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EXTRASOLAR PLANETS: THEORY AND OBSERVATIONS

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RESUMEN

Se discuten las propiedades globales de los casi 80 planetas extrasolares (o simplemente exoplanetas) descubiertos hasta el presente, y se comparan con nuestras expectativas previas basadas en modelos teóricos de formación planetaria. Los exoplanetas descubiertos tienen masas del orden de la de Júpiter o mayores pero, en claro contraste con Júpiter, se encuentran próximos a las estrellas centrales y la mayoría de ellos tiene grandes excentricidades. También analizaremos diferentes alternativas que podrían explicar las diferentes propiedades de los exoplanetas con respecto a los planetas jovianos de nuestro sistema solar. Ya que la técnica de búsqueda más generalizada al presente (espectroscopía) favorece fuertemente el descubrimiento de planetas masivos próximos a sus estrellas centrales, es posible que ellos sean casos anómalos, pocos comunes en comparación con los sistemas planetarios como el nuestro.

ABSTRACT

We discuss the global properties of the nearly 80 extrasolar planets (or exoplanets for short) so far discovered, and compare them with our previous expectations from theoretical models of planet formation. The discovered exoplanets have masses around that of Jupiter or larger but, in sharp contrast with Jupiter, they are close to their central stars and most of them have large eccentricities. We will also analyze different alternatives that could explain the different properties of the exoplanets with respect to the Jovian planets of our solar system. Since the current most widely used search technique (spectroscopy) strongly favors the discovery of massive planets close to their central stars, it is possible that they are very weird cases, uncommon in comparison with regular planetary systems like ours.

Key Words: **PLANETARY SYSTEMS**

1. SEARCH TECHNIQUES

Search techniques of exoplanets can be divided into direct and indirect. The direct search aims to detect photons coming directly from the exoplanet, preferably in the infrared where the ratio between the intensity of the radiation of the central star and that of the exoplanet is more favorable than in the visible. The brightness ratio star/planet goes from 10^9 in the visible to about 10^5 in the infrared (considering a Jupiter's size planet). Despite the gain of several orders of magnitude in the infrared, the direct IR imaging of exoplanets from the ground is beyond our current technology. The future use of space-born interferometric telescopes will allow to annul the light of the central star, leaving the faint light of any planet of its surroundings.

The indirect searches are so far the only affordable with the current instrumentation. They try to detect some observable effect on the central star caused by the presence of a massive planet as, for instance, the minute oscillations of the star around the center of mass star-planet caused by the gravitational pull of the planet (astrometric method). Alternatively, the oscillations in the motion of the star could be detected by the Doppler shift in the spectral lines of the star, either to the blue when the star moves toward the observer, or to the red when it recedes (spectroscopic method). It is also possible to search for planet transits, which will show up as a drop in the brightness of the star, by monitoring a large sample of stars (photometric method). The difficulty with the latter method is that the observer must be very close to the orbital plane of the planet to detect a transit. For a planet at a distance a to the central star of radius R_s, the probability to observe a transit, assuming that the orbital plane is randomly oriented, is $p = R_s/a$. Of course the previous equation only considers the geometry of the problem: if the orbital period of the planet is P and the star is observed during $\Delta t(< P)$, the probability p derived before has to be multiplied by $\Delta t/P$.

The availability of high-resolution spectrometers (around 10 m/s) has made the spectroscopic search of exoplanets possible. The first exoplanet was detected by Mayor & Queloz (1995) and it turned out to be at a mere 0.05 AU to the central star 51 Pegasi. Its minimum mass was about half that of Jupiter, which put it almost certainly in the planetary class. The announcement of the first exoplanet was quickly followed by reports of new detections by the Marcy and Butler team (Marcy & Butler 1996; Butler & Marcy 1996). The number of detected exoplanets has climbed up to nearly 80 (November/2001). We note that we cannot derive directly the planetary mass M by the spectroscopic method, but the product $M \times \sin i$, where i is the angle between the sight line and the perpendicular to the orbital plane of the exoplanet. Therefore, unless we know i, we can only set a lower limit for the mass of the exoplanet (by taking $i = \pi/2$). The discovered exoplanets have $M \times \sin i$ as low as that of Saturn and an upper limit of 13 M_{JUP}, i.e. the limit between a planet and a brown dwarf. Since we have the unknown factor $\sin i$ in the derived masses, it is possible that some of the exoplanets exceed 13 M_{JUP} and are actually brown dwarfs (characterized by the burning of deuterium in their interior).

Actually, the first exoplanets discovered did not use any of the methods described above. They were discovered in a serendipitous way around the pulsar PSR 1257+12 in 1992. Wolszczan and Frail (1992) found that the radio pulses of PSR 1257+12 showed slight advances and delays in their arrival times, which they interpreted as due to the presence of two planets around the pulsar, of masses about three times the Earth's mass. One may wonder how it is possible to find planets around a pulsar, the corpse left after a supernova explosion. The idea is that such planets are not primordial, but they formed out of the material ejected by the supernova that was re-accreted by the pulsar, forming around it a second-generation protoplanetary disk.

Microlensing may be another nonstandard way to detect planets around stars. Einstein's theory of relativity predicts the bending of light rays coming from a background star in the curved space-time caused by a massive body, such as a star, that acts as a lens. Therefore, lensing will produce an amplification of the light of the background star for a time span of a few days to months. The presence of a planet will show up as a secondary amplification with a much shorter duration: for hours to $\sim$ 1 day, depending on the planet's mass. Bennett et al. (1999) have claimed to have discovered a planet in this way. The problem is that lensing events occur only once, so they cannot be corroborated.

The photometric method could be more suitable to detect transits of giant planets close to the central star since in this case both R_s/a and $\Delta t/P$ may become large (cf. above). Bearing this in mind, two independent teams (Charbonneau et al. 2000; Henry et al. 2000) searched for transits of a planet discovered spectroscopically around the G0 star HD209458 on an orbit of a very small radius of 0.046 AU. Their search was successful and they reported a drop of 1.6% in the light of the star. The combination of the spectroscopic and photometric results allowed the researchers to determine for the first time the radius and mass of an exoplanet: $R = 1.42 \pm 0.10$ R_{JUP}, $M = 0.62 \pm 0.05$ M_{JUP} (Henry et al. 2000); $R = 1.27$ R_{JUP}, $M = 0.63$ M_{JUP} (Charbonneau et al. 2000). Therefore, its mean density turns out to be very low: 0.27 or 0.38 g cm^{-3}, which is in agreement with theoretical models of gaseous giant planets close to their central stars, bloated by the intense stellar illumination.

2. SEMIMAJOR AXES VERSUS ECCENTRICITIES

Figure 1 shows the plot of semimajor axes, a, versus eccentricities, e, for the sample of 76 exoplanets discovered spectroscopically, and for that of binary stars of classes F, G and K. The distributions of both samples in the parametric plane (a, e) show striking similarities, which raise the question on whether the discovered exoplanets actually formed like the planets of our solar system, or whether they formed like binary stars, i.e., as sub-condensations within the collapsing nebula. It is clear that both, stars and exoplanets, have in general rather high eccentricities, except for those members very close to the central star (or companion star in a binary) whose orbits have been circularized by tidal forces. Boss (1997) has indeed suggested that the discovered exoplanets formed in the same way as binary stars, namely by gravitational instability in the nebulae surrounding their central stars.

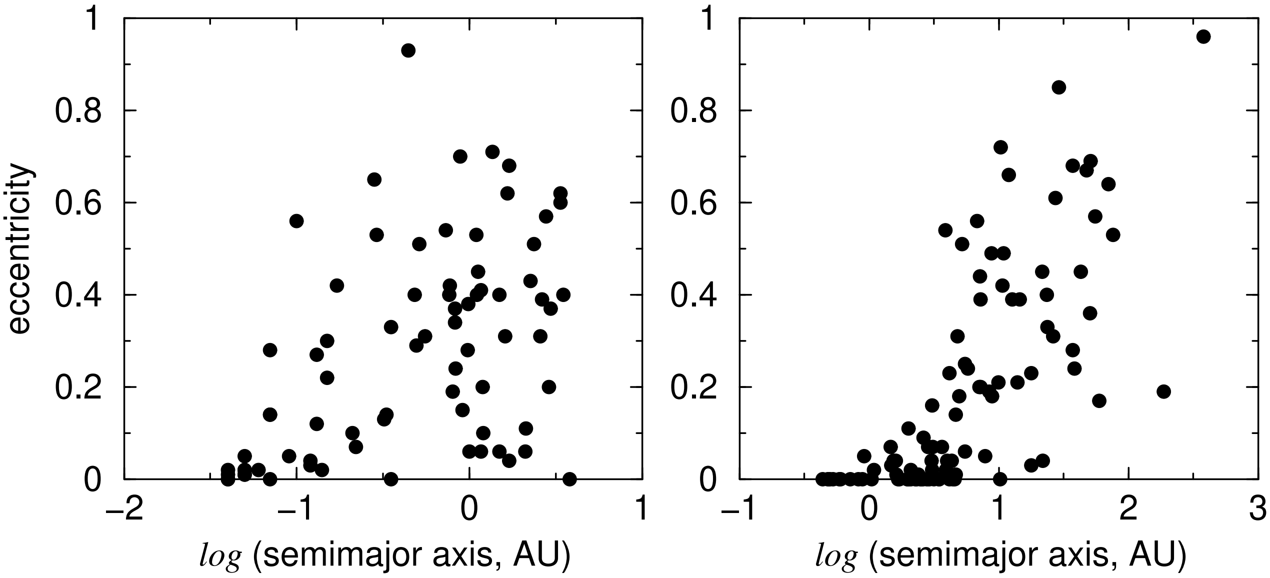

Fig. 1. Distribution of exoplanets (left) and binary stars of spectral types F, G and K (right) in the parametric plane: semimajor axis, eccentricity.

The standard model of planet formation in a protoplanetary disk predicts the formation of giant planets in regular orbits (near-circular and near-coplanar) (e.g. Lissauer 1987; Fernández & Ip 1996; Brunini & Fernández 1999) beyond the 'snowline', i.e., the region where H_2O can condense. The availability of much more solid material by the condensation of H_2O allowed the rapid formation of solid cores onto which the hydrogen and helium of the nebula were accreted. The temperature profiles of protoplanetary disks place the snowline at $\sim$ 5 AU for solar-type stars. This distance can vary somewhat for different disk opacities, but it is hard to think that temperatures as low as to condense water can be attained at the distances where most exoplanets have been discovered.

Several transport mechanisms have been proposed to explain the observed exoplanets under the standard model, among them: (a) the disruption of an orderly system of three or more giant planets by gravitational encounters, as their orbits become unstable due to their growing mass, causing the ejection of one or more planets and leaving others in very eccentric orbits (Weidenschilling & Marzari 1996); or (b) the giant planet forms by accretion of a solid core and capture of gas at a distance of $\sim$ 5 AU , from where it subsequently migrates inward by gravitational interaction with the inner circumstellar disk (Lin et al. 1996; Murray et al. 1998). It is required a complementary mechanism to stop the inward migration of the planet before it is engulfed by the star. In this regard, the above authors mention the drop of the disk density near the star, or tidal interactions of the planet with the star.

If one of the above explanations (a) and/or (b) were correct, we could come up to the conclusion that a regular planetary system - like ours - dynamically stable during several aeons, would be one of the possible outcomes among several others in which dynamical instability leading to irregular systems would be set in on short timescales. Indeed, several multiple planet systems so far discovered are irregular which gives support to the previous assertion. Nevertheless, it is interesting to point out that Fischer et al. (2001) have recently discovered a second planet around 47 UMa, which together with the planet discovered before, makes it a very regular planet system. The semimajor axes and eccentricities of the planets are: $a = 2.09$ AU, $e = 0.06$, $a = 3.73$ AU, $e = 0.1$. This pair is very close to the 5:2 mean motion resonance, like Jupiter and Saturn.

3. ASTROPHYSICS OF STARS WITH PLANETS

The exoplanets discovered spectroscopically belong to stars of spectral types typically of late F's, G's, or early K's, namely stars that are grossly solar type. Solar-type stars were chosen as targets for the spectroscopic search of exoplanets, so we cannot tell anything about the frequency of exoplanets around stars of other spectral types. However, an interesting feature about the stars with exoplanets is that they tend to be more metal rich than field stars of the sample spectral types (González 1998). González et al. (2001) find an average iron to hydrogen ratio [Fe/H] of $+0.17 \pm 0.20$ for a sample of 38 stars with planets, as compared to a mean ratio of -0.12 ± 0.25 for type G field stars not known to have planets.

Two possible explanations have been advanced for this interesting feature: (a) the formation of planets in the protoplanetary disk requires a high metal content in order to form solid cores large enough to grow into full giant planets by massive gas accretion; or (b) the atmospheres of stars with planets have been contaminated by massive planets plunging into them by the action of tidal interactions with the disk that drive the planets inward. The discovery of the rare ^{6}Li isotope in the atmosphere of the metal-rich, solar-type star HD82943, known to have a giant planet, has been interpreted by Israelian et al. (2001) as due to the engulfment of one (or more) giant planet by the star.

4. FUTURE SPACE-BASED SEARCHES

The goal for the near future will be to detect Earth-sized planets around nearby stars. For that, new procedures and instrumentation should be required. In particular, there are several proposals of telescope arrays placed into orbit that will act as interferometric systems. The two most ambitious projects of this kind are at the moment: Terrestrial Planet Finder by NASA, and Darwin by ESA, to be placed into a heliocentric orbit around 2011 and 2012, respectively. The light received by the telescopes will combine in such a way that the light of the central star will annul. At the same time the light beams will reach constructive interference at a small angle where potential planets sit. These interferometers will operate in the IR range between about 7-20 μm where bands of H_2O, O_3, and CO_2 are located. Therefore, the discovery of terrestrial planets will be followed by the study of their atmospheres and the first discussion on their suitability as harbors of life.

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