Direct Imaging

Kalas et al. (2008)

Lagrange et al. (2009)

Marois et al. (2008, 2010)

Chauvin et al. (2004)

Lafrénière et al. (2010)
Direct Imaging

Thalaman et al. (2009)

Wagner et al. (2016)

Rameau et al. (2013)

Macintosh et al. (2014)

Bailey et al. (2013)
Why bother?

direct Imaging
Why bother?

*Systems with substellar primaries excluded

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Slide from DeRosa (2016)
The primary observables are:

- Separation (usually expressed in seconds of arc)
- Contrast (usually expressed as delta magnitude)
Quick Refresher on angles and magnitudes

\[ d = \frac{1}{p} \]

- Distance \( d \) (parsecs)
- Parallax \( p \) (arc seconds)

**primary resources for parallaxes:** HIPARCOS (GAIA first data released, 2nd release in 2018)
Various other near-IR parallax programs

usually find this stuff with VizieR online search
Quick Refresher on angles and magnitudes

distance $d$ (parsecs)

$a$ (arc seconds)

\[ a'' = \frac{D\text{(AU)}}{d} \]

\[ D\text{(AU)} = da \]
Quick Refresher on angles and magnitudes

How far is this planet from Earth, if the planet separation is 13 AU?
Quick Refresher on angles and magnitudes

in practice, measure separation in pixels ... then use pre-determined “plate scale”

NIRC2/Keck-2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range</td>
<td>0.9-5.3 microns</td>
</tr>
<tr>
<td>Field of view</td>
<td>10x10 arcsec (narrow camera)</td>
</tr>
<tr>
<td></td>
<td>20x20 arcsec (medium camera)</td>
</tr>
<tr>
<td></td>
<td>40x40 arcsec (wide camera)</td>
</tr>
<tr>
<td>Pixel scale</td>
<td>0.009942 arcsec/pixel (+/- 0.00005&quot;)</td>
</tr>
<tr>
<td></td>
<td>0.019829 arcsec/pixel</td>
</tr>
<tr>
<td></td>
<td>0.039686 arcsec/pixel</td>
</tr>
<tr>
<td>Filters</td>
<td>z, Y, J, H, K, Ks, Kp, Lw, Lp, Ms, Hel, Pa, H2O, PAH, Br_alpha, Br_alpha_cont</td>
</tr>
</tbody>
</table>
The primary observables are:

- Separation (usually expressed in seconds of arc)
- Contrast (flux ratio often expressed as delta magnitude)
in practice, measure the “counts” ratio and piggyback off known magnitude of star

\[ \Delta m_K \sim 8 \]
Quick Refresher on angles and magnitudes

Magnitudes are evil and designed to confuse us -- especially theorists.
magnitudes

\[ F = \frac{L}{4\pi d^2} \]

\[ m_{\text{bol}} = -2.5 \log_{10} \left( \frac{L}{4\pi d^2} \right) + C \]
\[ = -2.5 \log_{10} L + 5 \log_{10} d + C \]

\[ M_{\text{bol}} = -2.5 \log_{10} L + 5 \log_{10} 10 + C \]

\[ m_{\text{bol}} - M_{\text{bol}} = 5 \log_{10} \left( \frac{d}{10 \text{ pc}} \right) \]

- L: total power output over all wavelengths
- F: bolometric flux
- m: apparent bolometric magnitude
- M: absolute bolometric magnitude
- M: absolute bolometric magnitude
• In practice, we measure the flux over specific bands determined by the instrument (filters, etc.)

\[
F_{\text{obs}} = \int_0^\infty f(\lambda) s(\lambda) d\lambda
\]

\[
m_V = -2.5 \log_{10} \left( \int_0^\infty f(\lambda) s_V(\lambda) d\lambda \right) + C
\]

The constant depends on filter and normalization of the photometric system being used
• many different filter sets: filter $X$ at one telescope may not be the same as filter $X$ at another!

• photometric systems have various normalizations (aka “zero-points”) with Vega’s spectrum being the most common

$$ZP = -2.5 \log_{10} \left( \int_{0}^{\infty} f_{\text{Vega}}(\lambda) s_{V}(\lambda) d\lambda \right)$$

• HST has their own (more sensible)
\[ m(AB) = -2.5 \log(F_\nu) - 48.60 \]
\[ m(ST) = -2.5 \log(F_\lambda) - 21.10 \]
# Flux Density Conversion

(\(E\) in keV; \(\lambda\) in Å)

<table>
<thead>
<tr>
<th>(S_\nu) (Jy)</th>
<th>(S_\nu)</th>
<th>(1.51 \times 10^3 S_\nu/E)</th>
<th>(1.51 \times 10^3 S_\nu/\lambda)</th>
<th>(3.00 \times 10^{-5} S_\nu/\lambda^2)</th>
<th>(10^{-23} S_\nu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_\nu) (photons cm(^{-2}) sec (^{-1}) keV(^{-1}))</td>
<td>(f_\nu)</td>
<td>(6.63 \times 10^{-4} E f_\nu)</td>
<td>(8.07 \times 10^{-2} E^2 f_\nu)</td>
<td>(1.29 \times 10^{-10} E^3 f_\nu)</td>
<td>(6.63 \times 10^{-27} E f_\nu)</td>
</tr>
<tr>
<td>(f_\lambda) (photons cm(^{-2}) sec (^{-1}) Å(^{-1}))</td>
<td>(f_\lambda)</td>
<td>(6.63 \times 10^{-4} \lambda f_\lambda)</td>
<td>(8.07 \times 10^{-2} \lambda^2 f_\lambda)</td>
<td>(1.99 \times 10^{-8} \lambda f_\lambda/\lambda)</td>
<td>(6.63 \times 10^{-1} \lambda f_\lambda)</td>
</tr>
<tr>
<td>(F_\lambda) (erg cm(^{-2}) sec (^{-1}) Å(^{-1}))</td>
<td>(F_\lambda)</td>
<td>(3.34 \times 10^{-4} \lambda^2 F_\lambda)</td>
<td>(4.06 \times 10^6 \lambda^3 F_\lambda)</td>
<td>(5.03 \times 10^7 \lambda F_\lambda)</td>
<td>(F_\lambda)</td>
</tr>
<tr>
<td>(F_\nu) (erg cm(^{-2}) sec (^{-1}) Hz(^{-1}))</td>
<td>(10^{23} F_\nu)</td>
<td>(1.51 \times 10^{26} F_\nu/E)</td>
<td>(1.51 \times 10^{26} F_\nu/\lambda)</td>
<td>(3.00 \times 10^{18} F_\nu/\lambda^2)</td>
<td>(F_\nu)</td>
</tr>
</tbody>
</table>
Key points:

• flux is weighted by filter response (can have significant structure)

• For Vega (and all A0V type stars) \( m_i = m_j = m_v \) (for all i,j filters)

• “zero point” of system defined by Vega’s spectrum

• in practice, you don’t observe Vega, but rather sets of photometric “standard stars”.

• In the Vega system, equal magnitudes do not necessarily have equal fluxes. (they do for ST and AB mags)

• “colors” are delta magnitudes
common filters for direct imaging of exoplanets
The primary observables are:

- Separation (usually expressed in seconds of arc)
- Contrast (flux ratio often expressed as delta magnitude)
What you can directly infer:

- Orbital elements: $P$, $a$, $e$, $w$, $T_o$, $i$, and $\Omega$
  
  ...if you wait long enough

- With $a$ and $P$, and estimate of $M_s$, you get $M_p$ (Kepler’s third law)

- Spectra or “colors” (reflected and emitted)
  
  $\rightarrow$ Atmospheric properties
  $\rightarrow$ $M_p$ by comparing to models in the absence of a long enough time baseline to map the orbit
Astrophysical Considerations:

- maximize contrast by looking for red planets near blue stars
- maximize planet brightness by looking for young massive planets
- maximize separation by observing nearby stars
- minimize fore/background star confusion by observing nearby stars with large proper motions
\[ \sigma T_{\text{eff}}^4 = \int F_\lambda d\lambda \]

\[ L_{\text{bol}} = 4\pi R^2 \sigma T_{\text{eff}}^4 \]
Blue

short lived

Red

long lived
Spectral Energy Distributions

main sequence

white dwarfs

Jupiter
Early “direct imaging” results:

GD165AB (brown dwarf + white dwarf)
(Becklin & Zuckerman 1988)

~ 7 arcsec
Brown Dwarf /Giant Planet Evolution:

Baraffe et al. 2003

M(Mjup)

104
94
83
73
62
52
41
31
20
10
8
6
4
2

Log (L/Lsun)

Log (gravity) [cgs]

Radius [Rjup]

Log (age) [Gyr]

M dwarfs

L dwarfs

T & Y dwarfs

Baraffe et al. 2003
Practical Considerations:

- Telescope diffraction
- Atmospheric turbulence
- Starlight suppression
- Instrumental speckles
- Zodiacal light
Telescope Diffraction

Plane wave of light converted to a spherical wave after passing through a circular aperture.

"Airy pattern"

The angle from the center to the first minimum is:

$$\theta_{\text{zero, } 0} \approx 1.22 \frac{\lambda}{D}$$

The width (FWHM) of the central peak is:

$$\theta_{\text{FWHM, } 0} \approx \frac{\lambda}{D}$$
Example (diffraction limit)

- Hubble Space Telescope: \( D = 2.4 \text{m} \) in the optical (0.5 microns)

\[
\theta(\text{radians}) = 1.22 \frac{\lambda}{D} = \frac{1.22 \times 5000 \text{Å}}{2.4 \text{m}} = \frac{6100 \times 10^{-8} \text{cm}}{240 \text{cm}}
\]

\[= 2.54 \times 10^{-7} \text{radians}
\]

\[= 2.54 \times 10^{-7} \text{radians} \times \frac{1''}{4.85 \times 10^{-6}} = 0.05''
\]
Telescope Diffraction

There is a second peak at $-2\lambda/D$ with contrast of $10^{-4}$

Can you see it?
There is a second peak at $-2\lambda/D$ with contrast of $10^{-4}$

Can you see it?
How do we remove the star light, while preserving that from the planet?
Basic Tools

- Adaptive Optics
- Coronagraphs
- Differential Imaging
- Post-processing of images

from D. Mawet (http://nexsci.caltech.edu/workshop/2016/Sagan2016_mawet_v2.pdf)
Terminology

- **Contrast**: ratio of the peak of the stellar PSF to the noise at the planet location

- **Inner Working Angle**: smallest angle on the sky at which the required contrast is achieved (and planet flux is reduced by no more than 50% relative to other angles)

- **Throughput**: ratio of the open telescope area remaining, after high-contrast is achieved.

- **Bandwidth**: wavelength at which high contrast is achieved

- **Sensitivity**: degree to which contrast is degraded in the presence of aberrations.

from D. Mawet (http://nexsci.caltech.edu/workshop/2016/Sagan2016_mawet_v2.pdf)
Terminology

- **AO**: adaptive optics
- **DM**: deformable mirror
- **Speckles**: (random and quasi-static) “copies” of the same star, randomly offset (short timescales, ms) and quasi-static aberrations caused by imperfect optics (longer timescales, minutes to hours).
- **Strehl ratio**: ratio of the peak intensity to that of a perfect image.

from D. Mawet (http://nexsci.caltech.edu/workshop/2016/Sagan2016_mawet_v2.pdf)
Atmospheric Turbulence

- convection
- wind shear
- ground-layer effects (wind over obstacles)
Atmospheric Turbulence

seeing and speckles

Very short timescale

Averaged over > a few seconds

approx 1"
$r_0 \propto \lambda^{6/5}$

$\theta_{\text{seeing}} \propto \lambda/r_0 \propto \lambda^{-1/5}$

$\theta_{\text{dif}} \propto \lambda$

$r_0 = \text{“Fried parameter”}$

Telescopes with diameter $> r_0$ are “seeing” limited with resolution comparable to telescope with $D = r_0$.

$r_0 \sim 10 \text{ cm in the optical and } \sim 70 \text{ cm in the infrared.}$

At longer wavelengths, the relative differences between the seeing limit and diffraction limit become less important.
Atmospheric Turbulence

Correction for wavefront errors with adaptive optics (AO)

AO off  AO on
Example: $v \sim 10 \text{ m/s}$  
$r_0 \sim 10 \text{ cm (optical)}$  
$t_2 - t_1 \sim 10 \text{ ms}$  
(this is the coherence times scale)

$r_0$ increases with lambda, so does delta $t$  
... AO corrections required less frequently in the infrared compared to optical.
LYOT CORONAGRAPH

STEP BY STEP

see move: https://www.youtube.com/watch?v=zkTHuqiH_1Y

from D. Mawet (http://nexsci.caltech.edu/workshop/2016/Sagan2016_mawet_v2.pdf)
Starlight Suppression

Coronograph:

Invented by Bernard Lyot in 1933 to observe the corona of the sun (contrast = $10^{-6}$)

Internal (e.g., Lyot) and External (star shade) occulter versions

Must be $\sim 40$ m across with 0.2mm tolerances for contrasts of $10^{-10}$
Starlight Suppression

Imperfections in the optical system will lead to wavefront errors that manifest as speckles.

Sources include: the support structure for the secondary mirror, an obscured aperture, a segmented primary mirror, imperfect pointing, imperfect coronagraph masking, and imperfect optical surfaces.
Post-processing (speckle suppression)

Techniques for removal:

• Angular Differential Imaging

• Chromatic Speckle Suppression

Instrument speckles will rotate with the telescope, while stars/planets will not

Clever data processing ...

Angular Differential Imaging (ADI)

Keck Ks-band 20s integration
Clever data processing ...
Clever data processing ...

Angular Differential Imaging (ADI)

Keck Ks-band 20s integration

ADI-processed 20s integration

Combined ADI

Total integration time (s) = 20
Simultaneous differential imaging
Speckle Removal

Wavelength

scale by $D/\lambda_m$

see also Sparks & Ford (2002)