The Wild Hunt:
Searching for Exoplanets and the Remnants of Planet Formation

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Connecting the Universe Through the Thread of Light

Alexander Pope, “An Essay on Man” 1733
– He, who through vast immensity can pierce,
– See worlds on worlds compose one universe,
– Observe how system into system runs,
– What other planets circle other suns,

Sir Isaac Newton, “Principia” 1687
– since the light of the fixed stars is of the same nature with the light of the sun, and from every system light passes into all the other systems… [then] the fixed stars are the centres of other like systems… [as] This most beautiful system of the sun, planets, and comets…

How Did We Get Here?

www.soulcare.org/gsinew_seminars_logikos_thinking.html

How Did Here Get Here?

planetquest.jpl.nasa.gov/news/exoplanets400.cfm
Framing the Exoplanet Pursuit

• State of the Problem
  – Contrast with the star
  – Angular resolution

• Methods and Tools
  – Space and ground based telescopes
  – Direct vs. indirect observation

• Theory
  – Stellar evolution, planet formation, and light scattering

• Current Research
  – Imaging, processing, and modeling

Problem 1: High Contrast
Looking at Light from the Star

- Light corresponds to a spectrum of wavelengths.
- Spectral lines account for the characteristic composition of a star.

http://quarknet.fnal.gov/quarknet-summer-research/QNET2010/Astronomy/
Comparing the Spectral Signal

• Just like a moving sound source, the “wobble” of a star due to the gravitational pull of an orbiting planet causes a Doppler effect.

• Measures radial velocity
  ➞ Orbital period

X Minimum mass of planet

X Requires high precision
Dancing Planets - Gliese 876

- Discovery of four planets b, c, d, e
- Two of the Jupiter mass planets found within the habitable zone (HZ)

http://lisa-falzon.blogspot.com/2010/12/goldilocks-zone.html

http://www.weirdwarp.com/2010/06/habitable-or-goldilocks-zone.html
Measuring Variation in Starlight

• Lightcurve is a measure of brightness vs. time
• Transit of planet correlates to an observed “dimming” of the star’s light
  ⇒ Can determine size
  ⇒ Atmosphere of planet through spectral shift
  X Orbits must be aligned
  X Requires confirmation

http://enersec.org/id2.html
Brothers in the Sky - Kepler-16

- Kepler Mission explores stars in our local environment
- Recent discovery of circumbinary exoplanet Kepler-16b
Problem 2: Angular Resolution

.31 arcseconds = penny at 12.5km!

http://scienecenotes.wordpress.com/2010/10/18/
Finding Exoplanets Directly

- Bright light from the star is blocked by a mask to reveal nearby objects and structure.
- Easiest to observe large, hot, and wide orbiting planets.

http://arxiv.org/abs/0707.2580
Hubble’s Eye in the Sky - Fomalhaut

• First directly observed planet in visible light

• Off center disk structure
Formation and Evolution

• The Circumstellar disk:
  Dynamical system of interaction among accreting gas, planetesimals, and dust grains

• The Debris disk:
  Dust grain distribution may be influenced by collisions and gravitational presence of co-orbiting planetary body

⇒ Asymmetric morphology

http://dos110.glogster.com/nebular-hypothesis/
First Rings - $\beta$ Pic and AU Mic

- Thermal infrared emission
- Scattered infrared light

Attacking the Problems

- Adaptive Optics: Improves resolution
- Image Processing: Boosts contrast

http://www.lyot.org/background/adaptive_optics.html
A Summer With the Stars
In the Afterglow of LA Zodiacal Light, “dust”

A Summer With the Stars
Scattered Light Around HD 32297: Modeling Debris Disk Structure
⇒ Mathematical Inversion:
- Recovers observable quantities from specified orientation

⇒ Forward Modeling:
- Predicts output from physical assumptions and instrumental response

How do we solve this problem?

• Input:
  – Scattered light image

• Output:
  – Fully developed image
  – Set of parameters that define the hypothesis

• Template:
  – Structure of the debris disk

• Processing:
  – Blurring caused by noise
  – Fitting provisional model to the data
Defining the Framework

- **Symmetry**
  - Geometrically and optically thin disk
  - Circularly symmetric

- **Orientation**
  - Position angle \((P.A.)\)
  - Inclination \((i)\)
Distribution of Grains

- Number Density (#/VOL)  \( n(r,z) = \sum (r,r_{\text{min}}) \cdot f(z,h) \)

  - Surface power law
    - Radii, \( r_{\text{min}} \) and \( r_{\text{max}} \)
    - Parent bodies, \( N_0 \)

  - Vertical Gaussian
    - Scale height, \( h \)
    - Smoothing
Accounting for the Observed Light

- **Mie Theory**: Light scattering where $\lambda \approx a$ and $m = n + kj$

- Provides the phase function, $P(\theta)$


- $x = \frac{2\pi r}{\lambda}$

Representing the Entire Disk

- Radiative Transfer: Conservation of energy throughout a system
- Defines the observable of “Brightness”
  - Specific Intensity: \( \text{dl} = \frac{dE}{dA dt dv dw} \)
- Ray approximation when scale » \( \lambda \)

3D \( \Rightarrow \) 2D
Tracing Light Scattering

\[ F_v = \frac{L^*_v}{4\pi r^2} \]
Tracing Light Scattering

Brightness

\[ I_s = F_v \cdot \frac{P(\theta)}{4\pi} \]
Tracing Light Scattering

3D Brightness

\[ j_v = \frac{dI_v}{ds} = I_s \cdot n(r,z) \cdot \sigma_s \]
Tracing Light Scattering

\[ I_v(r) = \int_{z_1}^{z_2} F_v \cdot \frac{P(\theta)}{4\pi} \cdot n(r, z) \cdot \sigma_{\text{sca}} \, dz \]

2D Brightness
Framing the Hypothesis

• $P.A.$ and $i$

• $N_0$, $\gamma$

• $r_{\text{min}}$, $r_{\text{max}}$, $h$

• $a$, $m$
Optimizing the Fitting Procedure

• Computationally expensive procedure
  – “Trim” the model and data
• Use $\chi^2$ as the metric of comparison
  – Explore small regions of parameter space

$$N_o = \sum \frac{2dm}{\sigma(r)^2}$$

$$\chi^2 = \sum \left( \frac{Data - Model}{\sigma} \right)^2$$
Comparing the Data and Model
Analyzing the \( \chi^2 \)

- Residual values limit grid searches

- Feature is located around 100-125 AU in average
- Region of \( \sim 14\sigma \)
Summary of Findings

• K-band 2.2\(\mu\)m grains could be isolated to regions of \(~146-235\) AU and within \(h \sim 8.2\) AU

• A single power law is not sufficient to describe the full structure of the disk, nor is a single grain population

• Future modeling should account for brightness asymmetry
Comparisons to Prior Studies

• Schneider et. al (2005) and Kalas (2005)
  – brightness asymmetry in 1.1 \( \mu \text{m} \); .647 \( \mu \text{m} \)
  – \( r_{\text{max}} \) ~400-1650 AU
  – Interstellar medium

• Fitzgerald et. al (2007) and Moerchen et. al (2007)
  – 11.2 \( \mu \text{m} \); 11.7\( \mu \text{m} \) and 18.3\( \mu \text{m} \)
  – \( r_{\text{min}} \) ~ 60-80 AU
  – Multi ring populations

Similar Worlds, Yet Worlds Apart

In the vast open Universe
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References

Returning to the Source

Slice comparison, radius=94 pixels=105 AU

Disk brightness (arbitrary units)

Phi (radians)

Data rot_mean_67

Model rot_mean_302
What causes a blurry image?

- Point Spread Function (PSF) describes the extended blurring of an unresolved image
- Response of the telescope to stellar signal
Convolution

\[ \mathcal{F}[f \ast g] = \mathcal{F}[f] \cdot \mathcal{F}[g] \]