Exoplanets
Direct imaging

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Direct method of exoplanet detection

• Direct imaging
  – The image of the planet is searched for in the field of the star

• Observational challenges
  – Planet-star luminosity contrast
  – Planet-star angular separation

• Both challenges set strong constraints on the observational techniques
  – The luminosity contrast can be quantified with simulations of stellar and planet spectra

Direct imaging: observational challenges

• Luminosity contrast
  \( \frac{L_p}{L_*} \)

  – Optical spectral band
    \( \Phi(t) = 1 - \sin i \sin \left( \frac{2\pi t}{P} \right) \)
    reflected stellar radiation depends on the orbital phase contrast \( \sim 10^9 \text{--} 10^{10} \)

  – Infrared spectral band (\( \sim 10 \mu m \))
    intrinsic planetary emission contrast \( \sim 10^6 \text{--} 10^7 \)

Black body flux (in units \( 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1} \)) of some Solar System bodies as “seen” from 10 pc. A putative hot Jupiter is also shown. The planets have two peaks in their spectra. The short-wavelength peak is due to sunlight scattered from the planet using the planet’s albedo. The long-wavelength peak is from the planet thermal emission estimated by a black body of the planets’s effective temperature.
Predicted planet/star flux ratios versus wavelength
Models for giant planets orbiting a solar-type star, cloud effects included

Planet with 1 $M_J$, age 5 Gyr, as a function of orbital distance

Predicted planet/star flux ratios versus wavelength
Models for giant planets orbiting a solar-type star, cloud effects included

5 Gyr planet at 4 AU as a function of planet mass

Direct imaging: observational challenges

- Planet-star angular separation
  Angular separations can be estimated as a function of stellar distance, $l$, and orbital semimajor axis of the planet, $a$
  \[ \vartheta = \arctan \frac{a}{l} \]
  Typical values are lower than 1 arcsec
e.g., the Earth-Sun separation as seen from 20 pc is 50 mas

  The luminosity contrast makes hard to attain the theoretical diffraction limit $\lambda/D$
  \[ D : \text{telescope diameter} \]
  \[ \lambda : \text{wavelength of the observations} \]

  The angular separations are significantly smaller than the optical blurring of astronomical images introduced by the Earth’s atmosphere.
Angular separation and luminosity contrast

The maximum luminosity contrast that can be attained for a given instrumental setup decreases with decreasing angular separation.

Direct imaging of exoplanets

- **Observable quantities**
  - Orbital parameters
    - Given the stellar distance, one can determine the orbital semimajor axis $a$ from the angular separation.
    - Given $a$, the orbital period $P$ is inferred with the third Kepler’s law.
  - Effective temperature
    - The effective temperature can be determined from the energy distribution of the planet spectrum.
    - The spectral distribution can be estimated by comparing photometric measurements taken in different spectral bands.
  - Emission spectrum of the planet
    - If the source is sufficiently bright, a spectrum can be taken.
    - The spectrum can be used to study the (atmospheric) chemical composition of the planet.

- **Model-dependent planetary parameters**
  - Planet mass and size
    - Mass and size can be estimated combining the measurement of planet emissivity with a model of planet evolution.
    - The error on the masses estimated in this way can be quite large and is also related to the uncertain age of the system.

- **Advantages of the direct imaging method**
  - Allows us to study planets distant from the star.
  - Not affected by the temporal baseline bias (a single observation yields $a$, from which one can determine $P$).
  - Not affected by variability of the central star.
  - Best way to obtain direct informations on the properties of exoplanets.

Direct imaging of exoplanets

• Observational bias
  – Due to the observational challenges specific of the direct imaging method, the following types exoplanets are preferentially found:
    1. orbiting nearby stars
    2. with wide orbits
    3. with high intrinsic emission (e.g. young and massive)
    4. with high planet/star mass ratio $M_p/M_*$

Direct imaging of exoplanets
**Direct imaging of exoplanets:**
Techniques to deal with the luminosity contrast

- Coronagraphic techniques
  - High contrast can be achieved by rejecting the stellar light from the area of interest in the focal plane
  - The technique, employing some form of mask in the telescope focal plane, is referred to as coronagraphy
  Coronagraphy was originally developed to study solar corona, a tenuous structure of highly ionized gas that surrounds the Sun, which is hard to observe due to the extremely high luminosity contrast with the solar disk

Ideally, a coronagraph coupled to an adaptive optics system would perform as if placed above the atmosphere

- The Lyot coronagraph
  - In the original Lyot coronagraph, the first objective lens forms an image of the solar disk and corona, and an occulting mask blocks the image from the disk
  - Light diffracted from the mask swamps faint off-axis structure
  - A field lens re-images the objective lens and its diffraction pattern
  - A “Lyot stop” intercepts the diffraction ring while allowing most of the light from the surrounding structure to pass
  - The second objective lens relays the resulting image onto the detector

**Direct imaging of exoplanets:**
Techniques to deal with the luminosity contrast

- Recent developments of coronagraphic techniques
  - Alternative concepts for high-rejection coronagraphs have been stimulated by the interest in exoplanet imaging
  - A variety of designs theoretically able to achieve $10^{10}$ contrast within $5 \lambda/d$ are being developed

**Direct imaging of exoplanets:**
The challenge of angular resolution

- Astronomical seeing
  - Turbulent mixing in the Earth's atmosphere varies the optical refractive index over very short time scales (~ms)
  - As a result, a point-like astronomical source is seen as a disk (the “seeing”) that is larger than the theoretical diffraction limit $\lambda/D$
  - The FWHM of the seeing disk measures the quality of the sky at a given time and location
  - The best conditions on Earth give a FWHM of ~0.4 arcsec and are found at high-altitude observatories on small islands (e.g., Mauna Kea or La Palma)

**Direct imaging of exoplanets:**
The challenge of angular resolution

- Solutions to the seeing problem:
  1) Space observations
  2) Adaptive optics + speckle imaging techniques
Direct imaging of exoplanets: Techniques to increase the angular resolution from ground

- Adaptive optics
  - A wavefront distorted by the atmosphere is reflected from a deformable mirror with hundreds of actuators glued to its rear
  - The system operates in close loop, measuring the residual wavefront error after reflection using a wavefront sensor
  - Corrections are applied such as to leave the wavefront flat, updated thousands of times per second to match the rapidly changing effects of atmospheric turbulence

- Speckle imaging techniques
  - In the image stacking, the short exposure images are lined up by the brightest speckle and averaged together to give a single image; in the Lucky Imaging approach, only the best few short exposures are selected
  - Speckle interferometry makes use of Fourier analysis to obtain the high-resolution structure of the object from the speckle patterns
  - Practical procedure
    - Record many frames rapidly
    - Take the power spectrum of each frame and average
    - Divide the power spectrum of the target by the power spectrum of a point source
    - Fit a model (e.g., planet around a central star) to the true Fourier transform of the object

Direct imaging of exoplanets: Techniques to increase the angular resolution from ground

- Speckle imaging describes a range of high-resolution astronomical imaging techniques that can dramatically increase the resolution of ground-based telescopes
- The principle of all the techniques is to take very short exposure images of astronomical targets, and then process the images so as to remove the effects of astronomical seeing

Examples

- Fomalhaut b discovered in 2008 from a re-analysis of previous HST data
  - $a = 119$ AU; $e = 0.11$; $M = 3 M_J$; $P = 870$ yr
  - Fomalhaut: $d = 8$ pc
  - Kalas et al. (2008)
Direct imaging of exoplanets

Examples

AB Pic b

\[ M = 13 \, M_J \]

close to the brown dwarf boundary
\[ a > 80 \, \text{AU} \]

AB Pic, K2 V

\[ d = 47 \, \text{pc} \]

Discovered using near-infrared Lyot coronagraphic observations

NACO at ESO-VLT

Chauvin et al. (2005)

A multiple planetary system detected with the direct imaging method

HR 8799 b, c, d

\[ M = 7, 10, 10 \, M_J \]
\[ a = 68, 38, 24 \, \text{AU} \]
\[ d = 39 \, \text{pc} \]

Coronagraphic and speckle imaging techniques in the infrared

(Marois et al. 2008)

Summary of results

GJ 504 b

\[ M = 4 \, M_J \]
\[ a = 44 \, \text{AU} \]

Sun-like star GJ 504
\[ d = 17.6 \, \text{pc} \]

Lowest temperature (510 K) exoplanet observed with direct imaging

Adaptive optics, occulting mask, near infrared

Kuzuhara et al. (2013)
Direct imaging of exoplanets

Summary of results

So far, only a few tens of planets have been detected with the direct imaging method. These planets are quite massive and distant from the central star.

Future perspectives

- Infrared space interferometers
- Nulling interferometry
- Occulters
- Space projects (suspended)
  - ESA Darwin
  - NASA Terrestrial Planet Finder (TPF)
- Ground based projects
  - many projects active or under development
  - examples:
    - SPHERE at ESO VLT (active)
    - EPICS at ESO E-ELT (under development)