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Planet formation in sun-like systems

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Abstract. Recent discoveries of substellar and planetary-mass objects in orbit around other stars represent the most remarkable progress achieved in the search for extrasolar planetary systems. The evidence for their existence is summarised. The physical properties and orbital characteristics of these systems are discussed and compared with those of the solar system. The new discoveries raise new questions for the theories of planet formation as part of the star formation process.

Keywords : Sun-like stars, extrasolar planets, star formation, planet formation

1. Introduction

Are we alone in the universe? Do planetary systems like our own exist around other stars? These profound questions have long occupied the human mind. The vastness of the universe seemed to suggest that extrasolar planetary systems are likely to exist in large numbers. Following Copernicus, Kepler and Galileo, studies of our own solar system made possible by the advances in science and technology beginning in the 17th century, strengthened the belief in the existence of extrasolar planetary systems. A physical model for the formation of the Sun and planets around it was suggested by Kant (1775) and Laplace (1796). In this model, the Sun as well as the planets formed from a single rotating, flattened cloud of gas (the protosolar nebula). If other stars also formed similarly from gaseous protostellar nebulae, then they could be expected to have attendant planetary systems around them.

However, the idea that there are stars, other than the Sun, that have planets orbiting them, remained a subject of speculation and controversy for two more centuries because the astronomical observing techniques used for the detection of planetary companions of stars did not have the necessary precision. During the past several years improvements in instrumentation and the observing techniques have reached a sensitivity level at which the gravitational effect of a massive planet on the motion of the star it orbits can be measured. The orbital motion of the star around the star-planet system barycentre is measured as periodic changes in the stellar radial velocity and the existence of a planet is thus indirectly inferred.

The discovery of the first extrasolar planet 51 Peg b (around the G2-3V star 51 Peg) was announced on 6 October, 1995 by Mayor and Queloz (1995), and was soon confirmed by Marcy and Butler (1995) and Noyes et al. (1995). The detection of 51 Peg b was based on precise radial velocity measurements of the star 51 Peg with an optical fibre-fed echelle spectrograph and by using a cross-correlation technique on the Doppler shifts of about 5000 stellar absorption lines that yielded a velocity resolution of about 13 m/s. The parameters of the planetary orbit deduced are : Period $P = 4.2293 \pm 0.0011$ day; Semimajor axis a sin i = 0.05 AU, where i is the unknown inclination angle of the orbital plane with the plane of the sky; Eccentricity e = 0.09 ± 0.06. The planetary mass M sin i = 0.47 ± 0.02 M_J, where M_J is the mass of the planet Jupiter. Since this startling discovery in October 1995, planetary-mass bodies have been detected around a number of other stars. Thus the existence of extrasolar planetary systems has been established as a hard fact.

In this paper we summarize our current understanding of the way planetary systems form as part of the star formation process and the observational evidence that supports this view. The existing observational techniques used for the detection of planetary systems and searches for them conducted in the 20th century are briefly described. The recently discovered extrasolar planetary systems are listed and their properties are discussed. The new results force us to revise our ideas about the formation and evolution of extrasolar-planetary systems and that of our own Solar system.

2. Planets as by-products of the star formation process

The notion that planets are a natural consequence of the star formation process can be traced back, in essence, to the writings of I. Kant and P. S. Laplace towards the end of the 18th century. Current models for the formation of stars and planets (e.g. Shu et al. 1987, Cameron 1988) suggest that the process begins with the gravitational collapse of the dense core of a rotating cloud of interstellar gas and dust. As a result, a fraction of the material forms a hydrostatic object at the centre, the *protostar*. Matter that does not fall on the central protostar due to its angular momentum forms a disk in the equatorial plane. Observations of star-forming regions at infrared and millimetre wavelengths have revealed a large number of such disks of gas and dust (Strom et al., 1993).

On a time scale of ~ 10^4 - 10^5 years, the dust grains segregate from the gas and settle to the disk midplane to form a dense carpet. Random motions of the dust grains cause collisions and coagulation, leading to the growth of solid particles from an initial size ~ 0.1μ to centimetre, meter and finally kilometre-size *planetesimals* on a time scale of ~ 10^3 - 10^4 years. Gravitational forces between the km-sized bodies then lead to further growth to form Earth-sized terrestrial planets in the inner regions of the disk closer to the central protostar on a timescale of ~ 10^7 - 10^8 years (Wetherill, 1986).

In the outer regions of the disk, where the temperatures are cooler and ice grains composed of water, carbon dioxide, methane, ammonia and other volatile species can condense, the ice and rock planetesimals could grow to masses of the order of ten times that of Earth. Further growth to giant-size planets as massive as Jupiter is thought to take place by dynamical collapse and accretion of cold nebular disk gas on to these rocky cores of 10 - 15 Earth masses

(Bodenheimer & Pollack 1986). $1M_J$ seems to be the largest giant planet mass that can be produced, as such a planet clears a gap in the disk that prevents further accretion (Lin and Papaloizou, 1980). There is evidence for such a gap in the protoplanetary disk around the star β Pictoris, whose dusty disk had earlier been observed by means of direct imaging (Smith and Terrile, 1984), cleared by massive planetary bodies (Roques et al., 1994).

Thus rocky Earth-like planets form in the inner terrestrial zone (within ~ 4 AU), while giant gaseous planets upto ~ $1M_J$ mass, with ~ 10 - 15 Earth masses of rocky cores form in the outer zone. All major planets are expected to have nearly circular orbits because they form in the quiescent environment of a dissipative, Keplerian disk. Now, our Solar system does exist; and protoplanetary disks similar to the hypothesized protosolar nebula have been observed to exist around young stellar objects in numerous star-forming regions, so planetary systems around other stars might be quite common.

3. Detection techniques

The observational techniques to detect extrasolar planetary systems can be divided into (i) indirect and (ii) direct methods.

(i) Indirect detection techniques :

Although it is difficult to observe the planet(s) in orbit around a star, the star itself is easy to study because it is bright. The indirect methods seek to detect the effects on the parent star of the planet(s) orbiting it. There are several effects that can be utilised.

(a) The gravitational pull of the planet on the star causes a wobble in the motion of the star. The star orbits the centre of mass (the barycenter, which is relatively closer to the star than the planet because of the large mass ratio) of the star-planet system with the same period as the planetary orbital period. The *Doppler spectroscopy* method measures periodic variations (of order 10 m/s for a Jupiter-size planet at a few AU from the star) in the radial velocity of the star to detect the presence of a planet.

(b) The *astrometric* method measures periodic variation in the position of the star on the plane of the sky, superposed on the mean motion of the star. This method would work best for the nearest stars with more massive planets in wide orbits, because the angular size of the orbit decreases with increasing distance of the star from the observer.

(c) For extrasolar planetary systems with orbital planes close to the observer's line of sight, it is possible that the planet blocks a measurable amount of stellar light during its transit across the star. This *occultation* method requires very sensitive photometric monitoring of the star.

(d) If a star with a planetary system passes very close to the line of sight to a more distant star, then the gravitational *microlensing* caused in the light from the background star will have distortions that can be used to infer the presence of planetary system around the lensing star (Martinez, 1996).

(e) *Timing* of the star's periodic radial motion can also be used to infer indirectly the presence of a planetary system. Planets around the pulsar PSR 1257+12 were thus detected by analysing the pulsar pulse arrival times (Wolszczan and Frail, 1992). However, the planets discovered around pulsars have a different formation history than the extrasolar planets around normal stars.

(ii) Direct detection techniques :

Direct observation of a planet means that light reflected or emitted by the planet itself is detected. This is, of course, not easy because the relatively faint radiation from the planet has to be detected in the presence of the overwhelming glare from the parent star. Coronographic and interferometric techniques, especially at the longer infrared wavelengths where the stellar contribution to the total light is falling off, can be used. Extrasolar planets could also be detected at metric radio wavelengths if they emitted cyclotron-maser radiation similar to that of Jupiter and other magnetized planets in the Solar system (Dulk et al., 1997).

4. Searches for extrasolar planetary systems

The first serious observational search for extrasolar planets can be said to have begun in 1938 when Peter van de Kamp took the first of over 2000 photographic plates of the nearby (distance 1.8 pc), large proper motion star, now known as Barnard's star (Barnard, 1916), which he and his students acquired at the Sproul Observatory during 1938-1962. From the astrometric analysis of the photographic plates, van de Kamp (1969) claimed that Barnard's star showed periodic wobble in its movement attributable to the presence of a planet of mass 1.6 M_J and orbital period of 24 years. He later revised the planetary parameters for this system to have two planets with masses 0.7 M_J and 0.5 M_J orbiting the star with periods of 12 and 20 years (van de Kamp, 1982). However, no other observers have confirmed van de Kamp's results (e.g. Gatewood and Eichhorn, 1973). In 1984 there was a report (McCarthy and Probst, 1984) of a direct detection of a planet around the star VB 8 by means of IR speckle interferometry. Again, further observations of this object did not confirm the reported detection.

Search programmes for the detection of extrasolar planetary systems, based on the measurement of radial velocity Doppler shifts, have been in operation at several observatories since 1980s (Latham, 1985; Mayor, 1985; Campbell et al., 1988; Cochran and Hatzes, 1990; Marcy and Butler, 1992), and have reached the precision (~ 10 - 20 m/s) needed to detect Jupiter-size planets at a few AU from a sun-like star. Over 100 bright nearby solar-type stars have been monitored. The first extrasolar planet was discovered by M. Mayor and D. Queloz in 1995 (Mayor and Queloz, 1995) around the sun-like star 51 Pegasi. They used the ELODIE spectrograph of the *Haute-Provence Observatory* for radial velocity measurements.

Since 1995 planetary systems have been detected around a number of other stars. Table 1 lists all the newly discovered planets with confirmed detections. The primary star's parameters (name, spectral type, metallicity, [Fe/H], V magnitude and distance) are given in columns 1-5, and that for the planetary companion discovered (name, orbital period, the semimajor axis of the orbit, the orbital eccentricity, the mass $M \sin i$, the expected effective temperature of the planetary surface and bibliographic references) in columns 6-12. The more recently revised parameters have been listed in the table.

5. Discussion

As can be seen from Table 1, eight extrasolar planetary systems have been detected (and confirmed) around stars similar to the sun in the solar neighbourhood (within ~ 25pc). A few more detections (e.g. Bernard' star; van de Kamp, 1969; HD 114762, Latham et al., 1989; Lalande 21185, Gatewood, 1996) have been reported (that are yet to be confirmed by independent observations) and many planetary system candidates are under study. The observed orbital periods range from a few days to a few years. The derived planetary masses ($M \sin i$) range from ~ 0.5 M_J to ~ 7 M_J. Because of the (unknown) sin i factor, these masses are lower limits. However, for a random distribution of orbital planes, the most likely value of the mass can be obtained by multiplying the lower limits by $4/\pi$. This does not increase the mass substantially. In the following discussion we consider the planetary masses listed in

Table 1. Extrasolar planetary systems around sun-like stars.

Primary star					Planetary companion						
Name	sp. type	[Fe/H] *	V (mag.)	Dist. (pc)	Name	Period (days)	SM axis (AU)	Eccen.	M sin i (M_J)	Temp. K	Ref.
51 Peg	G2-3V	+0.21	5.4	15.4	51 Peg b	4.23	0.05	0.02±0.02	0.47	1300	1
70 Vir	G4v	−0.03	5.0	18.1	70 Vir b	116.6	0.43	0.40±0.01	6.6	363	2
47 UMa	G0V	+0.01	5.1	14.1	47 UMa b	1090	2.11	0.03±0.006	2.8	180	3
55 Cnc A	G8V	+0.29	6.0	13.4	55 Cnc A b	14.65	0.11	0.05±0.01	0.84	700	4
τ Boo A	F6IV	+0.34	4.5	15	τ Boo A b	3.32	0.046	0.02±0.02	3.87	1400	4
υ And	F7V	+0.17	4.6	16.5	υ And b	4.61	0.06	0.15±0.04	0.68	1300	4
16 Cyg B	G2.5V	+0.06	6.2	22	16 Cyg B b	804	1.7	0.67	1.5	220	5
ρ CrB	G0-2V	−0.19	5.4	16.7	ρ CrB b	39.65	0.23	0.03±0.04	1.1	573	6

References to Table 1 :

* Metallicities from Gonzalez (1997)

1. Mayor and Queloz (1995)
2. Marcy and Butler (1996)
3. Butler and Marcy (1996)
4. Butler et al. (1997)
5. Cochran et al. (1997)
6. Noyes et al. (1997)

Table 1 as representative.

Masses : With the current level of precision (10 - 20 m/s) of the radial velocity measurements, planetary masses much smaller than that of Jupiter are not likely to be detected. So the lower end of the observed planetary mass range is understandable as due to the limitations of the observing techniques. However, the existence of planets with masses much larger than that of Jupiter is very surprising. Current theories of star/planet formation predict a gap in the mass range ~ 1 - 10 M_J. During the process of star formation, a molecular cloud can fragment into substellar ($\leq 80\ M_J$) clumps down to a mass of ~ 10 M_J at which opacity effects limit further fragmentation. These substellar objects are the *brown dwarfs*. Planets, on the other hand, form by collisional accumulation and accretion in the protoplanetary disk. Once a Jupiter-mass planet (*giant planet*) has been grown, it sweeps the disk clean of material producing a gap, and inhibits further accretion. Therefore, in the standard model of planet formation, planets with masses much larger than 1 M_J (*superplanets*) are not expected to form. Much more massive and cold disks could perhaps allow the formation of *superplanets* either by gravitational instabilities (Boss, 1996), or by the merger of giant planets (Lin and Ida, 1997).

Orbital sizes : Just as the existence of massive *superplanets* was unanticipated, so are their short (much less than 1 AU) orbital semimajor axes. In the inner terrestrial zone of the protoplanetary disk, the giant planets cannot form because it is too hot there for icy planetesimals, that are required for the formation of the giant planets, to remain stable. The cases of 51 Peg b, τ Boo A b and υ And b are the most extreme with their orbital semimajor axes ≤ 0.05 AU. It has been suggested (Lin et al., 1996) that *orbital migration* resulting from the frictional and gravitational tidal interaction of the giant planet with the disk can cause shrinking of the orbit (say, from ~ 5 AU to ~ 0.05 AU).

Orbital eccentricities : The orbits of all major planets in the solar system are very nearly circular. Formation of planets from dissipative keplerian disks is expected to lead, naturally, to circular orbits. Most of the newly discovered planets do indeed have circular orbits (51 Peg b, 47 UMa b, 55 Cnc A b, τ Boo A b, υ And b, ρ CrB b). However, large orbital eccentricities (70 Vir b, e=0.4; 16 Cyg B b, e=0.67) are also observed. The large eccentricity of 16 Cyg B b has been ascribed (Holman et al. 1997) to the gravitational perturbations due to the diatant companion star 16 Cyg A. Dynamical instabilities due to gravitational interactions in a multi-planet system can also produce large eccentricities (Rasio and Ford, 1996).

Effective temperature : No direct radiation from any of the extrasolar planets has been detected yet. However, if the planetary surfaces have albidoes similar to that of the giant planets (0.35 for Jupiter) of the solar system, estimates of the effective temperature of the planetary surface, at an average distance from the primary star, implied by the observed orbital parameters, can be made (Guillot et al., 1996). These are listed in Table 1. Planets with the shortest semimajor axes have uncomfortably high temperatures (51 Peg b, 1300 K; τ Boo A b, 1400 K; υ And b, 1300 K). At such high temperatures and so close to the parent star, thermal and non-thermal evaporative processes are likely to significantly affect the planetary atmospheres (Mayor and Queloz, 1995).

Stellar metallicity - planet connection : It is to be noted that a majority of the stars with planets (particularly, the short period "51 peg-like" systems, υ And, τ Boo, 55 Cnc and 51 Peg, with a mean [Fe/H] value ~ +0.25) listed in Table 1 are metal-rich. Gonzalez (1997) has suggested that metal rich stars may preferentially harbour planets. The higher metallicity could either be a prerequisite for the formation of a large mass, short period planet, or the formation of such a planet may lead to metal enrichment of the parent star. However, the statistics is still rather poor. Already, the new discovery of the ρ CrB planetary system, which is relatively metal poor, does not fit the suggested pattern.

Controversies : While a number of detections of extrasolar planets have been reported and confirmed since the discovery of 51 Peg b in 1995, the existence of the planet around 51 Peg itself has been questioned. David Gray (Gray, 1997) has suggested that stellar *non-radial pulsations* (manifesting as variations in the spectral line shapes) of the star 51 Peg are responsible for the observed Doppler velocity variations with a period of 4.23 d for this star, and the planetary companion does not exist. However, Mayor et al. (1997) argue that the star shows no photometric variations to one part in 5000 and shows no other overtones of the 4.23 d oscillations, effects that would be predicted by the non-radial pulsation model. Also, the variety of periods found for the other extrasolar stars with planets, all of nearly the same spectral type, shows that the observed radial velocity variations are not due to pulsations and the extrasolar planets are real.

6. Conclusions

The achievements of the past few years in the search for extrasolar planetary systems have been truly remarkable. A number of detections have been made and confirmed. The results obtained, on the physical and orbital parameters of the planets, were, however, totally unanticipated by any theories of planetary-system formation.

1. Some of the planets have masses much larger than that of Jupiter. These *superplanets* could not have formed by the normal collisional accumulation of rock and ice planetesimals and subsequent accretion from the protoplanetary disk. Perhaps the *superplanets* can form by *gravitational instabilities* in a cold massive protoplanetary disk, or by the *merger of many giant planets*. Another possibility is that they are low mass *brown dwarfs stripped down* to planetary masses by evaporative processes in the inner regions of the disk.

2. These massive planets are found too close to the parent star (as close as ~ 0.05AU). They could have formed farther out in the disk, and frictional processes resulted in their *orbital migration* to much shorter orbits.

3. While most of the planets have nearly circular orbits as is the norm for all major planets in our solar system, some planets have large orbital eccentricities. Highly eccentric orbits can result due to either *gravitational scattering* due to massive planets in the protoplanetary disk or, in a binary star system, due to the *perturbations caused by a distant companion star.*

4. Massive planets are found to exist in rather *small-sized orbits* ($\leq$ 1 AU). Gaseous planets in such orbits are likely to be significantly affected by thermal and non-thermal evaporative processes.

We are on the threshold of a revolution in our quest for extrasolar planetary systems and other worlds. The next step would be the *direct detection* of planets around nearby stars and the detection of Earth-sized extrasolar planets. Further improvements in technology and innovations in detection techniques and data analysis can be expected to make this possible. *Coronographic, interferometric and Lunar occultation measurments of extrasolar planetary system candidates, at longer infrared wavelengths, from a high-altitude, cold and dry site with low infrared background, like the one at Hanle, would be valuable.*

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