Notes on exoplanets

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Abstract. Our knowledge about exoplanets evolves rapidly. Here I give a short overview of some aspects of the exoplanet research and I also introduce shortly the reader to the Hungarian activities in the exoplanet field.

1. Introduction
This note summarizes the main points of the talk I had given in the 5th Workshop of Young Researchers in Astronomy and Astrophysics, held at Eötvös University, Budapest, Hungary. The talk was an introductionary talk to the session ‘Celestial Mechanics and Exoplanets’ in which I reviewed the methods of planet detection, the discovery statistics, transit spectroscopy results, and I listed the observed secondary eclipses and the most important properties of exoplanets. Because of lack of space, the present note does not reflect the whole content of that talk.

One can found recent, more detailed overviews about the properties of exoplanets in Udry & Santos (2007), Santos (2008), Baraffe, Chabrier & Barman (2010), Schneider (2010) and Swift et al. (2010).

2. Notes on exoplanets
2.1. Number of known exoplanets and exoplanetary systems
The following statistics is based on Schneider (2010). Up to now (2010 Feb 28) we know 430 confirmed planets, 69 unconfirmed or controversial planets and six free-floating planets. Most of the exoplanets (339 out of 430) were discovered by the so-called radial velocity method. Although this method gives only the lower mass limit for the companion object, we can assume that the orbits of these planets are really close to the line of the sight and they remain in the planetary mass range even if the inclination is little bit lower than 90 degrees. Nine planets were discovered by the timing method which also has the same problem, i.e. gives only the lower mass limit for the suspected planetary mass object. With other methods (including microlensing, direct imaging, etc.) further nine objects were detected. 70 objects show transits: their orbits are oriented in space such a way that a certain small part of the orbit is in front of the stellar disc, therefore we can observe periodically that the planet moves in front of the apparent stellar disc covering a certain part of the star and causing a decrease in the observable stellar flux. The detailed analysis of the flux variation – combining with spectroscopic measurements – can tell us the radius as well as the orbital inclination of the planet and the planet-star distance, too. In this case we are able to determine the real mass of the planet and hence its mean density which is important for studies of the internal structure and evolution of planets. As one can easily see,
the chance to have a transit is quite small (it is proportional to $1/a$, where $a$ is the semimajor axis of the planet orbit: the more distance the planet from the star, the less the chance to observe it by transit method). That is why it is not surprising, that 67 transiting exoplanets have orbital period shorter than 10 days and there are only three known exoplanets among the 70 known such ones which have orbital period longer than 10 days (HD 17156b: $P = 21.22$ days, Fisher et al. (2007), HD 80606b: $P = 111$ days Moutou et al. (2009) and CoRoT-9b: $P = 95$ days, Deeg et al. (2010) – only this latter one was discovered by transit method, the two other ones were detected by radial velocity method first and the transits were observed subsequently).

2.2. The smallest known exoplanets

There is a natural high interest in Earth-like exoplanets. The currently known smallest exoplanets belong to the class of ‘Super-Earths’ (planets with 1-10 Earth-masses, see Valencia, O’Connell & Sasselov 2006). So far the smallest known exoplanet is CoRoT-7b, which was detected by its transits from space using the CoRoT satellite, and it has 1.7 Earth-radius and $4.8 \pm 0.8$ Earth-masses (Léger et al. 2009, Queloz et al. 2009). Interestingly, the average density of this exoplanet is quite similar to the one of the Earth (Queloz et al. 2009), suggesting that its internal structure can be similar to the Earth’s one. It seems that CoRoT-7b, which orbits its K-type host star during only 20 hours (the orbital radius is only $\sim 4$ times larger than the stellar radius) cannot be a remnant of a hot-Jupiter or hot-Neptune which would lost its envelope due to the radiation of the host star (Lammer et al. 2009). An interesting question arises in Barnes et al. (2010): is CoRoT-7b a real Super-Earth or is it a super-Io? If it were a super-Io, then heated tidally by its host star – it would show volcanism (Barnes et al. 2010). Other authors state that CoRoT-7b can be a remnant of a former ocean-planet (Wagner et al. 2009).

The surface gravity on this exoplanet is 1.4-2 times larger than on the surface of the Earth (depending on its mass). The surface temperature in the substellar point is about 1800-2600 K and it decreases down to $\sim 50$ K in the coolest point on the night side (Léger et al. 2009). However, the temperature profile from the hottest point to the coolest one is thought to be continuous, so somewhere the temperature is between 0-50 °C. Theoretically, there can be water in this region, but it seems to be unlikely. Of course, this is true if and only if the planet rotational period is synchronized with the orbital period. However, one can assume that this is the case, because tidal locking will occur on the timescale (Guillot et al. 1996):

$$t_{lock} = \frac{2\pi Q_{star}}{P_{rot}} \frac{R_{star}^3}{GM_{star}} \frac{M_{planet}^2}{M_{star}} \left( \frac{a}{R_{star}} \right)^6$$

where $Q_{star} \sim 10^5$ (Guillot et al. 1996), $P_{rot}$ is the rotational period of the star, $G$ is the gravitational constant, $M_{star}$ and $R_{star}$ are the stellar mass and radius, $a$ is the planet’s orbital semimajor axis, and $M_{planet}$ is the planet’s mass. Substituting the values of CoRoT-7b system taken from Léger et al. (2009) and (Queloz et al. 2009) we have that the tidally locked spinning of the planet occurs within 50-60 Myrs. Since the stellar age is between 1.2-2.3 Gyrs (Léger et al. 2009), we can assume that the planet is already tidally locked (however, it is difficult to investigate this issue observationally yet).

The second smallest known planet is also a transiting exoplanet and it was announced recently (GJ 1216b Charbonneau et al. 2009). This object orbits an M-dwarf star. It has a mass of 6.55 $M_{Earth}$ and a radius 2.68 $R_{Earth}$ (Charbonneau et al. 2009). So far, only one star has been found in the habitable zone (Gliese 581d, see Mayor et al. 2009).

2.3. Periods and eccentricities

The periods of the known exoplanets range from 0.79 days (WASP-19b) to 876 years (Fomalhaut b). By this time, no period variation was found in any exoplanets.
The known planets and dwarf planets in our Solar System have a slightly eccentric orbit. Mercury has the most eccentric orbit among the giant planets in our Solar System \((e = 0.205)\). Among the dwarf planets we can find small and large eccentricities as well (Ceres has \(e = 0.080\) while Eris has \(e = 0.442\), Pluto has \(e = 0.249\) and Haumea has \(e = 0.189\)). There is a lower limit for eccentricity (and the natural \(e < 1\) upper limit also exists). The closest point of the planetary orbit to the host star is given by

\[ q = a (1 - e) \]  

where \(q\) is the closest star-planet distance. There is no orbit for which \(q < R_{\text{star}}\) (otherwise the planet would fall in the star). From Kepler’s third law we know that \(a \sim P^2/3\), so there is a lower period limit for every eccentricity (and stellar size). In the region of larger eccentricities, we cannot see very short period planets. It is remarkable that there are planets with very large eccentricities. Many examples are known with \(e > 0.1\), a few dozens are known with \(e > 0.5\) and three exoplanets have larger eccentricity than 0.9.

The gravitational braking (a general relativity effect) is negligible in exoplanets orbiting a normal star. However, the semimajor axis and the eccentricity continuously decrease due to the tidal interaction with the host star. After a certain time the eccentricity becomes zero. This process is called circularization. Its time-scale is given by

\[ \tau_c \sim \frac{4}{63} \sqrt{\frac{a^3}{G M_{\text{star}} M_{\text{planet}}}} \left( \frac{a}{R_{\text{planet}}} \right)^5 \]  

where \(a\) is the semi-major axis of the planet’s orbit, \(M_{\text{star}}, M_{\text{planet}}\) is the mass of the star and the planet, respectively, \(R_{\text{planet}}\) is the planet’s radius, and \(Q_p \sim 1/2\epsilon\), where \(\epsilon\) is the angle between the line of centers and the tidal bulge (Rasio et al. 1996). Typical circularization time for a hot Jupiter is about 20 million years only. For a similar object in a larger orbit, let us say \(a = 0.4\) AU the circularization period is much longer, it is about typically about 13 Gyr. Since a solar-like star spends about 9-12 Gyrs on the main sequence (depending on its mass and chemical composition) burning hydrogen in its center, we can see that if a normal Jupiter (orbiting the star in a distance of 0.4 AU or even more) had initially an eccentric orbit, then this eccentric orbit will not be destroyed and circularized by the planet-star tidal interaction during the main-sequence lifetime of the host star.

Transiting exoplanets are very promising targets to study the effect of gravitational perturbations. If there is no such or other kind of perturbations, i.e. if we have pure Keplerian-motion, then the consecutive revolutions will occur strictly periodically. But the orbital period and other orbital elements of the exoplanets can/will change due to the gravitational perturbation effects. These changes will lead to change in the transit light curve shape and/or to variations in the orbital period, so the consecutive transit instants will deviate from a linear ephemeris, and the length and the shape of the consecutive transit events will differ from each other. (These are usually called TTV-variations, but some authors separate the effects as TTV (Transit Timing Variation), TDV (Transit Depth Variation) and TDuV (Transit Duration Variation) etc). Therefore there are rooms for such investigation, but the time-scales and amplitudes of this kind of variations are in a very wide range (ranging from \(~1\) second to centuries in the timescales and \(~\)second to weeks in the amplitude of the O-C variations, see Steffen 2006). The perturbing third body can be an exomoon, another exoplanet in the system, or a brown dwarf, normal star or a compact object in a more distant orbit revolving the host star: the number of possible configurations and orbits are infinite. A recent review of the most important papers of the field can be found in Csizmadia et al. (2010). It is interesting to note at this conference that the school of celestial mechanic led by Prof. B. Érdi has also already contributed to the field with important and valuable investigations (many times in collaboration
with the Vienna group led by Prof. R. Dvorak), see e.g. Dvorak & Süli (2002), Sándor, Süli & Erdi (2005), Sándor (2006), Erdi, Sándor & Süli (2007), Erdi et al. (2007), Sándor et al. (2007), Süli, Dvorak, Erdi (2007), Schwarz et al. (2007a,b), Erdi et al. (2009), Schwarz, Süli & Dvorak (2009a, b) Dobos, Nagy & Orgoványi (2010). Maybe one of their most important contributions is “the stability catalogue of the habitable zones in extrasolar planetary systems” (Sándor et al. 2007). The present author with his co-workers investigated the TTVs in the CoRoT-1b system (Csizmadia et al. 2010). One of the most promising systems for TTV-studies is TrES-2. TTVs of TrES-2b were predicted by Freistetter, Süli & Funk (2009). Maybe inclination variation was found by Mislis et al. (2010) in this exoplanetary system, but the claim was questioned by Scuderi et al. (2010). Since the object is a Kepler target, the issue may be clarified soon.

The Hungarian Kepler team at the Konkoly Observatory is also contributed to the field by investigating the detectability of exomoons and exorings by different methods (photometry, transit timing and transit duration variations, applying the Rossiter-McLaughlin effect, see e.g. Simon, Szatmáry & Szabó 2007, Simon, Szabó & Szatmáry 2009).

One of the most successful ground-based exoplanet teams is the Hungarian Automated Telescope-team, led by Gáspár Bakos. They have already discovered 13 transiting exoplanets (and one more during RV-follow-up; note that WASP-11b = HAT-P-10b). So far the HAT team has detected the shallowest (4 mmag, Bakos et al. 2008) transit from ground – compare to the 0.4 mmag deep of CoRoT-7b detected from space (Léger et al. 2009), which shows that to discover very small planets around FGK dwarfs we have to go to space.

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