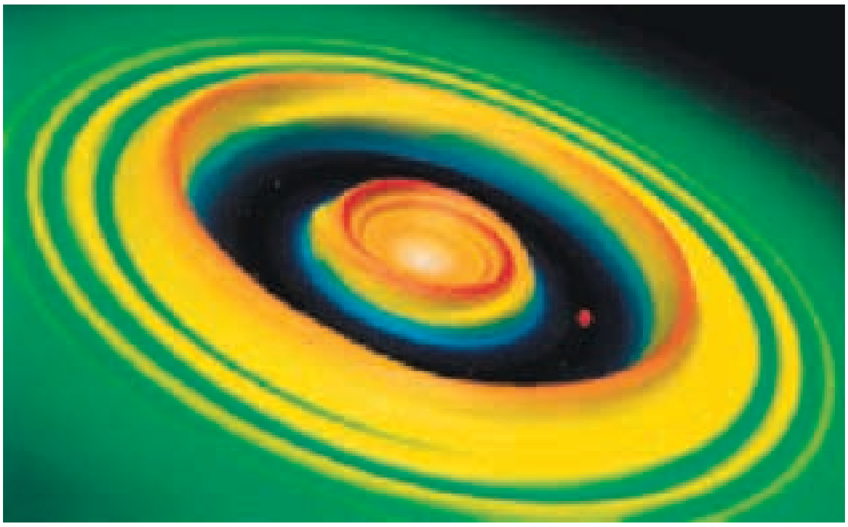


Figure 10
Simulation of a giant planet embedded in a gaseous disk. The local surface density is represented as the third dimension with red implying a high density. Notice the non-axisymmetric density perturbations in the disk induced by the presence of the planet (from G. Bryden).

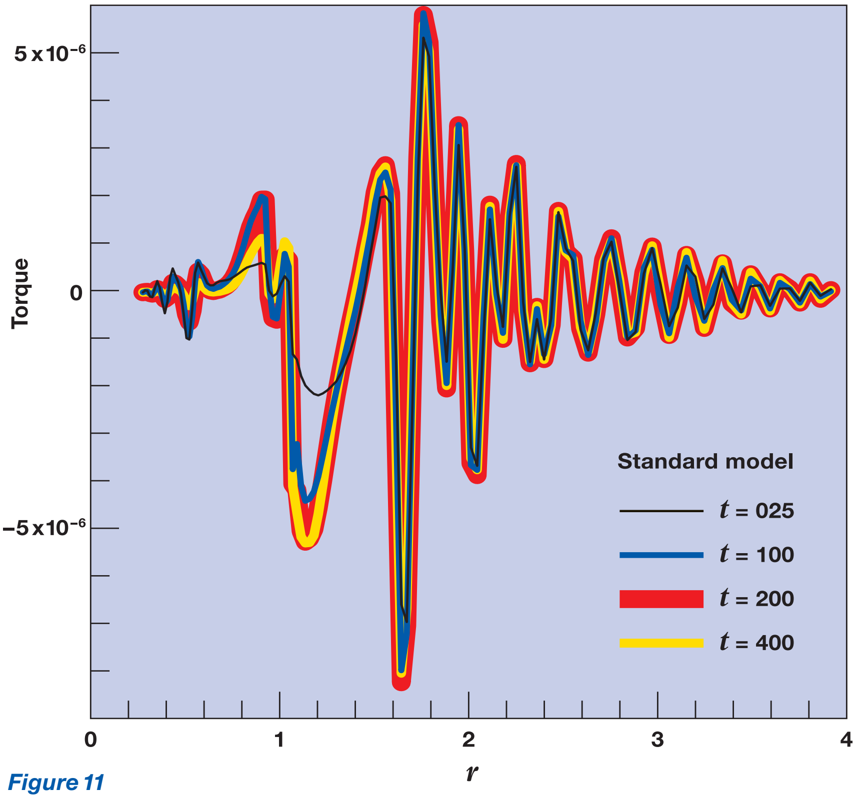


Figure 11
Torques exerted on a planet from various regions of the disk at different times during the simulation during which the planet was not allowed to move (units are arbitary). The net torque determining the radial migration of the planet is the sum of the local torques (from W. Kley).

While migration appears to solve some of the problems raised by the new systems, other issues remain puzzling and may hint to more fundamental problems in our understanding. For example, the migration timescale appears to be quite short (a few 100'000 years) therefore, why didn't the planets "fall" into their star but stop after having traveled 99% of the distance? A hint for the existence of a "stopping" mechanism is given by the apparent pile-up of planets visible in **Figure 9** at the shortest radii. Even more puzzling maybe is the fact that there are no signs of extensive inward migration in our own solar system. In particular, Jupiter does not appear to have migrated significantly.

In summary, while a few years ago it was believed that a relatively consistent working paradigm for the formation of planetary systems existed, today we are left with pieces of theories that do no longer provide a physically coherent picture!

For our understanding to make progress, further detections of extra-solar planets are required in order to have a statistically meaningful sample of objects to analyze. Ideally, this sample must include planets of all sizes not just giant planets so that the full extend of the existing diversity among planetary systems can be grasped.

Finding and studying earth-like planets

Indirect detections

So far the discovery of extra-solar giant planets has been made only through indirect methods in which the perturbations in the motion of the star induced by the presence of a planet are detected. The fact that these perturbations correspond indeed to orbiting planets has been confirmed recently by the detection of a transit, that is the decrease in stellar light as the planet passes between the star and us. These observations also yielded the radius and mean density of the object confirming its giant gaseous planet nature.

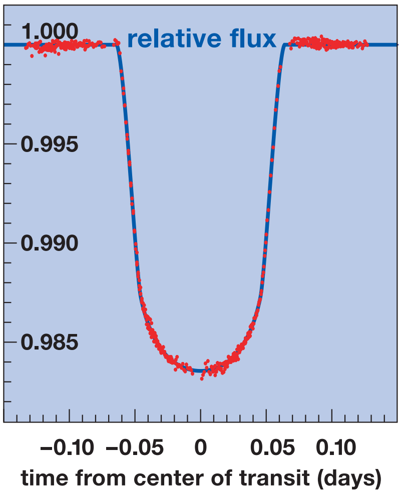


Figure 12
Light curve of HD 209458 during transmit as measured by HST (D. Charbonneau).

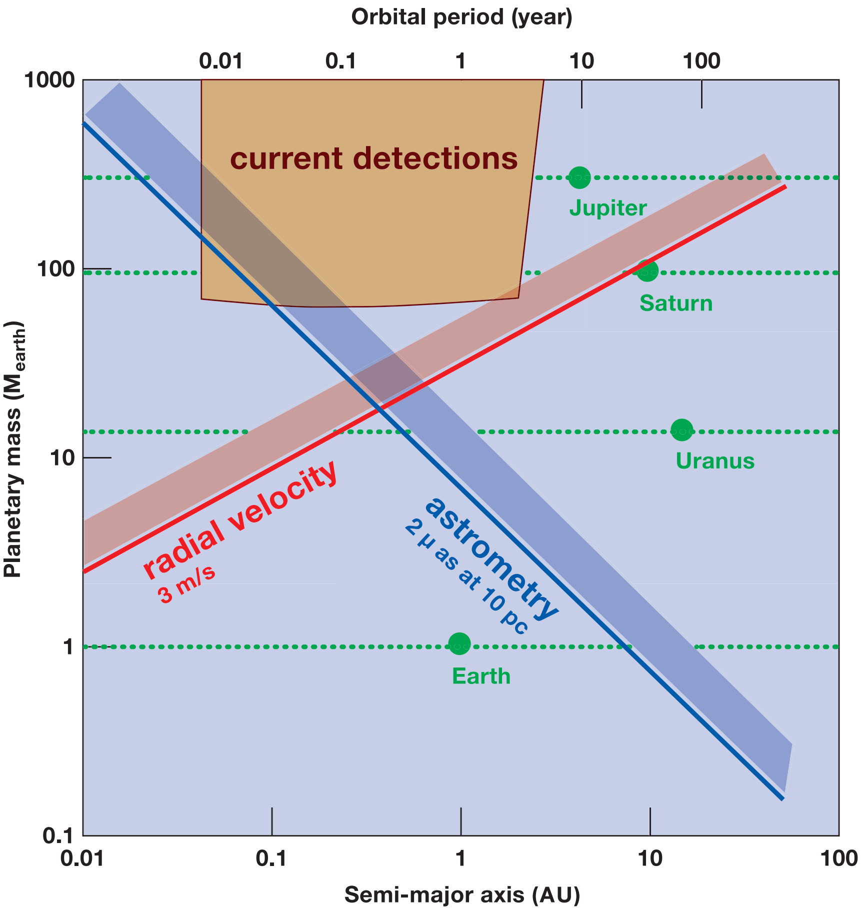


Figure 13
Detection limits of extra-solar planets for radial velocity searches (red line) and astrometric searches (blue line). The limit has been computed for the instrumental precision indicated. For reference, a few planets of the solar system are indicated. The brown box delineates the area of current discoveries.

Today, the most successful planet detection method remains the detection of radial velocity variations. The best measurements to date have an accuracy of approx 4 m/s (the speed of a casual biker). HARPS, a new instrument developed for ESO by a consortium including the Physics Institute of the University of Bern and led by Geneva Observatory, has been designed to reach an accuracy of 1 m/s (the speed of a pedestrian). Improving accuracy further is thought to be pointless because stellar surface motions induce an intrinsic noise in velocity measurements of this order. For comparison, the sun's reflex motion due to the presence of the Earth is about 8 cm/s, or more than an order of magnitude smaller.

Radial velocity searches are most sensitive to massive planets close to their parent star. To detect more distant and/or smaller planets, other methods are required. One of the most promising consists at measuring not the radial wobble of the star but its periodic displacements in the plane of the sky. In other words, high precision astrometry is used to detect again not the planet itself but the motion of the star. Since for a given measurement precision, one method is most sensitive to objects close to stars while the other to distant objects, both methods are actually complementary **(Figure 13)**.

To measure the difficulties involved in making these astrometric measurements, one has to realize that angles as small as 1 micro-arsecond have to be measured. This represents an angle smaller than the one sustained by a hair more than 100 km away! While just a dream a few years ago, such measurements will soon be possible using long baseline optical interferometers. Astrometry with an interferometer consists at combining the light of two or more separate telescopes and measuring angles (by adjusting optical delay lines) between the target star and a nearby reference star. To actually build such instruments is a very challenging technological task. For example, to get an efficient beam combination requires active distance control at a few tenths of nanometer precision level over more than 100 m of light path!

Despite these difficulties, long baseline optical interferometers, are scheduled to become standard facilities at the largest observatories in Europe as well as in the US. The European Southern Observatory (ESO) Very Large Telescope Interferometer (VLTI) located in Chile will be within the next three to five years the most powerful instrument of this sort **(Figure 14)**.

Figure 14
ESO's Very Large Telescope (VLT) array on the Paranal mountain in Chile consists of four 8.5 m diameter mirror telescopes. These telescopes can be coherently combined together with auxiliary telescopes (not on the picture but the rails are visible) to provide an interferometer with a baseline of up to 200 m).

Direct detection

While indirect methods will certainly yield a wealth of data about extra-solar planetary systems, the direct detection of photons originating from the planet itself would enable much more detailed physical studies. Examples include determining the chemical composition and temperature of the planet's atmosphere through spectroscopy, and studying surface structure and rotation by analyzing the light-curve. Even the presence of life could be tested by searching, for example, for oxygen lines in the spectrum. Indeed, the ozone absorption feature near 10 mm in the Earth's spectrum but absent in Venus' or Mars' only exists because of the photo-synthetic activities taking place on Earth.

Figure 15

In this colourful galaxy NGC 4214 star formation has taken place since billions of years (J. MacKenty/STScI et al. & the Hubble Heritage Team/AURA, STScI, NASA).

The major observational challenge in direct detections resides in observing a very faint object extremely close to a very bright one. Indeed, the most favorable brightness ratio (in the infra-red) between a planet and a sun is of order 10^7 and both objects are typically separated by 0.01 to 0.1 arcsec. While there are no direct detection of planets as of today, **Figure 16** illustrates the importance of resolution when it comes to detect faint objects close to bright ones. Such direct imaging of a faint object close to a bright one is again possible using optical interferometry. By combining the light of two or more arms of the interferometer in such a way that destructive interferences occur on-axis, the star is literally eclipsed thus revealing the fainter objects nearby.

To combine the light in such a way to "null" the star's light requires the exact knowledge of the phase of each light beam. Unfortunately, atmospheric turbulence renders this task extremely difficult and thus these so-called "nulling interferometer" will have to be flown in space. Such space-based instruments are on ESA's **(Figure 18)** as well as NASA's list of possible missions of the next decade albeit none has been definitively selected yet.

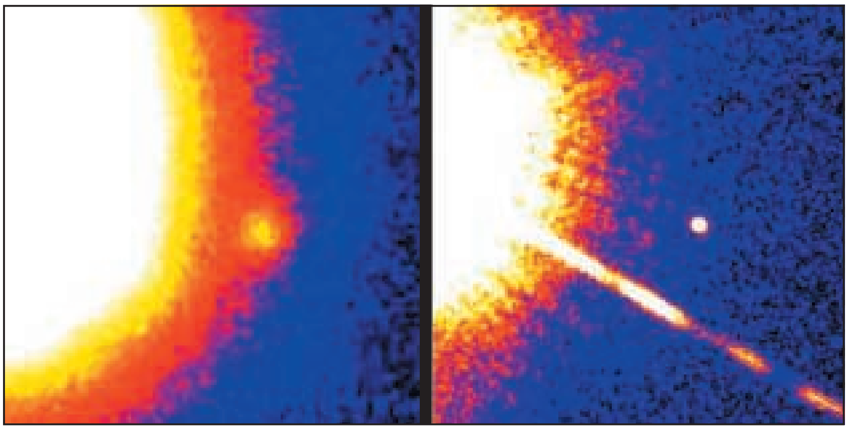


Figure 16

The direct detection of brown dwarf Gliese 229 from the ground (left) and from space using HST (right). This example illustrates how important high resolution is when it comes to detect faint objects close to bright ones. Detecting planets is orders of magnitudes more difficult and will be only possible from space.

Conclusions

The detection and study of earth-like planets outside our solar system will be one of the great scientific, technological, and philo-sophical undertakings of our time. Considered yesterday by most as a wild dream, the search for and studies of planets outside the solar system will become reality within the next decade or two. From the ground and later from space incredibly powerful instruments will search for and analyze the light of distant planets in an unprecedented world-wide effort to understand the origin and evolution of planets and maybe most importantly to check for the presence of even primitive life elsewhere in the universe.

Figure 17
Star formation in the Omega Nebula (European Southern Observatory).

Figure 18
DARWIN: The InfraRed Space Interferometer. Six free-flying telescopes are connected interferometrically to detect Earth-like planets orbiting nearby solar-type stars.

The author

Willy Benz was born in Neuchâtel, Switzerland in 1955. Fascinated by natural sciences, he went to the University of Neuchâtel, where he acquired the diploma in physics. He carried his studies further as a research assistant at Geneva Observatory working in the group of Prof. Mayor (the well- known Swiss scientist having discovered the first planet orbiting a star other than the sun). It is during this period that his interests lead him from observations (he has spent many nights observing from the South of France and from the European Southern Observatory at La Silla, Chile) to a more theoretically oriented research. A doctoral thesis on the subject of star formation and rotation concluded his Geneva years.

After his doctorate, he went for two years to the Los Alamos, National Laboratory, USA, to hold a postdoctoral position in the Theoretical Division working with S. Colgate with whom he is still collaborating. There, he became interested in collision theories which are at the heart of our understanding of planet formation. A visit by A. Cameron triggered another collaboration that lasted many years and that led to his move to Harvard University where he was an assistant and later an associate professor for 5 years. During these years, his research focused on giant impacts and stellar explosions. He explored the possibility of forming the earth moon from the ejecta thrown into orbit following the impact on the young earth of a mars-sized body.

In 1991, he joined the rank of the faculty of the University of Arizona in Tucson were he became a professor of astronomy and planetary sciences. It was the time when comet Shoemaker-Levy 9 fell into Jupiter and thus a great time for someone interested in the physics of collisions!

After 13 years in the USA, he received a call from the University of Bern in 1997, where he was offered the position of physics professor in the Group of Space Research and Planetology at the Physikalisches Institut.

Willy Benz is currently living in Neuchâtel on the foothills of the Jura mountain range. He is married and has three daughters. Mountain biking in the Jura and long walks together with his dog are among his favourite activities allowing him to dive deeply into the loneliness of a wonderful nature.

A recognized teacher, Willy Benz aims at conveying his fascination of nature and the intense pleasure provided by the understanding of some aspects of it to his students and to the general public as well. Space research has always benefited from the interest of the later and conveying to him the importance of the latest discoveries is seen by Willy Benz as an important task of a scientist. His sparkling lectures never fail the audience.

For him, despite its small size Switzerland plays an important role in the global scientific community. In many areas of space research Swiss scientists are at the forefront, as for instance in the discovery of planets outside the solar system. However, there is always the danger that Switzerland may loose this excellent position if the political will to support our stars dwindles, if we somehow fear to be ahead.