PLANETARY SYSTEMS

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Abstract. The past decade brought direct evidence of the previously surmised exoplanetary systems. A variety of planetary system types exist: those around pulsars, around both young and old main-sequence stars (as evidenced by planetesimal disks of the Beta Pictoris-type), and the mature giant exoplanets found in radial velocity surveys. The surprising diversity of the exoplanetary systems is addressed by several theories of their origin.

1. Planetary Systems around Pulsars

Distant planets have been predicted by the ancient doctrine of atomism. Democritus reportedly said: "In some worlds there is no Sun and Moon, in others they are larger than in our world, and in others more numerous. In some parts there are more worlds, in others fewer (...); in some parts they are arising, in others failing. There are some worlds devoid of living creatures or plants or any moisture." If this was a prescient prediction of planets (called worlds back then), accompanying various stars including binaries, it was correct. The first extrasolar planets have indeed been found in a strange system without a Sun (Wolszczan and Frail 1992, Wolszczan 1994). Nevertheless, the 1992 discovery of 2 Earth-class companions of the pulsar PSR B1257+12 was based neither on Democritus' prediction, nor on the work of N. Copernicus (in whose home town, Toruń, Wolszczan studied astronomy). It was fortuitous.

The pulsar planets are relatively uncommon (at most two systems per $\sim$ 500 pulsars known so far), yet the famous prototype remains up to now the only confirmed sensu stricto *planetary system* of several planets. Pulsar planets clearly demonstrate that planet formation occurs under a variety of potentially adverse conditions, e.g., in the aftermath of supernova explosion (Phillips & Thorsett 1994).

2. Planetary Material around Normal Stars

Since 1980s, there were very strong indications that planetary systems of some sort exist around a large fraction (now known to be $\sim$ 30%) of normal stars. The IRAS satellite discovered strong IR excess emission from what was later proved to be dust disks around many nearby stars, such as Vega, Fomalhaut, β Pictoris (β Pic), and others (more than a hundred have been identified subsequently, cf. review by Lagrange et al. 1999). The sizes of the disks, usually several hundred AU across, their central depleted regions (probably by planets located within several dozen AU), the amount of directly observed small meteoroids and dust, the mass of the inferred rock+ice planetesimals needed to replenish the directly observed dust, all the above make such systems resemble closely our Solar System. The strongest case can be made for β Pic, which resembles our system at the "early bombardment"

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epoch (age of $\sim 10^8$ yr). Direct spectroscopic evidence reveals up to several comet-sized planetesimals passing near the star's surface per week. Some of the β Pic grains, probably released by colliding and/or evaporating planetesimals, produce the 10-micron emission feature of a great similarity to that of Halley's comet. In addition, the edge-on dust disk imaged in scattered light and thermal radiation (12 and 18 micron bands) seems to be warped at distances < 100 AU from the star by an invisible planetary companion on a slightly inclined orbit (cf. references in a review by Artymowicz 1997, and the most recent HST/STIS observations by Heap et al. 1998). Nevertheless, a direct evidence for a planet is still lacking, even in this best-studied IR-excess system. We expect that some systems might originate from low surface density solar nebulae that are unable to form giant or any planets; those may be long-lived, undeveloped (or failed) planetary systems with only Moon- and comet-sized bodies. We do not know yet if most Vega-type star harbor true or failed planetary systems.

Several recent images taken in the sub-mm wavelengths indicate a possible existence of "blobs" of warm, radiating dust at some distance from β Pic, Vega, and Fomalhaut (Holland *et al.* 1998). Until confirmed, this observation must be viewed with caution, as the blobs may be instrumental or caused by background objects.

Imaging and modeling of the 10 Myr-old, IR-excess star HR 4796A by Koerner et al. (1998) and Jayawardhana (1998) revealed a medium sized disk of the β Pic–type seen at 18° short of edge-on, where most dust lies between 55 AU and some 120 AU from the star. It appears (Lagrange et al. 1999) that HR 4796A must be a transitional object between the massive and optically thick primordial accretion disks and later-stage, optically thin, post-T Tau disks (β Pic disks proper). If so, one should scrutinize the dust density distribution including possible disk density waves and edge features, diagnostic of the properties of planet(s) causing the central gap.

3. Exoplanets from Radial Velocity Surveys

By late 1998 13 candidate planetary systems have been found due to radial velocity variations (cf. an up-to-date listing by Schneider 1998, and a recent review by Marcy & Butler 1998), each with one confirmed planet. The curious lack of multiplanetary systems around normal stars may partly reflect observational limitations. Still, the working hypothesis or even a paradigm we used, that the our system is a typical planetary system, has been destroyed. Planets at least as massive 5–9 times the Jupiter mass ("superplanets") exist[1]. Planets on unfamiliar, very elongated orbits not only exist but are fairly common. Four superplanets, and two Jupiter-class planets, are on such elliptic orbits. The "hot Jupiter" or "51 Peg" family of systems has planets so close to the stellar surface that their temperatures exceed 1000 K.

[1] Inclinations are not known as a rule, which leaves us with the knowledge of only the minimum masses.

All these features, if not the existence of exoplanets themselves, were unexpected. Only one system remotely matches the sun-Jupiter system (47 UMa).

Existing theories are being verified and new ones created to account for the remarkable variety of planetary systems (e.g., Artymowicz 1992, Lin *et al.* 1996, Lin & Ida 1997, Artymowicz et al. 1998, Levison *et al.* 1998). Two common threads uniting the most promising theories are the processes of disk-planet and planet-planet interactions. Each can significantly affect mass, orbital radius, and eccentricity of a forming planet. Support for primordial disk-planet interaction as the dominant process comes mainly from: its necessity for giant gaseous planet formation, protoplanet migration that it causes (providing the explanation for hot Jupiters), and the natural explanation it offers for the mass-eccentricity correlation (planets much more massive than Jupiter will gain eccentricity from the resonant interaction, while smaller ones are circularized by the resonances and by mass inflow). Planet-planet (and companion star-planet) interaction may be the best explanation for Jupiter-class systems which have significant eccentricities. Alternative views proposed for extrasolar planet formation involve the early fragmentation of disks (Boss 1998) and the belief that they are not planets after all but brown dwarfs seen at a small inclination angle. Better statistics is needed to exclude or confirm these ideas. (Currently the mass histogram of substellar companions stands in favor of the planetary nature of companions in the sense of the standard core-instability mechanism; e.g., Marcy and Butler 1998).

We do not yet have the possibility to conduct spectroscopy of exoplanets (Burrows et al 1998). The question of how to best distinguish failed stars (brown dwarfs) from overgrown planets, or in fact how to best define a planet (based on mass, differentiated internal structure or origin?) remains wide open for future work, both observational and theoretical. Astrometry, interferometry, photometry of occultations, microlensing, and other techniques promise to paint in the near future a much more detailed picture of exoplanetary systems, possibly extending the list of surprises and wonders. One basic thing is already clear, however. More (perhaps much more) than 4% of sun-like stars have planets. We are not alone, at least not as a planetary system.

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