Chapter 6

Direct imaging of extra-solar planets

Direct imaging for extra-solar planets means that emission from the planet can be spatially resolved from the emission of the bright central star. The two key requirements for a detection of extra-solar planets are

- a high contrast,
- a high spatial resolution.

A good example is the detection of the planetary system around the star HR 8799 (see Slide 6.3).

If a substellar companion is detected via direct imaging then these types of observations may provide information about it:

- from the IR-brightness one can determine the spectral energy distribution of the thermal emission and derive the surface temperature,
- from the intensity and polarization of the reflected light one can derive albedos and surface scattering properties,
- variability studies in multiple spectral pass-bands provide information about phase effects, seasonal effects, rotational effects and weather changes (patchy clouds),
- a spectral analysis allows to gain information about the atmosphere or surface composition, and one may also search for biosignatures.

In principle, the direct imaging techniques can also be used to measure the reflex motion of the star and derive the mass of the planet if the astrometric precision of the instrument is good enough. So far, this has proven difficult to measure, because the required precision is not yet achievable, although the Gaia astrometric space mission may be able to produce such observations in the near future.

6.1 Science requirements

Depending on the planet type and the science goals the instrument must achieve different requirements. We distinguish three cases:

- young planets for which the thermal radiation produced by self-contraction is the dominant energy source,
– the thermal radiation of old planets for which the irradiated and reprocessed energy from the central host star is the main energy source; old just means that internal energy sources are not dominant,
– the reflected light of planets.

**Thermal radiation from young planets.** Newly formed planet will be hot because of the potential energy which is transformed during the formation and contraction phase into thermal energy. In general the evolution of the thermal luminosity is a function of planet mass and age (as will be discussed in a following chapter). An approximate description is

\[
L_P(M_P, t) \approx 10 (M_P [M_J])^2 \frac{1}{t\,[\text{yr}]} \quad \text{for} \quad t > 1 \, \text{Myr}.
\]

The luminosity of a planet \( L_P \) shows roughly an exponential decay and \( L_P \) is larger for higher mass planets. The luminosity evolution goes together with a radius and surface temperature evolution, and the planet to star luminosity contrast is given by:

\[
C_{\text{young}} = \frac{L_P(M_P, t)}{L_S} = \frac{R_P^2(M_P, t) T_P^4(M_P, t)}{R_S^2 T_S^4}.
\]

Note, that this expression applies to the “bolometric” contrast, i.e., referring to the ratio of total power emitted across all wavelengths. If we observe at long wavelengths, in the Rayleigh-Jeans limit, the flux contrast is

\[
C_{\text{young}}(\lambda \gg \lambda_{\text{max}}) = \frac{F_P(\lambda \gg \lambda_{\text{max}})}{F_S} = \frac{R_P^2(M_P, t) T_P(M_P, t)}{R_S^2 T_S}.
\]

The brightness and temperature of young planets are independent of the separation \( d_P \) and the luminosity of the star \( L_S \). Therefore, young hot planets at large separation are relatively easy to detect, like in the case of the HR 8799 system. Also, a young contracting giant planet around a low mass star would be an easy target for direct imaging. Unfortunately, there are not many young stellar systems in the solar neighborhood which may harbor young, bright, self-contracting planets.

**Thermal radiation from irradiated planets.** The energy emitted by the thermal radiation of an old planet is assumed to be equal to the irradiated energy, since one can neglect the internal energy sources. For planets with \( T < 1000 \, \text{K} \) the maximum of the thermal radiation is in the mid- or far-infrared spectral region. The contrast between planet and sun was already derived for Solar System objects in Section 4.2. The contrast is less extreme for the Rayleigh-Jeans part of the Planck spectrum of the planet at long wavelengths in the mid-IR or far-IR:

\[
C_{\text{old}}(\lambda \gg \lambda_{\text{max}}) = \frac{F_P(\lambda \gg \lambda_{\text{max}})}{F_S} = \frac{R_P^2 \, T_{\text{eq}}}{R_S^2 \, T_S} = \left( \frac{1-A_B}{4} \right)^{1/4} \left( \frac{R_P}{R_S} \right)^2 \left( \frac{R_S}{d_P} \right)^{1/2},
\]

where we have used the following relation for the equilibrium temperature

\[
T_{\text{eq}} = \left( \frac{1-A_B}{4} \right)^{1/4} \left( \frac{R_S}{d_P} \right)^{1/2} T_S.
\]
For shorter wavelength $\lambda < \lambda_{\text{max}}$ there is an exponential drop-off of the planet brightness and the detection becomes very difficult. The flux ratio at long wavelengths in the Rayleigh-Jeans regime depends on $1/\sqrt{d_P}$. The peak wavelength of the Planck curve also varies with $\lambda_{\text{max}} \propto 1/\sqrt{d_P}$. Thus, at shorter wavelengths there is a good chance to observe the shorter period planets. Thus, the detection of the thermal emission of irradiated planets requires high contrast capabilities and high spatial resolution. For a planet with $T_{\text{eq}} \approx 300$ K (in the habitable zone) one needs to observe in the mid-IR to far-IR range at wavelength of about 5 \(\mu\text{m}\) or longer.

Reflected radiation from planets. The reflected light is according to Section 4.3

$$C_{\text{ref}} = \frac{F_P}{F_{\text{star}}} = A_g(\lambda) f(\alpha) \frac{R_P^2}{d_P^2}.$$  

The reflected light from a planet depends strongly on the separation $C_{\text{ref}} \propto 1/d_P^2$. Further there are also the phase dependence described by $f(\alpha)$ and the spectral dependence of the reflectivity or geometric albedo $A_g(\lambda)$ which need to be considered.

**Figure 6.1:** Contrast as function of wavelength for young and old planets.

**Typical planet to star contrast ratios for a system at 10 pc.** Table 6.1 recalls some values from Section 4 for a solar system analog at 10 pc. The contrast is for a given system configuration independent of the distance $D$ but the apparent separation behave like $\propto 1/D$ and the flux of the star and the planet like $\propto 1/D^2$.

For stars with low luminosity the planet to star contrast is less extreme for a self-luminating, young planet. For “old” planets around low luminosity stars the contrast depends mainly on the separation and is therefore like for bright stars if the separation is the same. However, planets with the same surface temperature like Earth will have a smaller separation and therefore the contrast is more favourable for a detection.

**Requirements on the telescope size from the spatial resolution.** The angular separation of a planet is equal to $d_P/D$, where $D$ is the distance to a planetary system. For a planet at 1 AU the angular separation is only 0.1 arcsec for a system at 10 pc and only 0.01 arcsec at 100 pc. Of course planets further out, at 10 AU, or 100 AU will have
Table 6.1: Rough estimates for the expected contrast for Earth-like and Jupiter-like extrasolar planets and Earth-sized and Jupiter-sized young, hot planets.

<table>
<thead>
<tr>
<th>planet</th>
<th>separation at 10 pc</th>
<th>$C_{ref}$</th>
<th>$C_{near-IR}$</th>
<th>$C_{far-IR}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>“old planets”</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>exo-Earth</td>
<td>0.1 arcsec</td>
<td>$2 \cdot 10^{-10}$</td>
<td>$2 \cdot 10^{-10}$</td>
<td>$4 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>exo-Jupiter</td>
<td>0.52 arcsec</td>
<td>$1 \cdot 10^{-9}$</td>
<td>$1 \cdot 10^{-9}$</td>
<td>$2 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>“young, hot planets”</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 K, $R_E$</td>
<td>0.1 arcsec</td>
<td>$2 \cdot 10^{-10}$</td>
<td>$5 \cdot 10^{-6}$</td>
<td>$1 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>1000 K, $R_J$</td>
<td>0.52 arcsec</td>
<td>$1 \cdot 10^{-9}$</td>
<td>$5 \cdot 10^{-4}$</td>
<td>$1 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>

a correspondingly larger angular separation. In any case, a high angular separation is desirable to resolve the inner regions of planetary systems.

The inner working angle (IWA) of a high contrast imager is defined as the minimum angular separation at which a faint object can be detected near a bright star $\theta_{IWA} = 2 \left( \frac{\lambda}{D} \right)$. The factor 2 applies for the best high contrast instruments available today. Many instruments are not optimized for this task and then this factor is 3 or 5 with a correspondingly larger IWA. Table 6.2 gives some examples for existing and future telescopes for the inner working angle just considering wavelengths and telescope sizes. This table shows that the VLT has, in principle, enough spatial resolution to search for scattered light at 0.6 $\mu$m of a Sun-Earth analog out to a distance of 30 pc, while for the thermal radiation at 5 $\mu$m the object must be closer than 4 pc to be resolved from the hot star. However, there are only 4 solar type stars within this distance. Therefore, a 38 m telescope is required to find the thermal radiation of an Sun-Earth analog within 10 pc.

Table 6.2: Inner working angle (IWA) in milli-arcsec [mas] for different telescopes and wavelengths $\lambda$.

<table>
<thead>
<tr>
<th>telescope</th>
<th>$D$</th>
<th>IWA 0.6 $\mu$m</th>
<th>IWA 1.6 $\mu$m</th>
<th>IWA 5 $\mu$m</th>
<th>IWA 10 $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>HST</td>
<td>2.5 m</td>
<td>96 mas</td>
<td>260 mas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>JWST</td>
<td>6.5 m</td>
<td>100 mas</td>
<td>310 mas</td>
<td>620 mas</td>
<td></td>
</tr>
<tr>
<td>VLT</td>
<td>8 m</td>
<td>30 mas</td>
<td>80 mas</td>
<td>250 mas</td>
<td>500 mas</td>
</tr>
<tr>
<td>E-ELT</td>
<td>38 m</td>
<td>6.3 mas</td>
<td>17 mas</td>
<td>53 mas</td>
<td>105 mas</td>
</tr>
</tbody>
</table>
The requirements on contrast and separation for the detection of an extra-solar Earth-like planet or a Jupiter-like object are shown in Fig. 6.2. The inner working angle of the telescopes given in Table 6.2.

Figure 6.2: Contrast vs. separation for Earth-Sun and Jupiter-Sun analogs and young, self contracting planets at 10 pc.