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# Regularity of Extrasolar Planetary Systems and the Role of the Star Metallicity in the Formation of Planets (Review)

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**Abstract**—The discovery in 1995 of the first extrasolar giant planet 51 Peg b initiated the physics of extrasolar planetary systems. By May 2004, the total number of the detected planets orbiting other stars was 122, including 24 “hot jupiters,” which have a semimajor axis of the orbit of less than 0.15 AU. Due to the high activity of researchers who work with the radial-velocity method, the probable candidates, say, in the 75-parsec radius, are quickly exhausted. The OGLE-type objects, even if their number increases, may only slightly contribute to the physics of extrasolar planets (or exoplanets), because even to determine the type of the companion (a giant planet, brown dwarf, or star of small mass) is extremely problematic for such weak objects. A search for Earth-like planets is still far beyond the technical capabilities: the Keplerian velocity of the Sun induced by the Earth is only 0.09 m/s, which requires to improve the results obtained by a factor of 20–30. Particularly important results were obtained in the observations of transits of the object HD 209458b, which became the only object of this type namely due to transits. The hope of finding another short-period object with similar transits is becoming less and less. The important role of the star metallicity in the formation of planetary systems predicted during the first years after the discovery of exoplanets has gained recognition and been developed successfully. Metallicity has become an indicator of the possible presence of planetary systems and, probably, even determines the type of planets. This review also considers the statistical data on the orbital and mass characteristics of exoplanets.

## INTRODUCTION

The first planetary system around star 51 Peg was discovered in 1995 (Mayor and Queloz, 1995). Thus, it was enough time to reveal the most important regularity of the physics of extrasolar planetary systems. However, researchers are still at the beginning of the journey, which, figuratively speaking, leads far away from the properties of the Solar System. The statistical data is now based on a considerable number of the objects discovered (122 extrasolar planets in 107 planetary systems by May 2004).

An overwhelming majority of exoplanets are known to be found around F- and G-type stars. One exoplanet was found orbiting a giant, and three, orbiting subgiants. Only one M dwarf (GJ 876) is known to host a planetary system, although many M dwarfs were included in the surveys. It is still not clear why so few planets are found around these stars. No progress has been achieved in searching for exoplanets around stars of early F subtypes. This is naturally explained by the limitations produced by their photosphere dynamics known for the method of radial velocities (MRV), rather than by the proven absence of planets orbiting these stars. The small number of planetary systems around K-type stars registered in surveys attracts attention especially because the first object of this kind was found quite early. One of the causes lies in the fact that the spectrum of K stars (especially of mid and late subclasses) is so rich in spectral lines that a well-developed method of echelle-spectra analysis encounters difficulties.

The search for Earth-like planets with the radial-velocity method is still beyond technical capabilities: for example, the Keplerian velocity of the Sun induced by the Earth is only 0.09 m/s; to detect it, the obtained results must be improved by a factor of 20–30. Unquestionably, it would not be serious to make any prognosis on perspectives in searching for habitable planetary systems on the basis of the limited information known about exoplanets. It seems ingenuous to suppose that there is life (in the amino-nucleate form, the only form we know) on giant exoplanets. However, the conditions for the formation and evolution of life can be still realized on hypothetical satellites of exoplanets. Borkowski and Schneider (2003) studied the possible approaches to the search for such moons.

The main characteristics of exoplanets, such as, for example, their division into two large groups by orbital parameters, were revealed during the first four years of studies. A review (Ksanfomality, 2000) published in our journal in 2000 was based on the observational data obtained in 1995–1999, when the first 32 exoplanets were found. The material and problems presented in the review are still topical and are becoming even more complicated in the course of new investigations. The present work can be considered as a chronicle of the evolution of the studies described in that review.

Recently, the “metallicity” of the stars hosting planets has become a subject of the most important studies. The hypothesis on an important role of metallicity, which was suggested in the years of the first discoveries of exoplanets (Gonzalez, 1997), was confirmed and developed. Convincing evidence was found showing that the metallicity is inherent to the star's nature and has no connection with any enrichment of the convective envelope of a star in "heavy" elements. The role of metallicity was inspected in many careful recent studies (see the review by Gonzalez (2003)), and it will be considered in detail at the end of the present paper.

## STATISTICS OF ORBITAL CHARACTIRISTICS

The investigations of the main regularity of the structure of extrasolar planetary systems are being continued, and this led to some unexpected results. Thus, a definite connection was found between the low circular orbits of exoplanets and the relatively narrow mass limits for orbiting bodies. A conventional boundary between circular short-period orbits (several days) and mainly eccentric orbits with a period of more than 30 days is accepted at a distance of $a$ = 0.15–0.16 AU from the star. For almost all the exoplanets in very low circular orbits, the parameter $M\sin i$ is less than the mass of Jupiter $M_J$ (Santos 2003; Udry 2003), being about 0.5–0.6 $M_J$ on average. Apparently, this natural selection is associated with the migration mechanism, which draws the planets from high orbits, where they were formed, to circumstellar orbits. Massive planets (with $M\sin i$ ranging from 1 to 10 Jupiter masses) in the short-period orbits are in an apparent minority (Fig. 1). According to the well-known catalog "Masses and Orbital Characteristics of Extrasolar Planets" (2004), there are 24 objects in the interval from 0.037 to 0.15 AU, and only 6 of them have $M\sin i > 1$ $M_J$, and the brown dwarf HD162020 has $M\sin i = 14.4$ $M_J$. Among the first 11 exoplanets with nearly circular orbits, only two have $M\sin i > 1$ $M_J$, and one of them, Tau Boo, has $M\sin i$ = 4.13 $M_J$. The objects with $M\sin i > 1$ $M_J$ make up only 25% within $a$ = 0.15 AU and 85% (including brown dwarfs) beyond 0.15 AU. Figure 1 shows schematically the mass distribution for these 24 planetary systems; four of them are already known to include several planets.

In general, the number of systems containing several planets is continuously rising; it reached 13 by May 2004 (Schneider, 2004).

The experimental data reveal groups of orbits with higher or lower population compared to the others (Udry 2003). Figure 2 displays the "semimajor axis–number of planets" histogram constructed on the basis of the data available in 2003. Around 0.3 AU in the histogram, there is a clear minimum, which was unknown before because it is related to bodies of relatively low masses, the main portion of which was detected only after the radial-velocity method achieved its present high level. There are several suppositions why exoplanets seem to avoid these orbits. However, a more significant point is that the grouping of short-period planets according to their orbital periods is also irregular, which is most prominent at periods of 3–5 days (Fig. 3). The number of objects in this range is large enough to consider this minimum nonrandom.

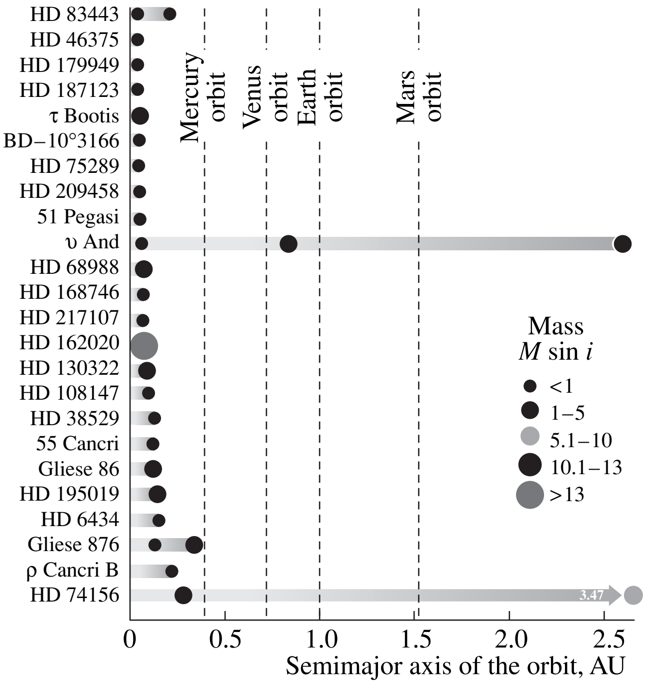

**Fig. 1.** Mass distribution of short-period exoplanets (in Jupiter masses). In low orbits, there are mostly planets of small masses (adapted from a paper by Kaisler (2002)).

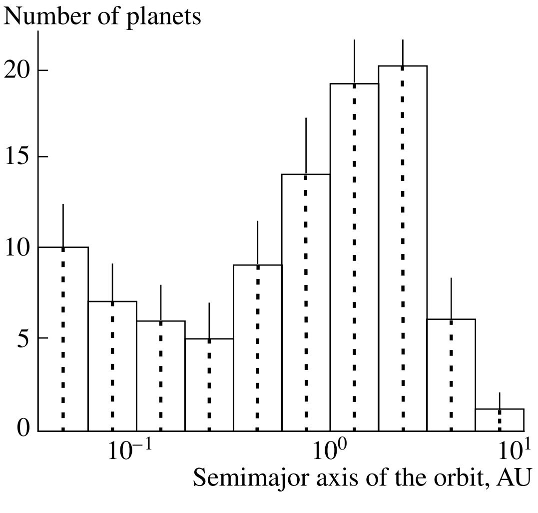

**Fig. 2.** The number of planets in the orbits near 0.3 AU is noticeably smaller than that in higher and lower orbits (Marcy *et al.*, 2003a).

The statistics of exoplanets is still scanty to make definite conclusions; nevertheless, the observational data on the mass distribution clearly distinguish the groups of planets and brown dwarfs (Fig. 4; Santos 2003). At the same time, the histogram in Fig. 4 shows a more complicated structure of the distribution in the range of small masses. Along with the peculiarities of

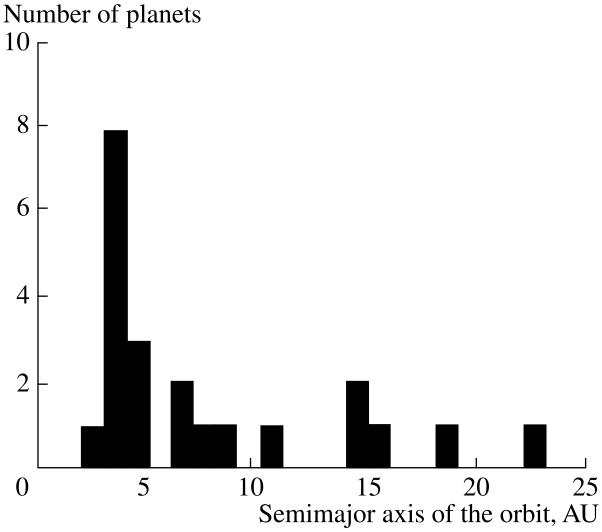

**Fig. 3.** The distribution of short-period exoplanets in their orbital periods points to their preferred grouping in an interval of 3–5 days (Marcy *et al.*, 2003a).

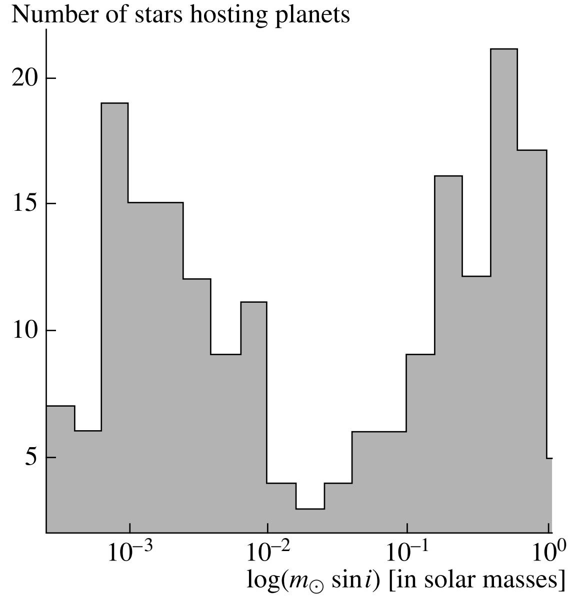

**Fig. 4.** Mass distribution of planets, brown dwarfs, and stars of small masses (Santos *et al.*, 2003).

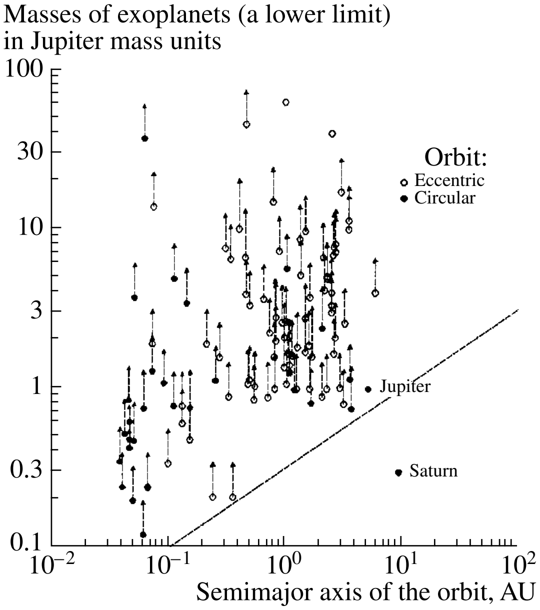

**Fig. 5.** Distribution of circular (points) and eccentric (open circles) orbits versus the height of the orbit and the mass of exoplanets. A lower limit of the masses is shown, which is indicated by up-directed arrows. Positions of Jupiter and Saturn are shown on the right (Boss, 2003).

the distribution versus the semimajor axis, which was presented in Fig. 2, the near-star exoplanets evidence some other, still concealed, mechanisms.

“A desert of brown dwarfs,” an unfilled region in the “mass–number of planets” histogram, discussed in the papers by Ksanfomality (2000, 2001), has become even more distinct in a new histogram (Fig. 4). The region from 13 to the right to roughly 80 $M_J$ remains waste for some unknown reason. The coincidence of the mass 13 $M_J$ (equal to 1.3% of the solar mass) with the extreme mass at which the thermonuclear reaction with deuterium may start (see below) seems rather interesting (and probably significant).

Large orbital eccentricity of the planets in high orbits is a rule (Fig. 5). And, vice versa, the orbits of almost all short-period planets have practically no eccentricity; they are shown by black points in the left part of Fig. 5. As for the exoplanets with a semimajor axis larger than 0.16 AU, an overwhelming majority of them have very large or huge orbital eccentricities, which occur in the Solar System only for comets and some asteroids. The eccentricity averaged over 90 exoplanets with a semimajor axis of their orbits larger than 0.15 AU is 0.32 (Marcy *et al.*, 2003b). To explain the origin of high eccentricities, several mechanisms were suggested. The main ones are still (a) the planet–planet gravitational interaction (Chiang, 2003) in mutual resonance influence (gravitational scattering) and (b) the interaction between the planet and the protoplanetary disk (Goldreich and Sari, 2003). Among the other probable mechanisms are the influence of the protoplanetary disk instabilities on the forming giant planet (Boss, 2003) and the gravitational influence of other stars.

It is worth noting that bodies with practically circular orbits can nevertheless be found among known exoplanets. For example, an object with a high orbit and a low eccentricity was detected in 2000. It is the third planet in the system of the star $\rho^1$ Cnc (55 Cancri), where a hot jupiter with a period of 14.7 days was discovered among the first exoplanets. As it became clear later, a slow drift of the absolute radial velocity interpreted as the presence of another planet was superimposed on the Keplerian component. The second planet, with a period of 44.3 days, has a high orbital eccentricity. The third planet attracts attention because of its orbital period of 14.7 years, which is rather close to that of Jupiter, its semimajor axis of 5.9 AU (5.2 AU for Jupiter), and, most interesting, its relatively low orbital eccentricity, 0.16. These parameters may be estimated more precisely only after the orbital period is completed. The mass of the planet is at least 4.06 $M_J$.

Among the other extrasolar planetary systems with low orbital eccentricities of less than 0.1, the planets 47 UMa b and c with masses $M\sin i$ 2.41 and 0.76 $M_J$ and with $a$ = 2.10 and 3.73 AU are worth mentioning (Fischer *et al.*, 2002; Schneider, 2004). For the component 47 UMa c, the position of which approximately corresponds to the asteroid belt in the Solar System, the mass can be even less than $M_J$. The orbit of the planet HD 70642 b also has an eccentricity of about 0.1, $a = 3.3$, and $M\sin i = 2\,M_J$. However, there are only a few objects of this type. In general, a low eccentricity is the exception, not the rule.

## ECCENTRICITIES AND MIGRATION OF GIANT PLANETS: A DANGER TO THE FORMATION OF EARTH-LIKE PLANETS

Low eccentricities of giants and other planets in the Solar System, contrary to those in extrasolar planetary systems, remain a challenge to the theory. Approximately zero eccentricities of hot Jupiters are thought to be easily explained by the tidal effect leading to planetary orbit circulation at the final stage of migration. The stability of the Solar System is determined namely by the very low eccentricity of the high orbit of Jupiter (and, to a lesser extent, of Saturn). However, the practically circular orbit of Jupiter cannot be explained by tidal effects. The very existence of terrestrial planets obligated to both the low eccentricity of Jupiter and its stable orbit (Wetherill, 1996). Such an inference is based on the calculations of the interaction between massive bodies having eccentric orbits and other planetary bodies (Thébault and Brahic, 1999). The calculations show that the interaction most likely results in the ejection of Earth-like planets from the planetary system under the influence of a much more massive body which is in an eccentric orbit. The migration of giants from high orbits toward the star through a zone of the orbits of internal planets doubly threatens the latter. Even if gravitational ejection did not occur, giant-planet migration through a zone of the orbits of internal planets makes catastrophic collisions possible and leaves little chance for the long-term evolution of the Earth-like planets and for the origin of life and a biosphere on them. Figure 6 shows the probability of such a catastrophic collision of a migrating giant and a terrestrial planet (Ksanfomality, 2003). The estimate is made on the basis of simple geometrical suppositions. The size of the giant planet was assumed to be equal to that of the object HD 209458b. The duration of the migration through the orbit of the terrestrial planet for decrease of the giant planet semimajor axis by the giant diameter was assumed to be 250 × $10^3$ years. The catastrophic collision inevitably takes place at angles of mutual inclination of the orbits of the giant and the terrestrial planet ranging from 0′ to 2.4′. The probability falls to 0.01 if the angle is equal to 2.5°. When the orbital eccentricities are high, the collision probability also decreases. The restrictions due to the giant-planet migration for the formation of Earth-like planets are also considered in some other papers (e.g., Armitage, 2003).

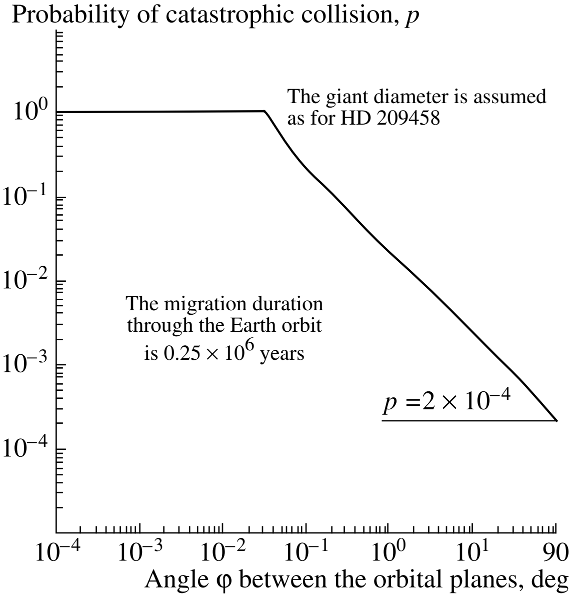

**Fig. 6.** Probability of a catastrophic collision between a migrating giant planet and a terrestrial planet, depending on their mutual orbital inclination (Ksanfomality, 2003). The duration of crossing the Earth's orbit is assumed to be 0.25 × $10^6$ years.

## PLANETS, BROWN DWARFS, AND STARS OF SMALL MASS

The boundary determining the distinction between exoplanets and brown (infrared) dwarfs has become sharper. As might be expected, the physics of dwarfs works in its own framework compared to exoplanets. A celestial body can be rather rigorously determined as a brown dwarf based on the physical criterion of the realization of the start conditions for thermonuclear fusion of deuterium. These conditions are not achieved in planetary bodies. To achieve such conditions, the body mass must be as large as 1.3% of that of the Sun. These conditions are valid up to 4% of the solar mass, when the threshold of thermonuclear reactions with hydrogen is achieved (Kumar, 1994) and the body becomes a star. Depending on the composition, the minimal mass can be larger, up to 7% of the solar mass. The evolution diagram from the paper by Burrows *et al.* (1997) is presented in Fig. 7, where the luminance ver-

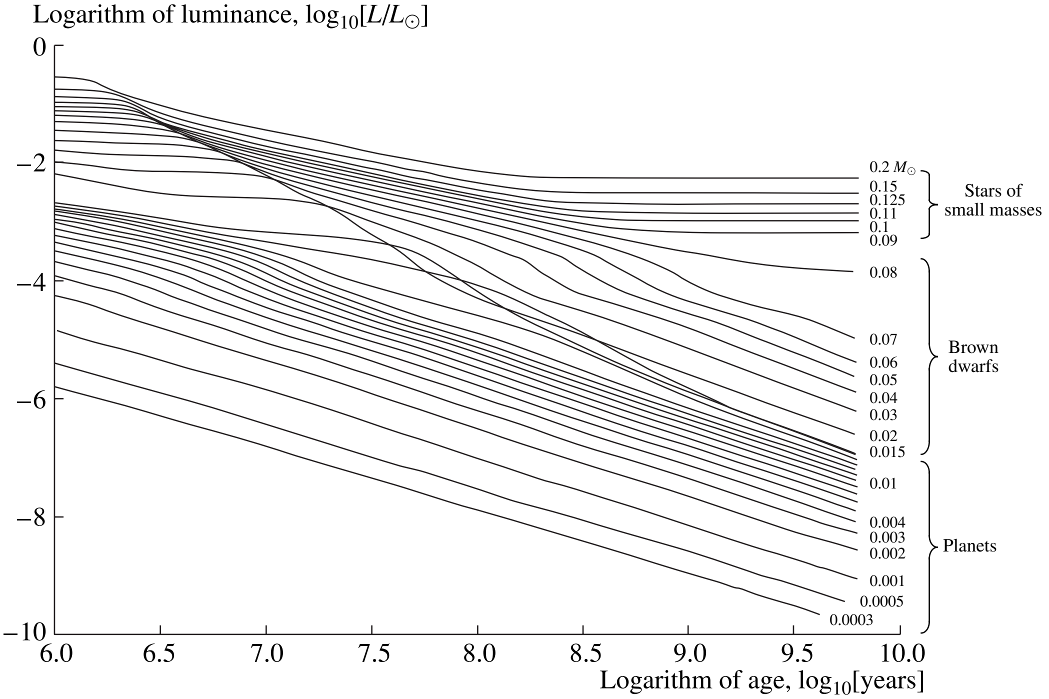

**Fig. 7.** Evolution diagram for the luminance of planets, brown dwarfs, and stars of small masses (in solar luminance units) versus the age (years). Numbers near the curves indicate the body mass (in solar mass units). The three lower curves correspond to the mass of Jupiter, a half of its mass, and the mass of Saturn. Inflections in the curves on the left for bodies with masses larger than 1.3% of the solar mass correspond to the thermonuclear reactions with deuterium (from the paper by Burrows *et al.*, 1997).

sus the body age is given in logarithmic scale for these three types of bodies. The shape of the diagram depends on the body metallicity, which is assumed to be identical to the solar metallicity in Fig. 7. Bodies with masses smaller than 0.013, from 0.015 to 0.08, and from 0.09 to 0.20 of the solar mass are referred to as planets, brown dwarfs, and stars of small masses, respectively. The inflections in the curves correspond to the start of nuclear reactions. Since a thermonuclear reaction with deuterium gives relatively low energy, it is difficult to ascertain whether the reaction occurs in such weak objects as brown dwarfs. In a body of a larger mass, $63M_J$, a thermonuclear reaction with lithium isotopes can be initiated.

Gonzalez (2003) notes that the body genesis can be another criterion used to class it as a planet: brown dwarfs are formed as stars, and planets are born in the protoplanetary cloud. A considerable number of brown dwarfs were found in the Orion nebula as freely moving bodies independent of stars, which confirms their origin from the collapse of interstellar clouds. At the same time, brown dwarfs that are star companions and could form in the protoplanetary cloud are also known. It is interesting to note that the question of what kind of body can be considered a planet had never arisen before the discovery of exoplanets. The situation became more complicated when the bodies in the Kuiper belt were found (this even led to the discussion of the abandonment of Pluto from the list of planets) and when the Centaur belt was discovered. Now, various criteria of the unique definition of a planet are suggested (e.g., Stern and Levinson, 2002).

## DISK INSTABILITY

A new approach to the physics of planet formation in a protoplanetary cloud, which has been recently developed by Boss (2003), is based on the disk-instability theory (mentioned already in Ksanfomality, 2000) proposed by G. Kuiper long ago. On the one hand, it allows some serious contradictions of the classic paradigm of planet formation to be resolved, and, on the other hand, this approach encounters its own difficulties.

The essence of the problem is worth recalling. In the second half of the 20th century, a two-stage theory of the formation of Jupiter and Saturn was generally accepted (Safronov, 1969; Safronov and Ruscol, 1982; Hayashi *et al.*, 1985; Wetherill, 1990). Its schematic scenario supposed collisional accretion of solid particles (mainly of silicate composition) in the inner part of the protoplanetary disk (first into submicron particles and then into lump several centimeters in size) and their subsequent integration into kilometer-sized planetesimals and larger planetary embryos. The planetesimals accumulated in the protoplanetary disk and then merged in collisions and formed the nucleus of a future planet with a mass ranging from 10 to 25 masses of the Earth. (The nucleus mass was revised in recent works, which suggest lower values for it, 5–10 or even 2–3 Earth masses (Weidenshilling, 1997; Wuchterl, 1991; 1995).) Then, accretion on the nucleus of the gas (mainly hydrogen) from the protoplanetary disk occurred. The calculations showed that the whole process must take about $10^8$ years (Pollack 1996). The formation time is reduced to $8 \times 10^6$ years if the surface density of the $Z$ component of the protoplanetary-disk material at a distance equal to that to Jupiter's orbit is 10 g cm$^{-2}$. This time becomes as large as $50 \times 10^6$ years at a density of 7 g cm$^{-2}$. Pollack *et al.* (1996) pointed out that an increase of the surface density up to 15 g cm$^{-2}$ decreases the time needed for Jupiter's formation to $1.6 \times 10^6$ years. However, in these simulations, the mass of Jupiter's nucleus exceeds theoretically acceptable limits (Guillot *et al.*, 1997). At the same time, numerous observations of protoplanetary disks permanently evidence an extremely short time of hydrogen escape from the disk. In any case, hydrogen remains in the disk for less than $10^7$ or even $10^6$ years (Zuckerman *et al.*, 1995; Bally *et al.*, 1998; Briceño *et al.*, 2001; Makalkin, 2003). This naturally contradicts the known hydrogenous (mainly) composition of the atmospheres of Jupiter and Saturn. The latest calculations took into account the runaway growth of planetesimals, which shortens the time of the formation of a planet. However, this time remains too long, about $10^7$ years (Ruskol and Safronov, 1998). Another difficulty in the classical scheme appeared when extrasolar planets had been discovered: the scheme fails to explain the huge eccentricities of their orbits.

The disk-instability model shows that strong turbulence in the protoplanetary disk results in the fragmentation of the disk into high-density condensation within a short time of 5000–10000 years. These clumps are not smaller than Jupiter in mass (Fig. 8). Disk instability easily explains both the short time of giant formation and the small nucleus of Jupiter (if it really is small). The orbital eccentricities and migration of giants are also explained (Boss, 2003). However, the models show that this hypothesis has its own problems: a protoplanetary disk must be very massive, and turbulence not only produces condensation but also destroys them. Therefore, neither the disk instability nor the classic accretion scheme can likely be ruled out. Since some data show that Jupiter is several million years older than the Earth, one may suppose that disk instability contributes to the formation of giant planets, while terrestrial planets were formed in the planetesimal accumulation (see the review by Kaisler, 2002). In the hypothesis about the formation of giant exoplanets, the disk-instability theory is favored because of the gaseous composition and migration of these planets (Ksanfomality, 2004).

## TRANSIT SEARCH

The situation in detecting new exoplanets with the radial-velocity method is rather special, because, on the one hand, objects, say, in the 75-parsec radius, which can be covered with MRV, quickly become exhausted, and on the other hand, the sensitivity of the method is increasing. A maximum sensitivity of 1.5 m/s achieved in MRV has been reported (Santos *et al.*, 2003). An extremely promising astrometric method, especially in its orbital (satellite) version, is waiting its turn and could give results in the near future. There are no certain reports on detecting exoplanets using other methods, with only one exception.

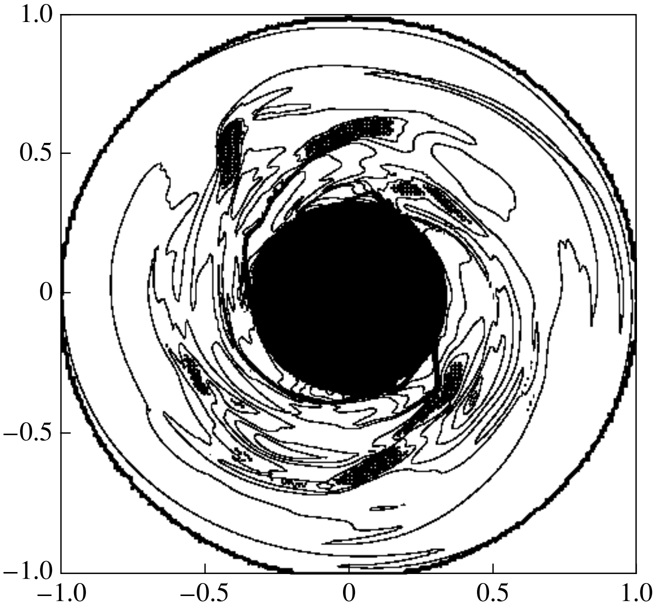

**Fig. 8.** Defragmentation of a protoplanetary disk into clumps formed due to turbulence. The further collapse of clumps and their rapid (within $10^4$ years) transformation into giant planets is possible (Boss, 2003).

This exception is the transit method. It is known that the only object of this kind which is actively and fruitfully investigated is HD 209458b (Charbonneau *et al.*, 2000; Henry *et al.*, 2000; Ksanfomality, 2004). At the same time, the number of known exoplanets and the observational geometry of transits of exoplanets allow us to expect a second object of this kind to be detected. However, the published announcements on transit observations relate to objects that are 10 or 100 times farther than HD 209458b; these observations were performed by a method that can be called the "large-bucket method." One of the latest papers (Konacki *et al.*, 2003) presents data on the object OGLE TR-56, which has the shortest period (1.2 days) among hot Jupiters known at the end of 2003 (Fig. 9). The observations were made with the new method and simultaneously covered several tens of thousands of stars approximately in the direction of the Galactic center. Then, the data were computationally processed in order to find transits. Compared to the system HD 209458b (47 pc apart), the remoteness of the objects exceeds 1500 pc and does not allow one to obtain such detailed and impressive results or even to determine the type of the transiting body. The number of objects OGLE for which transits are

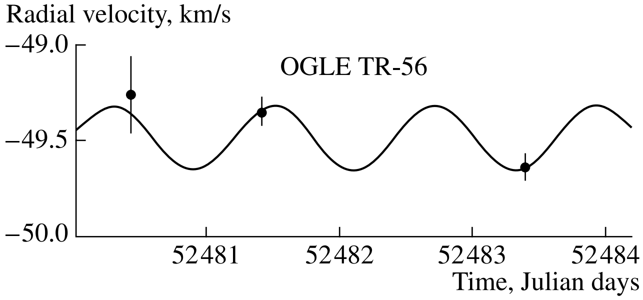

**Fig. 9.** Keplerian velocity component of the object OGLE TR-56 with the shortest period of 1.2 days (Konacki *et al.*, 2003).

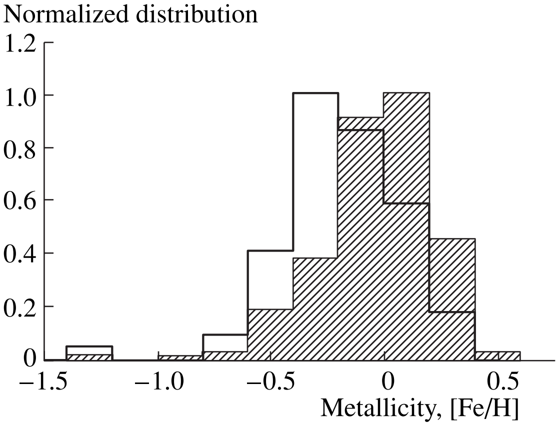

**Fig. 10.** Normalized distribution of the metallicity for field stars (solid line) and stars hosting planets (shaded). From the paper by Fischer *et al.* (2003).

observed is continuously growing: according to Schneider (2004), there were three of them found by May 2004, OGLE TR-56, TR-113 (1.43 days), and TR-132 (1.69 days). Taking into consideration the difficulties of these investigations, one may suppose that the short periods of the OGLE-type objects were the result of observational selection.

Undoubtedly, globular clusters of stars, many of which can be referred to as relatively close (on a galactic scale) objects, are even more promising for searching possible transits with the "large-bucket method". Having in mind that transits are highly probable for hot jupiters, observers made two attempts to detect them near the stars of the globular cluster 47 Tuc. Although about ten transits were expected, the search in 47 Tuc gave no result. Probable causes of this failure will be discussed below. It is quite possible that the hot jupiter HD 209458b will forever remain the only relatively close hot jupiter with transits observed (Ksanfomality, 2004).

## THE METALLICITY OF A STAR AND A PROTOPLANETARY NEBULA AND ITS ROLE IN THE FORMATION OF A PLANETARY SYSTEM

After the first stage in the investigations of the first extrasolar planets was over, the idea about a link between the properties of an exoplanet system and the metallicity of the protoplanetary cloud and the host star (Gonzalez, 1997) began to progress quickly. It was established that the detected systems have host stars with a rather high metallicity, with the star $\rho^1$ Cnc being highest. It is worth recalling that metallicity is determined as the content of heavy metals relative to the hydrogen content. All the elements heavier than hydrogen ($Z > 2$) are assumed to be "metals" or "heavy elements," having in mind that metals give a large fraction of electrons in a stellar interior, and Ca, Na, and Fe produce the strongest lines in the stellar spectra. The metallicity [Fe/H] of stars is defined relative to the Sun, which itself is an order of magnitude (or even more) more strongly enriched with metals relative to the mean composition of halo objects. The metallicity [Fe/H] is the difference between the logarithms of ratios of the atom concentration of iron $N_{\mathrm{Fe}}$ to that of hydrogen $N_{\mathrm{H}}$ for the star and for the Sun:

$$[\mathrm{Fe/H}] = \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{*} - \log(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{\odot}.$$

If it is supposed that, in the studied object, the contents of C, N, O, and other heavy elements, contributing mostly to $Z$, are roughly in the same proportion as in the Sun, the approximation $[\mathrm{Fe/H}] \cong \log(Z/Z_{\odot})$ is often assumed. Note that the mean type of stars hosting planets does remain that of the Sun.

Echelle-spectrogram analysis allows the equivalent widths of neutral and ionized iron absorption lines (Fe I and Fe II, respectively) to be determined. A spectral resolution of 70 000 or better can be achieved with the methods developed. Together with the models of stellar atmospheres, assuming the local thermodynamic equilibrium, these data allow one to obtain the four basic parameters of the star: effective temperature $T_{\mathrm{eff}}$, gravity at the photosphere level $g$, turbulence velocities $j_{\mathrm{t}}$, and metallicity [Fe/H]. The uncertainty now achieved in the estimate of [Fe/H] is 0.02 (in logarithmic scale). The exact estimate of this parameter requires a lot of factors to be taken into account, and the most important among them is the effective temperature of the star, which influences the depth of spectral lines.

There are a large number of publications devoted to the metallicity of stars hosting planets; among the most recent papers, the works by Fischer *et al.* (2003), Santos *et al.* (2003), Udry *et al.* (2003), and the detailed review by Gonzalez (2003) are worth mentioning.

Fischer *et al.* (2003) studied the link between the metallicity of 971 stars of F, G, and K types and the presence of planetary companions. Vast observational material was used: for two years, 754 stars were observed no less than ten times each. The authors developed a complicated program to process the data in order to eliminate possible errors caused by the differences in $T_{\mathrm{eff}}$ and turbulence velocities $j_{\mathrm{t}}$. All the information available on the stars within a radius of 15 pc (including stars without planets) was processed by this program. The data obtained by Fischer *et al.* (2003) on the distribution of the normalized number of field stars and stars hosting planets versus their metallicity are given in Fig. 10. The histogram contains data on 71 stars. As was mentioned, the scale for [Fe/H] is logarithmic. Although the number distribution of stars hosting planets is almost the same as that for field stars, their distribution is shifted along [Fe/H] by approximately 0.2 to higher metallicity. This confirms the conclusions of many papers (starting from the paper by Gonzalez (1997)) that planetary systems do appear around stars with a high metallicity. This paper especially considered factors which may skew the result, for example, the influence of $T_{\text{eff}}$, influx of the material fallen out of the protoplanetary disk to the convective zone of the star, or the remoteness of the planet from the host star. No such effects were found.

The data obtained independently and with another experimental setup by Gonzalez (2003) (Fig. 11) are in complete agreement with the conclusions made by Fischer *et al.* (2003). The distribution of stars hosting planets (a gray histogram, 55 stars with planets) differs little from Fig. 10 and is shifted by the same interval. Two peaks of the histogram for the number of field stars appeared due to insufficient statistics (43 stars) and do not reflect any physical reality.

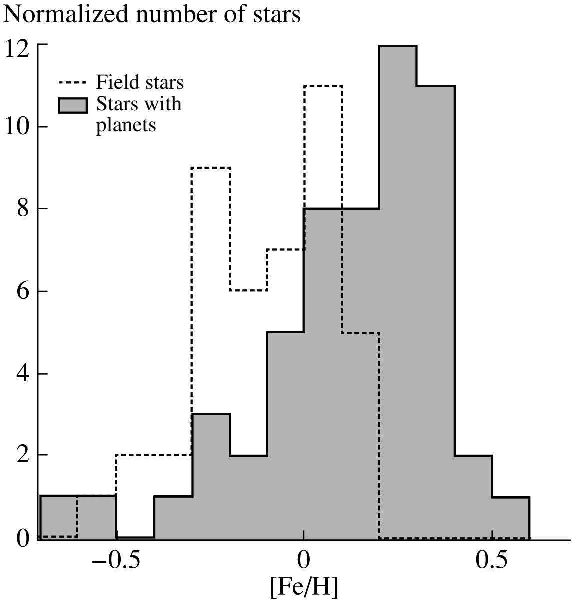

**Fig. 11.** Star metallicity distribution obtained independently of the data presented in Fig. 10. The field stars (dashed line) and stars hosting planets (gray histogram). From the paper by Gonzalez (2003).

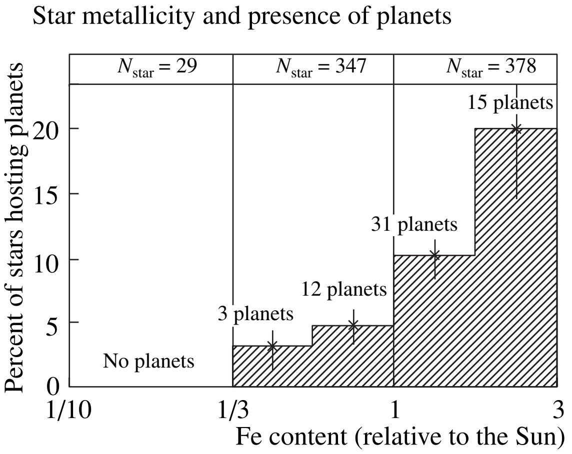

**Fig. 12.** Presence of planetary systems depending on the iron enrichment of the star constructed on the basis of the data for 754 stars (Fischer *et al.*, 2003).

## DEVELOPMENT OF THE HYPOTHESIS ON THE DETERMINING ROLE OF METALLICITY

Figure 12 presents the number of planets (or planetary systems) as a function of the star metallicity. The histogram is constructed on the basis of the data on 754 stars (Fischer *et al.*, 2003). Stars with planets having $M\sin i > M_J$ and an orbital period less than 3 years were selected. The observations lasted for at least 2 years. The authors give the following number distribution of detected exoplanets versus the metallicity of 754 stars inspected: 5–10% of stars with solar metallicity have planets. When [Fe/H] increases by +0.5, their number increases to 20%. When [Fe/H] decreases to –0.5, the number of detected planets sharply decreases to a few percent.

Thus, the experimental data convincingly show that the presence of a planetary system is linked with the star metallicity. Gonzalez (2003) gives examples of how a high metallicity can be used to predict objects promising for a search. The planets HD 4203b and BD–10°3166b were found by this means. And, vice versa, the lack of success in the search for planets for the cluster 47 Tuc can be explained by the low metallicity of stars in the globular cluster (Gonzalez, 2003). However, the author notices that there are factors favoring the selection of high-metallicity objects. About 4% of the stars in the 25-parsec radius have giant planets (nothing is known yet about other planets). Gonzalez (2003) believes that the incidence rises to 20% with increasing metallicity [Fe/H] by +0.2 (not by 0.5, as Fischer *et al.* (2003) predicted), and all the stars might have planetary systems when [Fe/H] ≥ +0.4. This estimate is probably too optimistic, and this does not mean, however, that all high-metallicity stars are accompanied by giant planets.

Lineweaver (2001) went further and attempted to connect the star metallicity with the problem of the survival of Earth-type small planets (ETP), which have not been found yet. As was already mentioned above, the migration of giant planets toward the host star through a zone of orbits of small planets very likely leads to the ejection of ETP out of the system under the gravitational disturbance from the giant planet. The chance of a direct catastrophic collision of giant planets with ETP

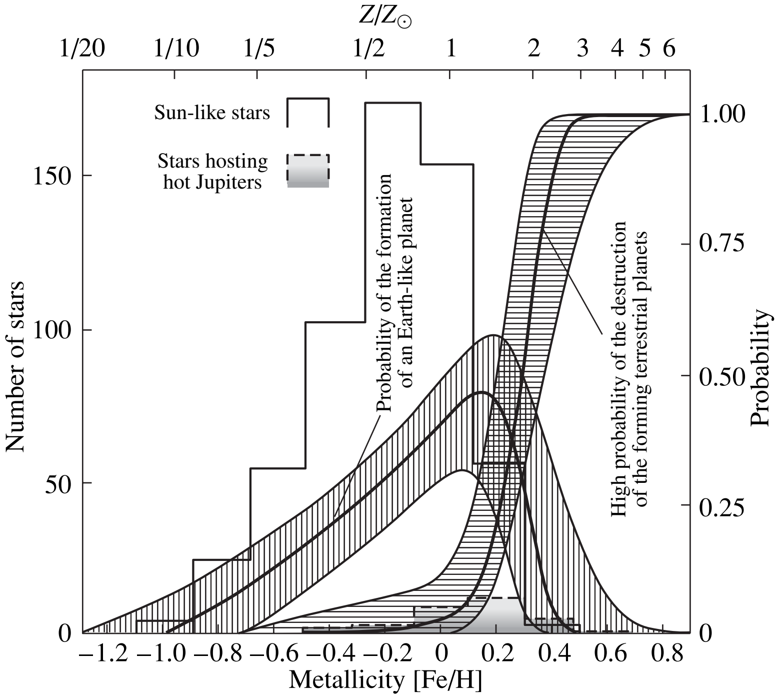

**Fig. 13.** Probability of the formation of an Earth-like planet depending on the metallicity of the protoplanetary disk (Lineweaver, 2001).

cannot be excluded as well. Lineweaver (2001) supposes that, when the metallicity of a protoplanetary cloud grows, starting from negative values of [Fe/H], ETP first appear in their typical orbits (with a semimajor axis ≈1 AU). With a further increase in [Fe/H], the number of ETP grows, but simultaneously giant planets appear (Fig. 13). Their number rises with an increase in [Fe/H], and the interaction with ETP first diminishes the number of the latter and then results in their complete disappearance. Further, Lineweaver (2001) gives his own estimate of the mean age of Earth-like planets in the Universe, which he believes to be 1.8 Gyr larger than the Earth's age.

This estimate can be compared to more general characteristics of the galactic interstellar medium, the high metallicity of which could originate only from the evolution of stars of much earlier generations or from supernova explosions. It is interesting to note that this benchmark (approximately 6.4 billion years) strangely coincides with the time when the Universe changed from slowing down to speeding up its expansion, or, what is the same, when the prevailing role of dark matter changed to the prevailing role of dark energy in the Universe (Kirshner, 2003; Miralda-Escude, 2003; Ostriker and Steinhard, 2003; Seife, 2003).

It is tempting to deviate from the subject and imagine an intelligent civilization which preceded that on the Earth by a good 1.8 billion years and to conclude the paper by the citation from E. Fermi: So, where are they all?

## CONCLUSIONS

Accumulation of information on extrasolar planetary systems is still in progress and gives unexpected results. This new division of astrophysics brings into use conceptions and laws unknown before and requests that the classic theory of the Solar System origin be revised and the unique stability of the Solar System be explained. Even in the first years after detecting the first extrasolar planets, the assumption about the decisive role of a star's (or protoplanetary disk's) metallicity for the probability of the formation of a planetary system was proposed. The experimental material accumulated in subsequent years not only confirmed this hypothesis but also showed that the probability of the formation of a planetary system increases approximately by a factor of 4 when the star metallicity [Fe/H] exceeds the solar one by 0.4. Attempts are being made to link the metallicity with the type of appearing planetary systems.

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## REFERENCES

Armitage, P.J., A Reduced Efficiency of Terrestrial Planet Formation Following Giant Planet Migration, *Astrophys. J.*, 2003, vol. 582, pp. 47–50.

Bally, J., Testi, L., Sargent, A., and Carlstrom, J., Disk Mass Limits and Lifetimes of Externally Irradiated Young Stellar Objects Embedded in the Orion Nebula, *Astron. J.*, 1998, vol. 116, pp. 854–859.

Borkowski, V. and Schneider, J., New Approaches for the Search for Moons of Extrasolar Planets, *SF2A-2003: Semaine de l'Astrophysique Francaise*, Combes, F., Barret, D., and Contini, T., Eds., EdP-Sci., 2003, p. 67.

Boss, A., Outlook: Testing Planet Formation Theories, *ISSI Workshop on Planetary Systems and Planets in Systems*, Udry, S., Benz, W., and Von Steiger, R., Eds., *Space Sci. Rev.*, 2003.

Briceño, C., Vivas, A.K., Calvet, N., The CIDA–QUEST Large-Scale Survey of Orion OB1: Evidence for Rapid Disk Dissipation in a Dispersed Stellar Population, *Science*, 2001, vol. 291, pp. 93–96.

Burrows, A.M., Marley, W.B., Hubbard, W.B., A Non-Grey Theory of Extrasolar Giant Planets and Brown Dwarfs, *Astrophys. J.*, 1997, vol. 491, pp. 856–875.

California and Carnegie Planet Search. Masses and Orbital Characteristics of Extrasolar Planets, 2004, http://exoplanets.org/planet_table.txt.

Charbonneau, D., Mayor, M., and Queloz, D., A Jupiter-Mass Companion to a Solar-Type Star, *Nature*, 1995, vol. 378, pp. 355–358.

Charbonneau, D., Brown, T.M., Latham, D.W., and Mayor, M., Detection of Planetary Transits Across a Sun-like Star, *Astrophys. J.*, 2000, vol. 529, no. 1, pp. 45–48.

Charbonneau, D., Brown, T.M., Gilliland, R.L., and Noyes, R.W., New STIS Data of the Transiting Planet System HD209458, *IAU Symp. no. 219, XXV General Assembly of IAU*, Sydney, 2003.

Chiang, E.I., Excitation of Orbital Eccentricities by Repeated Resonance Crossings, *Astrophys. J.*, 2003, vol. 584, pp. 465–473.

Guillot, T., Gautier, D., and Hubbard, W.B., New Constraints on the Composition of Jupiter From GALILEO Measurements and Interior Models, *Icarus*, 1997, vol. 130, pp. 534–539.

Fischer, D.A., Marcy, G.W., Butler, R.P., *et al.*, A Second Planet Orbiting 47 UMa, *Astrophys. J.*, 2002, vol. 564, pp. 1028–1034.

Fischer, D., Valenti, J.A., and Marcy, G., Spectral Analysis on Planet-Search Survey, *IAU Symp. no. 219, XXV General Assembly IAU*, Sydney, 2003.

Goldreich, P. and Sari, R., Eccentricity Evolution for Planets in Gaseous Disks, *Astrophys. J.*, 2003, vol. 585, pp. 1024–1037.

Gonzalez, G., The Stellar Metallicity-Giant Planet Connection, *Mon. Not. R. Astron. Soc.*, 1997, vol. 285, pp. 403–412.

Gonzalez, G., Stars, Planets, and Metals, *Rev. Mod. Phys.*, 2003, vol. 75, pp. 101–120.

Hayashi, C., Nakazava, K., and Nakagava, Y., Formation of the Solar System, *Protostars and Planets II*, Black, D.C. and Mathews, M.S., Eds., Tucson: Arizona University Press, 1985, pp. 1100–1153.

Henry, G.W., Marcy, G.W., Butler, R.P., and Vogt, S.S., A Transiting 51 Peg-Like Planet, *Astrophys. J.*, 2000, vol. 529, no. 1, pp. L41–L44.

Kaisler, D., The Puzzles of Planethood, *Sky Telesc.*, 2002, no. 8, pp. 32–38.

Kirshner, R.P., Throwing Light on Dark Energy, *Science.*, 2003, vol. 300, pp. 1914–1918.

Konacki, M., Torres, G., Jha, S., and Sasselov, D., A New Transiting Extrasolar Giant Planet, *Nature*, 2003, vol. 421, pp. 507–509.

Ksanfomality, L.V., Extrasolar Planetary Systems, *Astron. Vestn.*, 2000, vol. 34, no. 6, pp. 529–544 [*Sol. Syst. Res.* (Engl. Transl.), 2000, vol. 34, no. 6, p. 481].

Ksanfomality, L.V., XXIV IAU General Assembly, IAU Symposium S202 "Planetary Systems in the Universe," *Astron. Vestn.*, 2001, vol. 35, no. 2, pp. 188–192 [*Sol. Syst. Res.* (Engl. Transl.), 2001, vol. 35, no. 2, p. 171].

Ksanfomality, L.V., On the Probability of a Survival of the Terrestrial Planets under the Condition of Migration of Massive Bodies in Extrasolar Planetary Systems, *Proc. IAU Symp. no. 219, XXV General Assembly IAU*, Sydney, 2003, p. 85.

Ksanfomality, L.V., To the Nature of HD 209458b Object: Conclusions From Comparing of Experimental and Theoretical Data, *Astron. Vestn.*, 2004, vol. 38, no. 4, pp. 344–353 [*Sol. Syst. Res.* (Engl. Transl.), 2004, vol. 38, no. 4, p. 300.

Kumar, S.S., Very Low Mass Stars, Black Dwarfs and Planets, *Astrophys. Space Sci.*, 1994, vol. 212, p. 57.

Lineweaver, C.H., An Estimate of the Age Distribution of Terrestrial Planets in the Universe: Quantifiyng Metallicity as a Selection Effect, *Icarus*, 2001, vol. 151, pp. 307–313.

Makalkin, A.B., Problems of Protoplanetary Disks Evolution, *Sovremennye problemy mekhaniki i fiziki kosmosa* (Contemporary Problems of of Cosmos Mechanics and Physics), Avduevskii, V.S. and Kolesnichenko, A.V., Eds., Moscow: Fizmatlit, 2003, pp. 357–396.

Marcy, G., Butler, P., Fischer, D., and Vogt, S., Orbital Eccentricities, California&Carnegie Planet Search, 2003, http: //exoplanets.org/planet_table.txt.

Marcy, G., Butler, P., Fischer, D., and Vogt, S., Properties of Extrasolar Planets, *Scientific Frontiers in Research on Extrasolar Planets*, Deming, D. and Seager, S., Eds., vol. 294, San Francisco: ASP, 2003, p. 1.

Miralda-Escude, J., The Dark Age of the Universe, *Science*, 2003, vol. 300, pp. 1904–1909.

Ostriker, J.P. and Steinhard, P., New Light on Dark Matter, *Science*, 2003, vol. 300, pp. 1909–1913.

Pollack, J.B., Hubickyj, O., Bodenheimer, P., *et al.*, Formation of the Giant Planets by Concurrent Accretion of Solids and Gas, *Icarus*, 1996, vol. 124, pp. 62–85.

Ruskol, E.L. and Safronov, V.S., Jupiter Growth as an Essential Factor for the Formation of the Planetary System, *Astron. Vestn.*, 1998, vol. 32, no. 4, pp. 291–300 [*Sol. Syst. Res.* (Engl. Transl.), 1998, vol. 32, no. 4, p. 255].

Safronov, V.S. and Ruskol, E.L., On the Origin and Initial Temperature of Jupiter and Saturn, *Icarus*, 1982, vol. 49, pp. 284–296.

Safronov, V.S., *Evolyutsiya doplanetnogo oblaka i obrazovanie Zemli i planet* (The Evolution of the Protoplanetary Cloud and the Formation of the Earth and the Planets), Moscow: Nauka, 1969.

Santos, N., Israelian, G., Mayor, M., Statistical Properties of Exoplanets II. Metallicity, Orbital Parameters, and Space Velocities, *Astron. Astrophys.*, 2003, vol. 398, pp. 363–371.

Schneider, J., Extrasolar Planets Encyclopaedia, 2004, jean.schneider@obspm.fr.

Seife, C., Dark Energy Tiptoes Toward the Spotlight, *Science*, 2003, vol. 300, pp. 1896–1897.

Stern, S.A. and Levinson, H.F., Toward a Planet Papadigm, *Sky Telesc.*, 2002, no. 8, pp. 42–46.

Thébault, P. and Brahic, A., Dynamical Influence of a Proto-Jupiter on a Disk of Colliding Planetesimals, *Planet. Space Sci.*, 1999, vol. 47, pp. 233–243.

Udry, S., Mayor, M., and Santos, N.C., Statistical Properties of Exoplanets. I. The Period Distribution: Constraints for the Migration Scenario, *Astron. Astrophys.*, 2003, vol. 407, pp. 369–376.

Weidenshilling, S.G., Growing Jupiter'S Core by Runaway Accretion, *Mon. Not. R. Astron. Soc.*, 1997, vol. 180, pp. 57–70.

Wetherill, G.W., Formation of the Earth, *Ann. Rev. Earth Planet. Sci.*, 1990, vol. 18, pp. 205–256.

Wetherill, G.W., The Formation and Habitability of Extra-Solar Planets, *Icarus*, 1996, vol. 119, pp. 219–238.

Wuchterl, G., Hydrodynamics of Giant Planets Formation. III. Jupiter'S Nucleated Instability, *Icarus*, 1991, vol. 91, pp. 53–64.

Wuchterl, G., Giant Planet Formation, *Icarus*, 1995, vol. 106, pp. 323–334.

Zuckerman, B., Foveille, T., and Kastner, J.H., Inhibition of Giant-Planet Formation by Rapid Gas Depletion Around Young Stars, *Nature*, 1995, vol. 373, pp. 494–496.