Extra-solar planets

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The generally accepted picture of stellar formation teaches us that a planetary system is a natural by-product of the stellar formation process. When a cloud of gas and dust contracts to give origin to a star, conservation of angular momentum leads to the formation of a flat disk of gas and dust around the central newborn "sun". As time passes, in a process still not completely understood, dust particles and ice grains in the disk are gathered to form the first planetary seeds. In the "outer" regions of the disk, where ices can condensate, these "planetesimals" are thought to grow in a few million years. When such a "planetesimal" achieves enough mass (about 10 times the mass of the Earth), its gravitational pull enables it to accrete gas in a runaway process that gives origin to a giant gaseous planet similar to the outer planets in our own Solar System. Later on, in the inner part of the disk, where temperatures are too high and volatiles cannot condensate, silicate particles are gathered to form the telluric planets like our Earth.

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Recent images taken by the NASA/ESA Hubble Space Telescope (HST) have revealed a multitude of such proto-planetary disks in the Orion stellar nursery, showing that disks are indeed very common around solar-type stars. This supports the idea that extra-solar planets should be common. However, such systems have escaped detection until very recently, and the idea of finding other worlds was until the mid 90's no more than an old and fantastic dream.

Detecting extra-solar planets

The reason why this was so has to do with the difficulty to detect such systems. Planets are cold bodies, and their visible spectrum results basically from reflected light of the parent star. As a result, the planet/stellar luminosity ratio is of the order of 10^{-9}. Seen from a distance of a few parsec, a planet is no more than a small "undetectable" dot embedded in the diffraction and/or aberration of the stellar image.

But a planet also induces dynamical perturbations into its "parent sun", giving the possibility of detecting the presence of a planet by indirect means [1]. Astronomers have long tried to use this fact to measure the small astrometric periodic motion (of the order of 1 milli-arcsecond for the best cases) of a star as it moves around the centre of mass of the star-planet system. The results were quite disappointing, with some false and discouraging detections.

Another technique used to search for stellar motions induced by an orbiting planet is based on the measurement of the star's radial-velocity (in the direction of the line of sight). The biggest challenge of this technique is that one needs to measure the stellar velocity with a very high precision. For example, Jupiter induces a periodic perturbation with an amplitude of only 13 m s-1 on the Sun! For comparison, current techniques have already permitted to achieve precisions of about 3 m s^{-1} ($\Delta\lambda / \lambda = 10^{-8}$).

The first discovery of what could be called a "planetary system" was, however, unexpected and of a completely different nature. By measuring the time delays of the radio pulses of the pulsar PSR 1257+12 (a rapidly rotating and highly-magnetized neutron star) astronomers [2] have detected the presence of three planetary-mass companions, with masses comparable to that of the Earth, orbiting the central object in quasi-circular orbits. These planets, however, have certainly not been formed at the time of the star formation, since the circular orbits could not have survived the strong stellar mass loss at the time of the supernova explosion. These "second generation" planets probably originate from an accretion disk created after the formation of the neutron star.

In any case, it was not until 1995 that the first planet around a "normal" star like the Sun was detected. Using the radial-velocity method, astronomers have induced the presence of an object with only 0.5 times the mass of Jupiter orbiting the solar-type star 51 Pegasi [3]. The curse was broken. Finally an exo-planet! There was, however, a completely unexpected detail: the planet

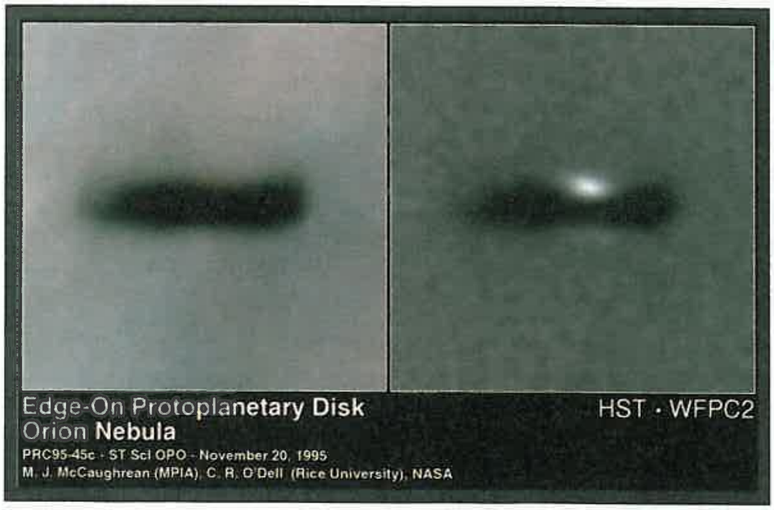

Fig. 1: Images taken with the ESA/NASA Hubble Space Telescope (HST) of an edge-on proto-planetary disk in the Orion stellar nursery. Both images are of the same object observed at different wavelengths. The disk is seen as a dark "silhouette" against the bright background of the nebula, since the light is absorbed by dust grains. The bright point at the centre is due to light from the central star reflected in the dust. These disks around newborn suns are probably the places of planetary formation, as dust grains coagulate to form the first planetary seeds. The planets in our Solar System, including our Earth, are believed to have formed, about 4.5 billion years ago, out of a structure very similar to the one seen in the images. (Credit: Mark McCaughrean (Max-Planck-Institute for Astronomy), C. Robert O'Dell (Rice University), and NASA.)

around 51 Pegasi orbits its host star every 4.2 days, corresponding to an orbital radius of only 0.05 AU (1 Astronomical Unit, or AU, is the average Earth-Sun distance). This is much less than the distance from Mercury to the Sun. Such a system has nothing to do with our own Solar System and most importantly, following the "traditional" paradigm of planetary formation, a giant gaseous planet is definitely not supposed to be formed in such conditions.

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Today, almost 70 exo-planets have been detected using high-precision radial-velocity techniques. These detections include 7 multi-planetary systems, the first of which was found orbiting the star υ Andromedae [4]. A significant percentage of the newly found planets belongs to the "hot-Jupiter" class, i.e. jupiter-like giant planets orbiting close to their parent stars (like 51 Pegasi).

Impact on theories of planetary formation and evolution

The major consequence of these detections was the strong need to revise theories dealing with planetary formation and evolution. But soon it was realized that an answer to the origin of the "hot-Jupiter's" could already exist. Work in the early 80's [5] has predicted that a giant planet, formed in the outer regions of the proto-planetary disk, could indeed migrate inwards as the result of gravitational interactions with the latter. This orbital migration could explain the presence of giant gaseous planets so close to their host stars. But that explanation also poses some problems. It is still not completely understood, for example, how the migration can be halted before the planet falls into the star.

Recent observations suggest that planets might in fact be engulfed by their parent stars [6], whether as the result of orbital migration or, e.g., of gravitational interactions with other planets or stellar companions. Astronomers have recently found strong evidence for such an event, by detecting the presence of the lithium isotope ^{6}Li in the planet-host star HD 82843. This fragile isotope is easily destroyed (at only 1.6 million degrees, through (p,α) reactions) during the early evolutionary stages of star formation, when the proto-star is completely convective, and the relatively cool material at the surface is still deeply mixed with the hot stellar interior (this is not the case when the star reaches its "adulthood"). ^{6}Li is thus not supposed to exist in stars like HD 82843, and the simplest and most convincing way to explain its presence is to consider that a planet, or at least planetary material (but perhaps also more than one planet), has fallen into HD 82843 sometime during its lifetime.

One other particularly troubling point related to the newly found systems has to do with their orbital eccentricities [7]. While the major planets in our Solar System all are in nearly circular orbits, most of the currently found planets follow rather elongated trajectories (Figure 2). This may be e.g. the result of the interaction between planets in a multi-planetary system, or with a distant stellar companion. Evidence exists that planets in multi-planetary systems can indeed suffer some orbital evolution; a nice example comes from the discovery of orbital resonances.

Trying to understand how the observed systems, including our own, were formed and evolved can in fact be a particularly arduous task. But current data are already giving us clues about the processes involved. Very important information is brought to us by the mass distribution of the planetary companions (see Figure 3). This distribution is observed to decrease smoothly with increasing mass (note that the higher the mass, the easier it is to find a planet using the radial-velocity technique), reaching "zero" at about 10 Jupiter masses [7]. But from that mass on, and up to masses of around 50 times the mass of Jupiter, there is the so called Brown-Dwarf desert, a mass region for which only a very few companions to solar-type stars were found (Brown Dwarfs are very low mass stars that do not have high enough central temperatures to sustain hydrogen fusion; theoretically they have masses in the range from ~13 to ~75 times the mass of Jupiter). This feature strongly supports the idea that the discovered planets and low mass stellar companions have indeed a different physical origin: stars, even the low mass ones, are thought to be formed as the result of the gravitational collapse and fragmentation of a cloud of gas and dust, while a planet forms in a circumstellar accretion disk.

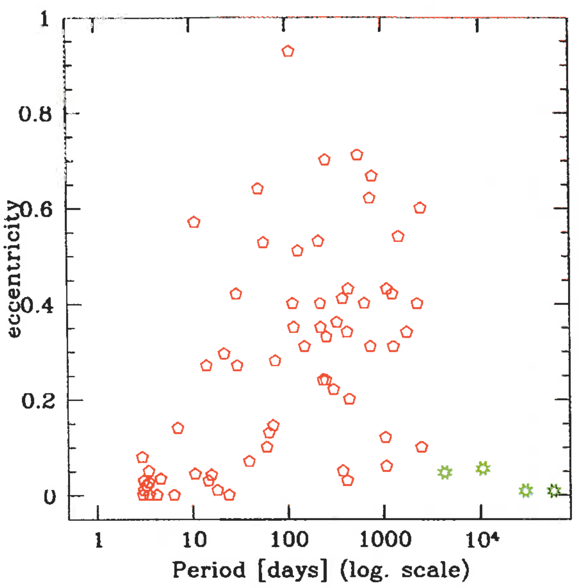

Fig. 2: Eccentricity vs. orbital period (in logarithmic scale) for the discovered extra-solar planets (red pentagons) and for the giant planets in our Solar System (green stars). Although some long-period exoplanets having low eccentricity exist, most of the systems have much higher eccentricities that those of the giant planets in the Solar System. This trend was unexpected before the discovery of the first exoplanets. The explanation may lie in mechanisms capable of pumping the eccentricity, like gravitational interactions between planets in a multi-planetary system, or with a distant stellar companion.

The planet host stars

Another particular fact that is helping astronomers understand the mechanisms of planetary formation has to do with the planet host stars themselves. In fact, they were found to be particularly metal-rich, i.e. they have, in the average, a metal content higher than the one found in stars without detected planetary companions [8],[9]. (In astronomy, all elements heavier than hydrogen or helium are called metals.) The most recent results seem to favour that this metallicity "excess" is actually related to the planetary

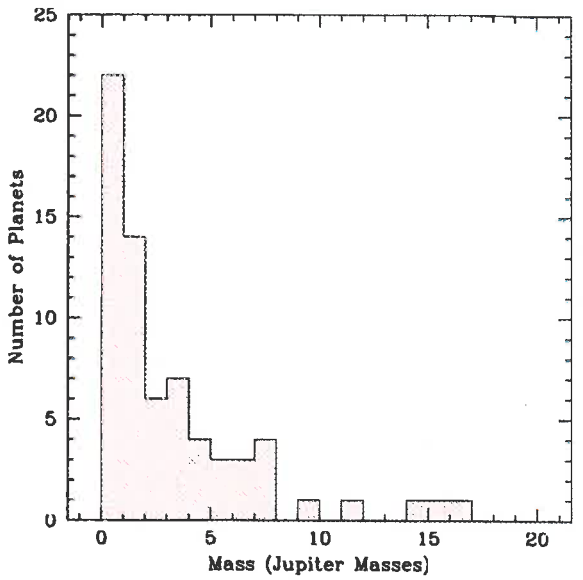

Fig. 3: Distribution of masses for the currently discovered low-mass companions to solar-type stars. Although the radial-velocity method, which permitted the discovery of these systems, has a higher sensitivity to higher mass companions, the observed distribution rises very steeply towards the low-mass domain. The distribution reaches "zero" at a mass of about 10 times the mass of Jupiter, which probably corresponds to the upper limit for the mass of a giant planet. From this mass up to the stellar regime, only a few objects were detected; this region is usually denominated the "Brown-Dwarf desert". The gap in the mass distribution of low-mass companions to solar-type stars shows that the physical mechanisms involved in the formation of the two populations (planets vs. stars) are probably very different.

formation process. The higher the metallicity of the cloud that gives origin to the star/planetary system (and thus the dust content of the disk), the faster a planetesimal can grow, and the higher the probability that a giant planet is formed.

But current observations are also starting to teach us something about the planets themselves. Recently, astronomers have detected the dip in the luminosity of the star HD 209458 as a previously detected planet crossed its disk [10]. This detection not only represents an independent confirmation of the nature of the discovered body, but also permits to precisely constrain some planetary physical properties, like its mass, radius, or mean density.

The study of extra-solar planetary systems is just in its first steps. After only 5 years, we can say that at least 5% of the solar-type stars have giant planetary companions. But the understanding of how giant planets are formed is still wanting in many respects. To help solve some of the problems, several projects are currently in the pipeline.

Huge developments are expected in the radial-velocity surveys by the development of instruments capable of measuring velocities down to a 1 m s^{-1} precision. For astrometric measurements, instruments like the VLTI interferometer (ESO) will permit to combine the light of the four VLT 8-m telescopes, enabling astronomers to obtain unprecedented high-resolution astrometric observations. But even greater hopes come from space missions like GAIA (ESA) or SIM (NASA), that will completely change the current landscape by adding tens of thousands of new planets. On the other side, photometric transit searches, mostly based upon space missions like the European COROT and Eddington or the North-American mission Kepler, achieving a photometric precision better than 0.01%, will permit the detection of transiting earths.

All these steps will give the opportunity to revise the current knowledge about the mechanisms leading to the formation of planetary systems and will thus somehow represent an important step towards the search for life in the Universe. Two similar projects are currently directed towards this goal (Darwin/ESA and TPF/NASA, cf. the article by Quirrenbach). Using nulling-interferometry techniques (to remove the light from the brighter star and leave the one coming from the planet), they will try to find traces of life in the spectrum of exo-earths. In a few decades human beings have to prepare themselves for the prospect that the whole Universe may be teeming with life.

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