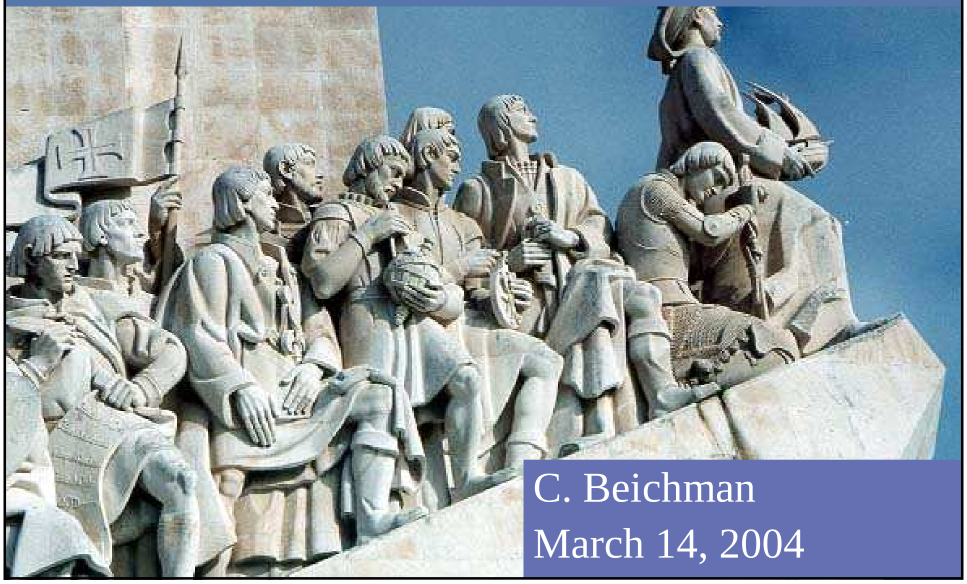
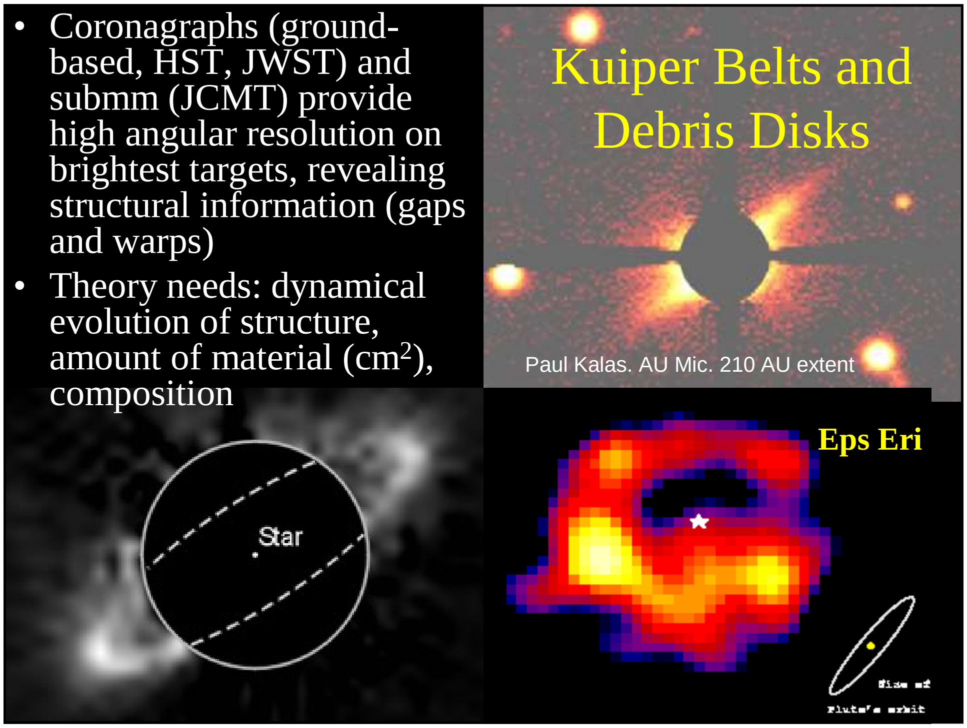
The Golden Era of Planetary Exploration: From Spitzer to TPF



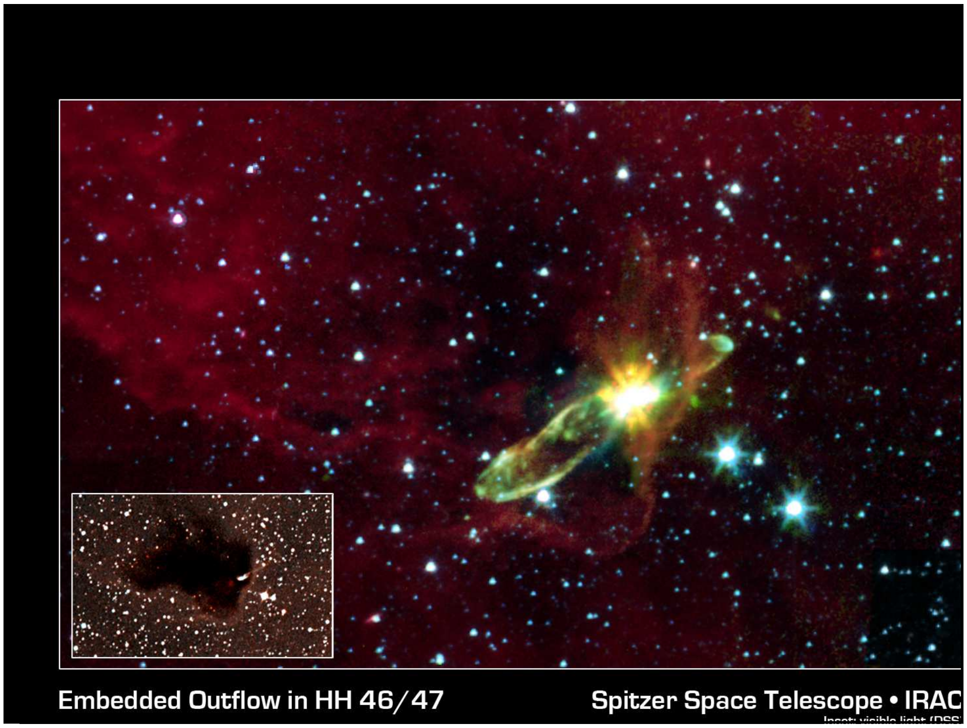
C. Beichman
March 14, 2004

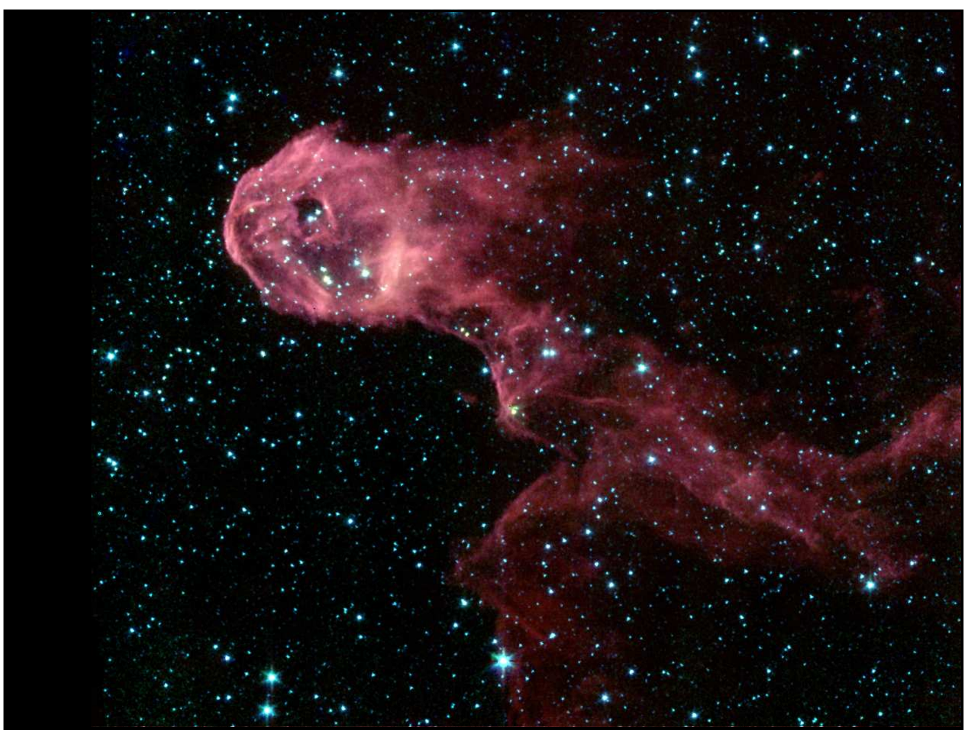
The Observational Promise

- In the next decade we will progress from rudimentary knowledge of gas giant planets around ~10% of solar type stars to a detailed knowledge of the constituents of planetary systems around a large variety of stars
  - From Kuiper Belts and comets to asteroid belts
  - From primordial gas to remnant dust
  - From gas giants to rocky planets
  - From barren worlds to evidence for life
- A network of theory must accompany this observational progress to knit together disparate facts into a compelling narrative that reveals the evolution of planetary systems and life

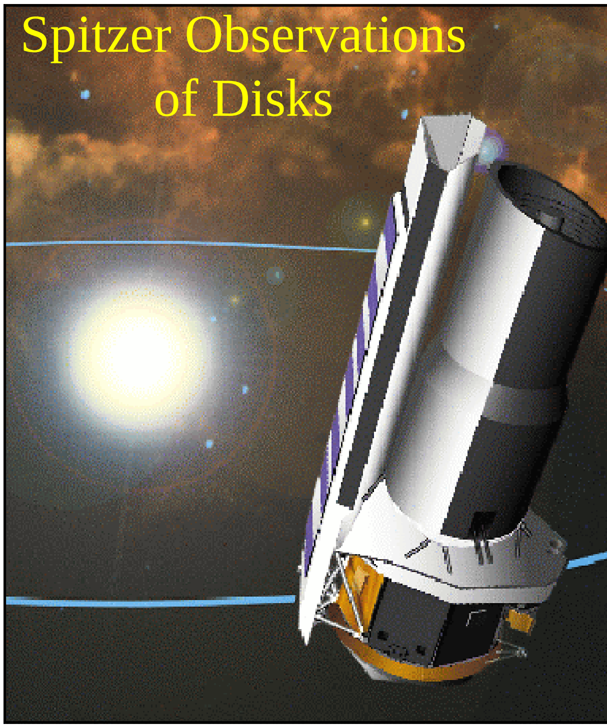

• Coronagraphs (ground-based, HST, JWST) and submm (JCMT) provide high angular resolution on brightest targets, revealing structural information (gaps and warps)
• Theory needs: dynamical evolution of structure, amount of material (cm²), composition
Kuiper Belts and Debris Disks
Paul Kalas. AU Mic. 210 AU extent
Star
Eps Eri


After 25 years, NASA's Spitzer Space Telescope (neé SIRTF)
Is In Full Operations.
(Thanks to Mike Werner and lots of others)


Embedded Outflow in HH 46/47
Spitzer Space Telescope • IRAC

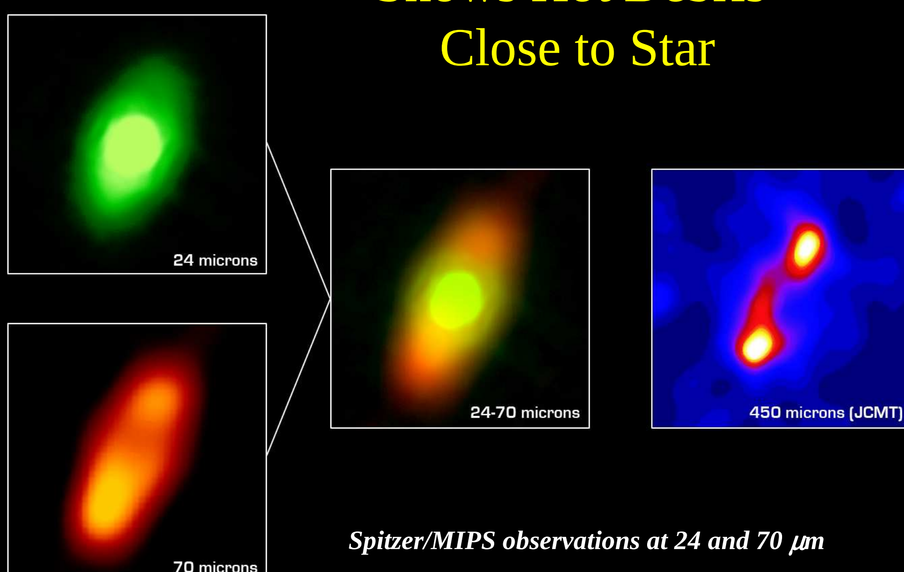


Spitzer Observations of Disks



- Poor angular resolution, but great sensitivity to weak disks
  - 10x Kuiper belt
- Spitzer will map, survey, take spectra of disks around 100s of stars
  - single, binary
  - spectral types, ages
  - with & w/o planets
  - Lo/high metals
  - Age:1 Myr → 5 Gyr
  - Grain growth and composition

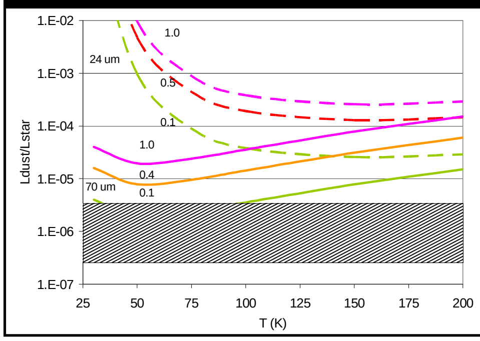
Disk Around Fomalhaut Shows Hot Debris Close to Star

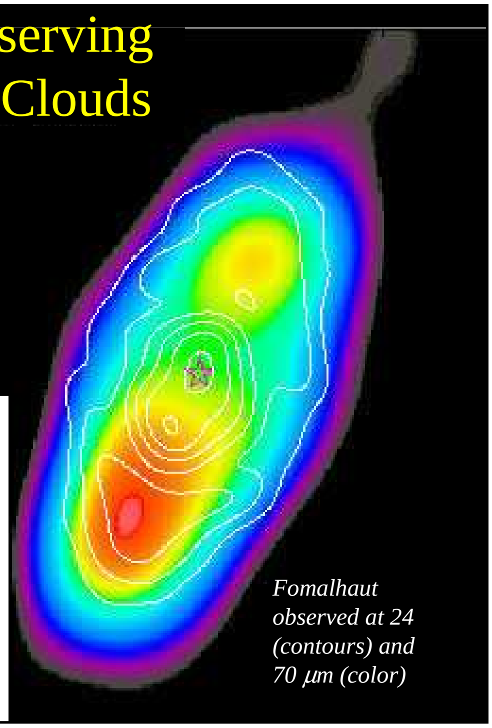


Spitzer/MIPS observations at 24 and 70 μm

Spitzer Starts Observing Exozodical Dust Clouds

- Spitzer will observe ~150 stars at 24 and 70 μm in GTO/Legacy programs with another 150 proposed for GO observations
- Sensitivity approaches few times Kuiper Belt, 100x zodiacal cloud

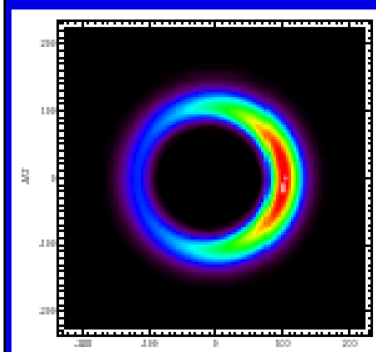


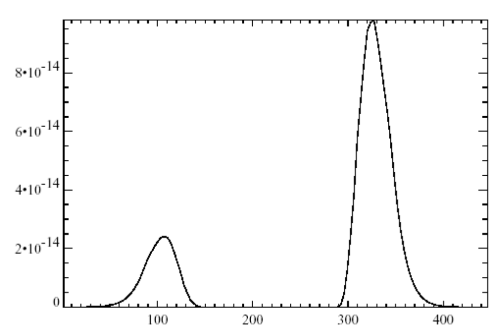


Fomalhaut observed at 24 (contours) and 70 μm (color)

Orbital Dynamics Of Disks

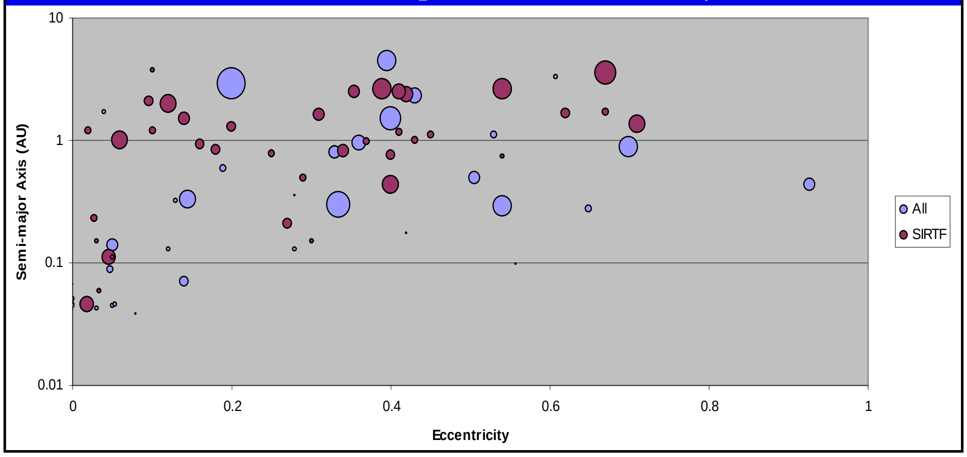
- Secular perturbation theory models effect of planet(s) on eccentricity and longitude of pericenter of the dust particles as a function of semi-major axis (Holmes et al 2004; Ozernoy 2002; et al)
- Reproduce asymmetries in Fomalhaut disk seen in Spitzer.
  - Gradual decrease in asymmetry with wavelength as differential heating of material closer to star becomes less important





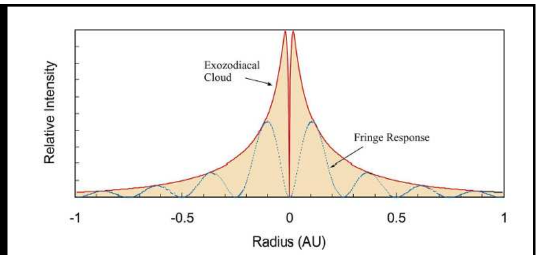
Volume Limited Sample: Stars With Planets

- Broad range of radii, eccentricity, planet masses
- Planets now known in >3 AU orbits which can affect the distribution of dust responsible for 12-25 µm radiation

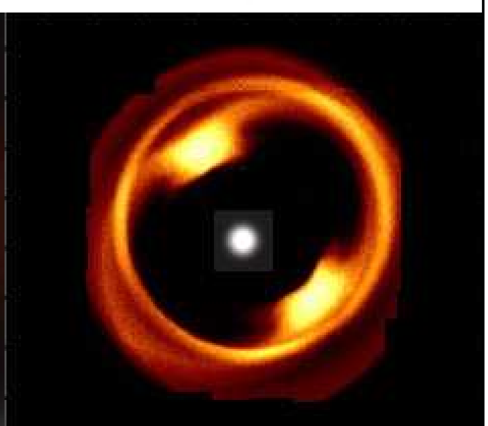


Beyond Spitzer

- Keck-I/JWST-MIRI will bring angular resolution and sensitivity to study of mid-IR disks, including spatially resolved spectroscopy



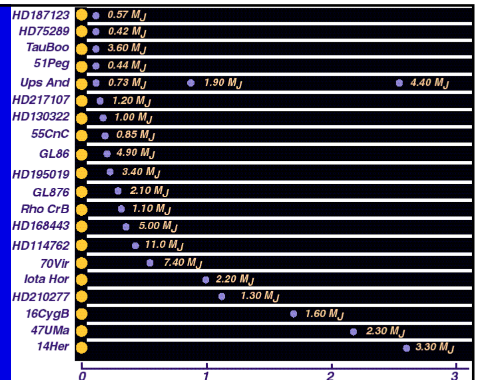
Model of Vega at 24 um (Wilner): Spitzer

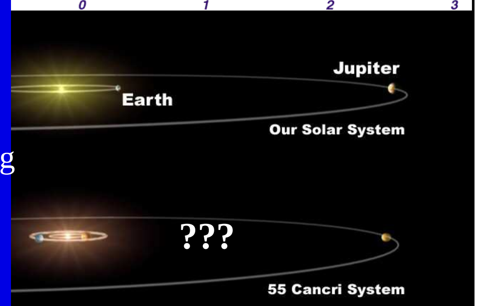


Model of Vega at 24 um: JWST

How Common Are Planets?

- Over 115 gas giant planets found using radial velocity
  - ~10-15% of stars have planets
  - Complete for orbits < 2-3 AU
  - Half may be multiple systems
- Planets on longer periods starting to be identified
  - 55 Cancri is solar system analog
- Astrometry (SIM) and radial velocity will determine solar system architecture to few $M_\oplus$

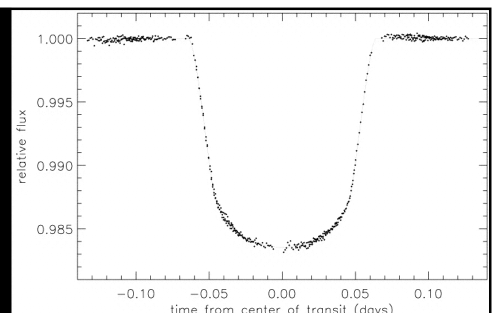


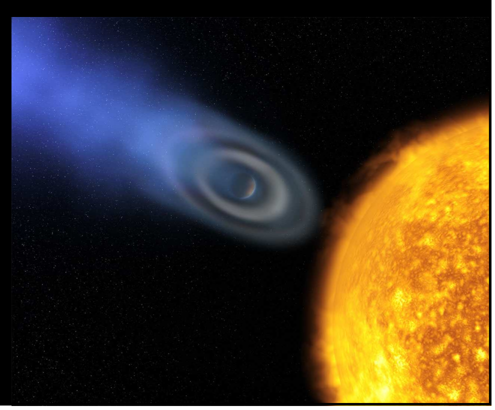


Marcy et al.

Transits Reveal Planets

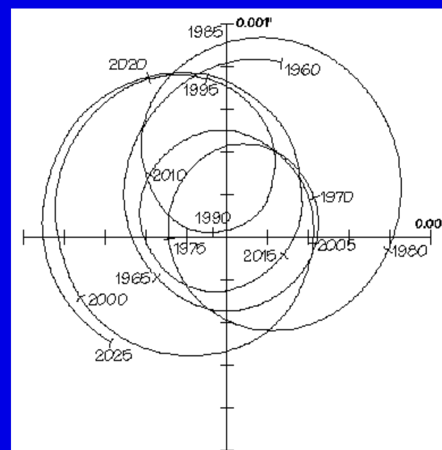
- Transits of planet orbiting HD 209458 confirm RV interpretation, give physical information
- Spectroscopy probes atmosphere
  - Reveal H, C,O
  - Cloud heights, heavy-element abundances, temperature and vertical temperature stratification
- Active ground-based efforts to identify new planets
- COROT and Kepler will monitor 10^4-10^5 stars <1kpc
  - About 50 planets <R> ~ 1.0 Re
  - About 640 planets <R> ~ 2.2 Re
  - About 1,000 giant planets with periods less than one week
    - Albedos for ~100 of these planets





Astrometric Census for Planets Around Nearby Stars

- Astrometry measures positional wobble due to planets
- Interferometry enables measurements at the micro-arcsecond level
  - *Identify Left or Right Headlight on a Mars Rover!*
- Space Interferometer Mission (SIM) will complete a census of planets down to a few M_{earth} over the next 10-20 years



Space Interferometer Mission (SIM) Will Make Definitive Planet Census

What We *Don't* Know

- Are planetary systems like our own common?
- What is the distribution of planetary masses?
  - Only astrometry measures planet masses unambiguously
- Are there low-mass planets in 'habitable zone' ?

A Deep Search for Earths

- Are there Earth-like (rocky) planets orbiting the nearest stars?
- Focus on ~250 stars like the Sun (F, G, K) within 10 pc
- Sensitivity limit of ~3 M_e at 30 l.y.

A Broad Survey for Planets

- Is our solar system unusual?
- What is the range of planetary system architectures?
- Sample 2,000 stars within ~75 l.y. with <<Jupiter accuaracy

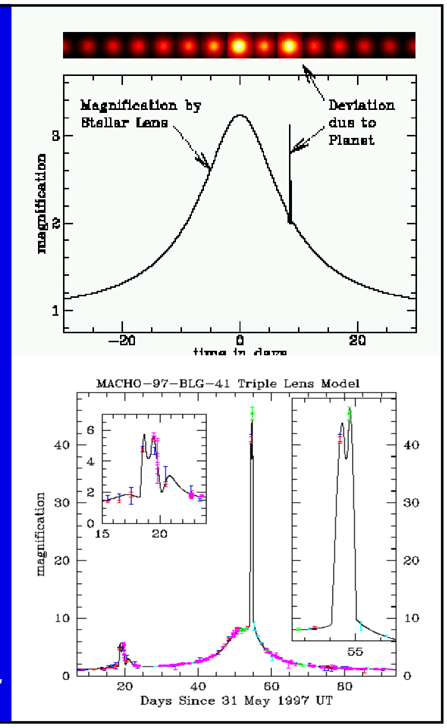
Evolution of Planets

- How do systems evolve?
- Is the evolution conducive to the formation of Earth-like planets in stable orbits?
- Do multiple Jupiters form and only a few (or none) survive?

Microlensing Searches for Planets

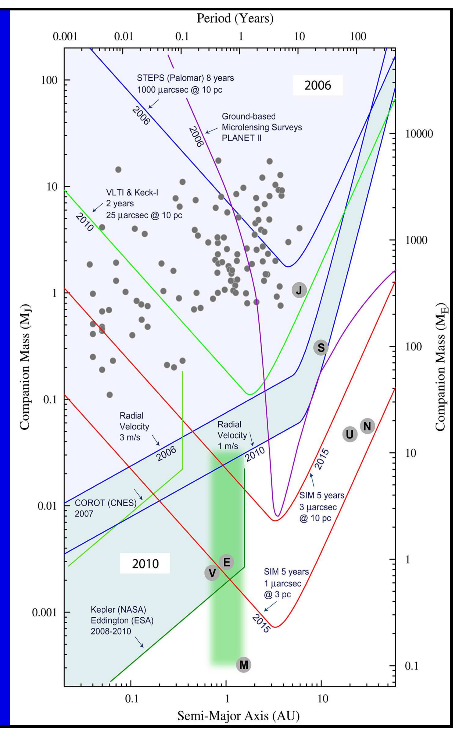
- Presence of planet around lensing star affects lens
  - Large photometric signal of a few hours to days duration
- Space mission (GEST) could discover hundreds of planets, from Jupiters to Earths
- Typical lensing stars are 4-8 kpc away and of unknown, but late spectral type (M, L dwarf)

Binary + Jupiter



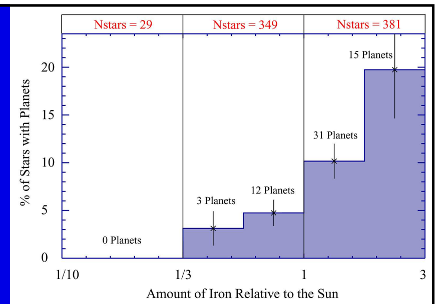
Observations and $\eta_{\oplus}$

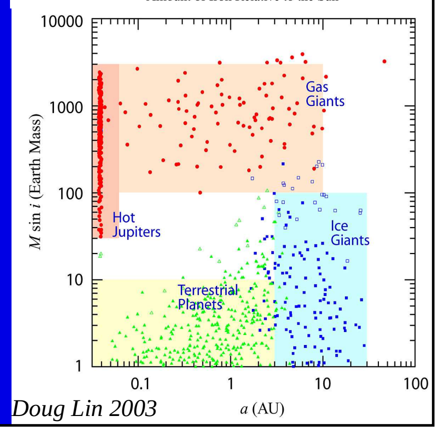
- Improving sensitivity and temporal baseline for RV may detect 10 Earth Mass at <1 AU
- Ground-based mircolensing might find few earth mass planets around distant stars
- Transit experiments (MOST, COROT, Kepler) will determine incidence of 1~few Earth masses at orbits 0.1~1 AU
- Eventually, SIM will identify few $M_{\oplus}$ planets for TPF and, retroactively, SIM archive can be used to determine masses for objects found by TPF.



Theory and $\eta_{\oplus}$

- Theory combines disparate data to permit extrapolation to desired range of (mass, orbit)
  - Formation scenarios for gas giant, icy (oceanic) and rocky planets
  - Orbital migration
  - Long term stability
- Models, simulation, theory (Lin, Lunine, Tremaine) suggest $\eta_{\oplus}$ >0.1
  - Number helps to determine scope of TPF mission

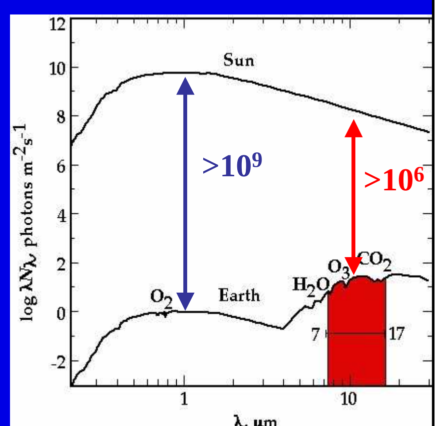




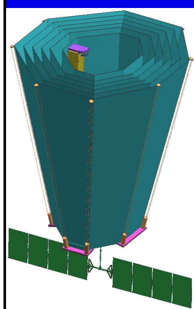
Doug Lin 2003

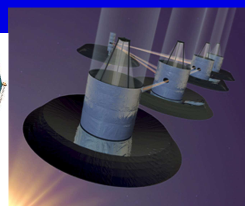
Four Hard Things About TPF

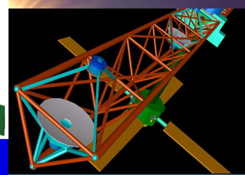
- Solar neighborhood sparsely populated
  - Perhaps 10% of stars have Earth-like planets (uncertain)
  - Surveying 30-50 stars means looking to ~30-45 light years
- Sensitivity (relatively easy)
  - Detection in hours → spectroscopy in days for a star at 30 l.y.
- Angular resolution (hard)
  - 100 milliarcsec is enough to see ~25 stars, but requires ≥4 m coronagraph or ≥20 m interferometer
- Starlight suppression (very hard)
  - 1,000,000:1 in the mid-IR
  - 1,000,000,000:1 in the visible/near-IR



Terrestrial Planet Finder (TPF)







Mission Features

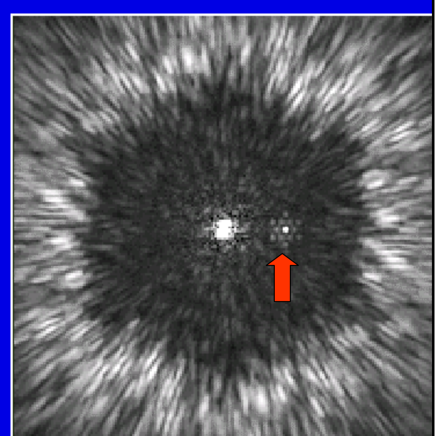
- Infrared Interferometer (structurally connected or formation flying type) or visible Coronagraph for star suppression
- 5 year mission life with 10 year goal
- Potential collaboration with ESA DARWIN

Science

- Search solar type stars (out to ~30 light years) for Earth-sized planets in the "habitable (Goldilocks) zone" --- not too cold, not too hot, just right for liquid water
- Look for *habitable* planets using O_2, O_3, CO_2 and H_2O.
- Study gas giant planets, comets, dust in in other solar systems

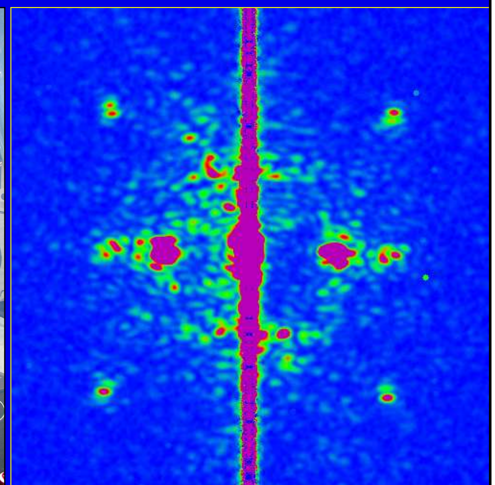
Visible Light Planet Detection

- A simple coronagraph on James Webb Space Telescope could detect Jupiters around the closest stars
- Optimized telescope & coronagraph
  - 2 m telescope (Jupiters)
  - 4 m telescope (Jupiters and survey nearest 30-50 stars)
  - 8~10 m telescope (>150 stars)
- Presence and Properties of Planets
  - Planet(s) location and size×reflectivity
  - Atmospheric or surface composition
  - Rotation → surface variability
  - Structure and composition of disks



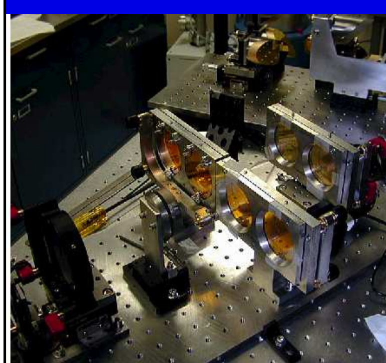
Simulated NGST coronagraphic image of a planet around Lalande 21185 (M2Vat 2.5pc) at 4.6 μm

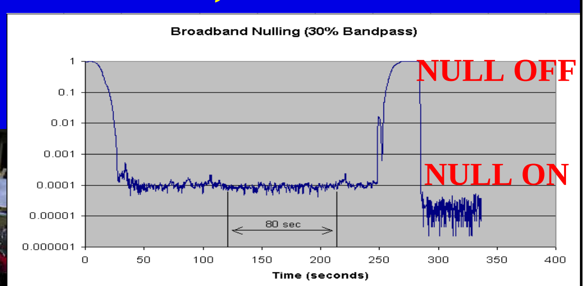
Laboratory Coronagraph Blocks Starlight to >100,000,000:1

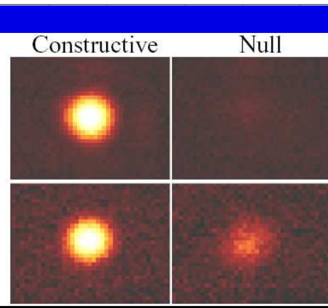


Excellent technical progress on most difficult part of the problem

Laboratory Nulling Blocks Starlight to >10,000:1





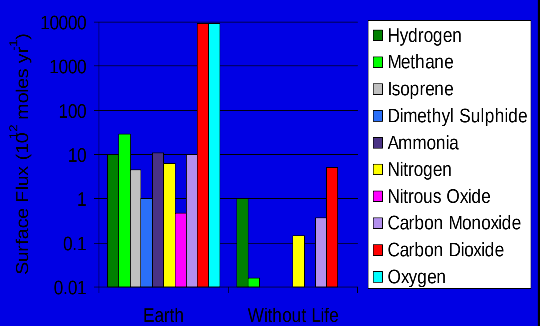


Remote Sensing Can Identify Signatures of Life

- *Oxygen* or its proxy *ozone* is most reliable biomarker
  - *Ozone* easier to detect at low *Oxygen* concentrations but is a poor indicator of quantity of *Oxygen*
- *Water* is considered essential to life.
- *Carbon dioxide* indicates an atmosphere and oxidation state typical of terrestrial planet.
- Abundant *Methane* can have a biological source
  - Non-biological sources might be confusing
- Find an atmosphere out of equilibrium
- Expect the unexpected → provide broad spectral coverage

The Case for 2 TPF's: IR & Visible

- Improved knowledge of physical properties of planets
  - Unique determination of albedo, radius, temperature
  - Improved characterization of sources too faint for spectroscopy



- Improved knowledge of atmospheric properties
  - Simultaneous solution for strengths of mid- and near-IR lines of CO_2 or H_2O would yield information on concentration, temperature, vertical temperature gradient, and atmospheric pressure that would be hard to obtain from a single line.
  - For planets with atmospheres, we get complementary information since IR primarily characterizes atmosphere while visible sees down to planet's surface (in absence of clouds!)

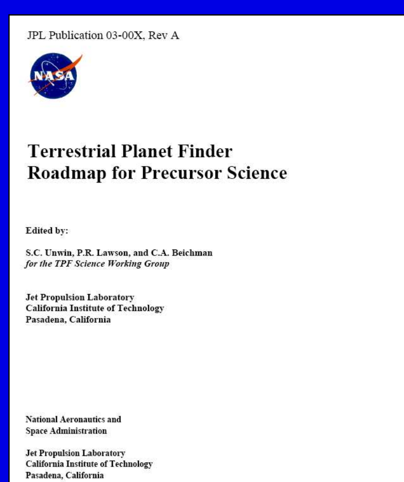
The Case for 2 TPF's: IR and Visible

- More robust detection of life
  - Detection of both O_3 (mid-IR) and O_2 (visible) yields critical confirmation of the presence of oxygen in planet's atmosphere – the smoking gun for the presence of life
  - Multiple lines allow rejection of abiotic mechanisms for "biomarkers", e.g. runaway greenhouse
  - Data in two different wavelength regions would help with identification of secondary biomarker gases, e.g. CH_4 and N_2O
- Simultaneous observations are not required because of relatively long time scale of planet-averaged measurements being considered for TPF.

"Both the mid-infrared and the visible to near infrared spectral ranges offer valuable information regarding biomarkers and planetary properties, therefore both ranges merit serious scientific consideration for TPF. The best overall strategy for the Origins program includes a diversity of approaches, therefore both wavelength ranges ultimately should be examined prior to launching the "Life-Finder" mission." (DesMarais et al 2002).

Focus of TPF Precursor Science

- Estimating the frequency of earth-like planets
- Determining the level of exozodiacal dust
- Refining the characteristics of stars that might harbor earth-like planets
- Predicting the characteristics of planets that might support life
- Ensuring the development of TPF science community and infrastructure
- *Funded through NASA's Origins and TPF Foundation programs*


JPL Publication 03-00X, Rev A

Terrestrial Planet Finder
Roadmap for Precursor Science

Edited by:

S.C. Unwin, P.R. Lawson, and C.A. Beichman
for the TPF Science Working Group

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Space Administration

Jet Propulsion Laboratory
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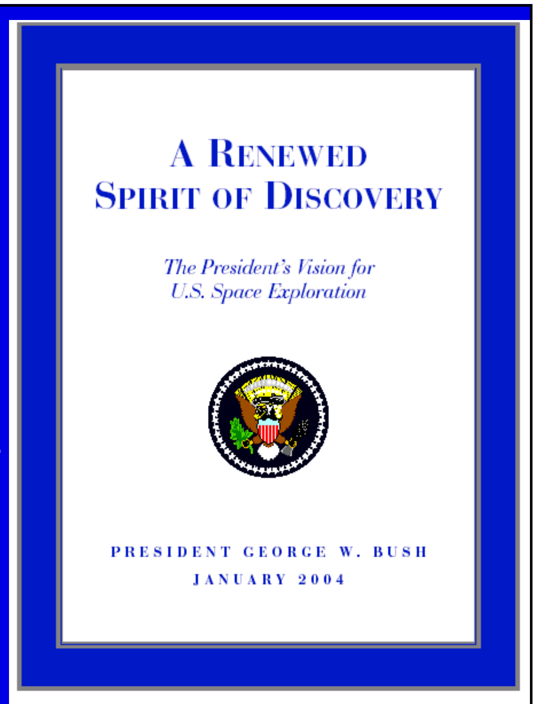
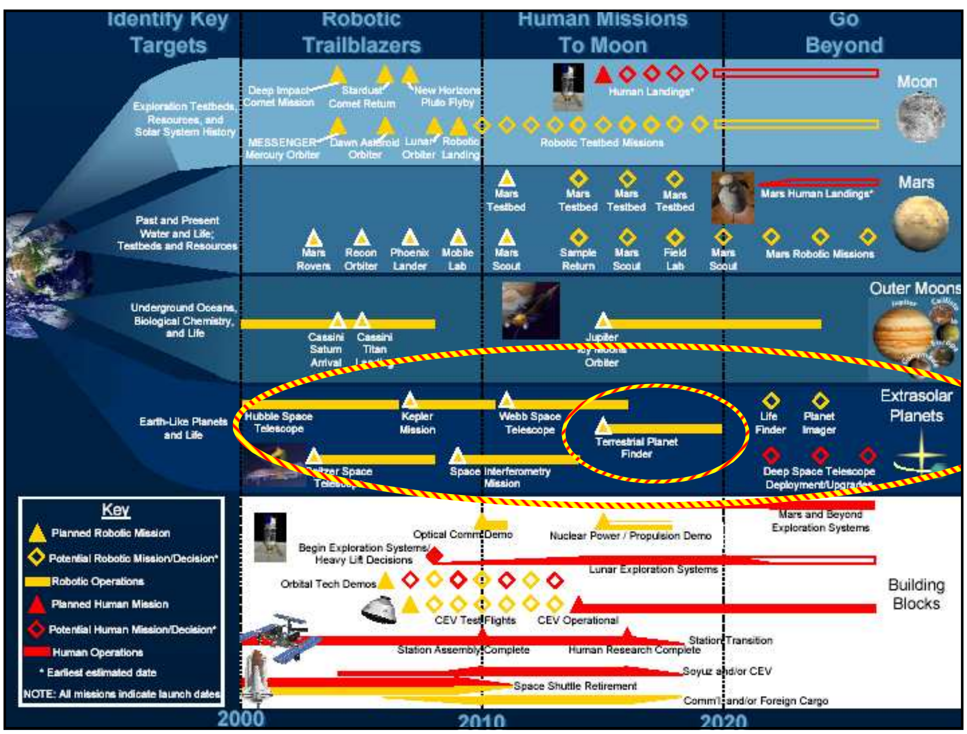
Post-Columbia Vision for NASA Explicitly Incorporates TPF

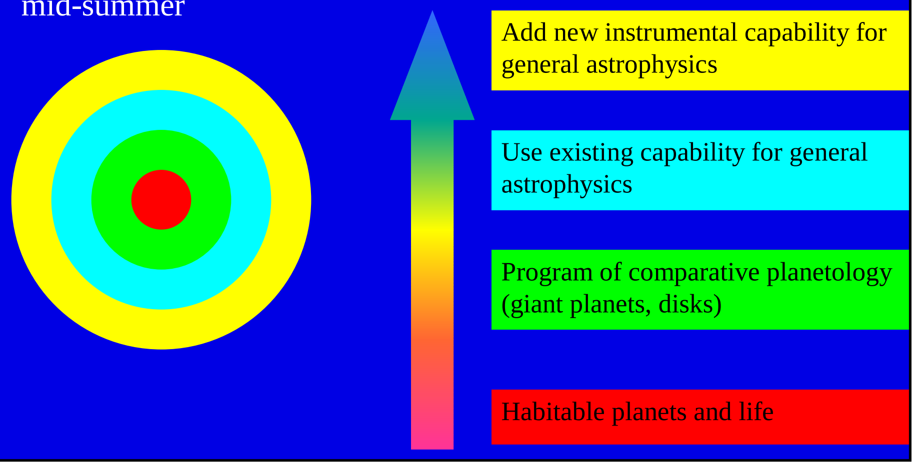
- Focus on manned mission to Moon and Mars, robotic exploration of solar system, and search for life around other stars
- Among ~20 specific goals the President set for NASA is the following:
  - ***"Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars"***





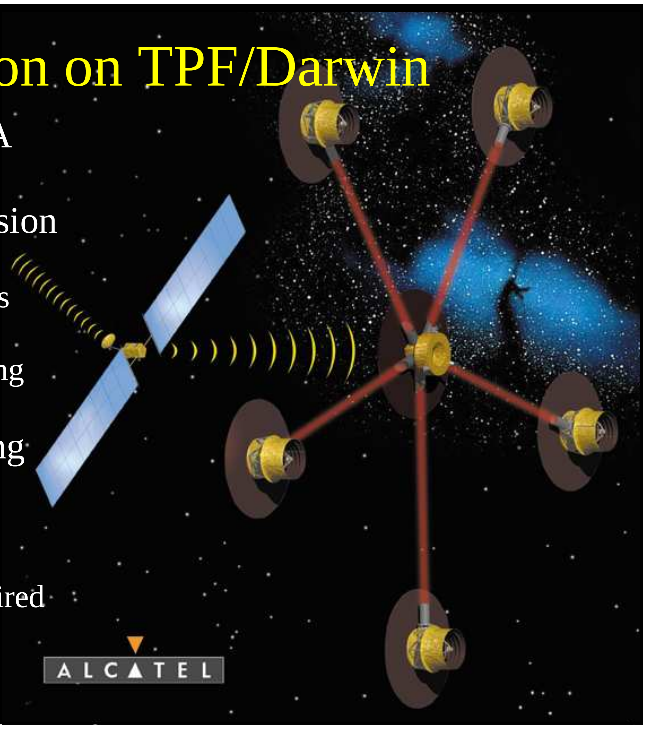
Ancillary Astrophysics for TPF

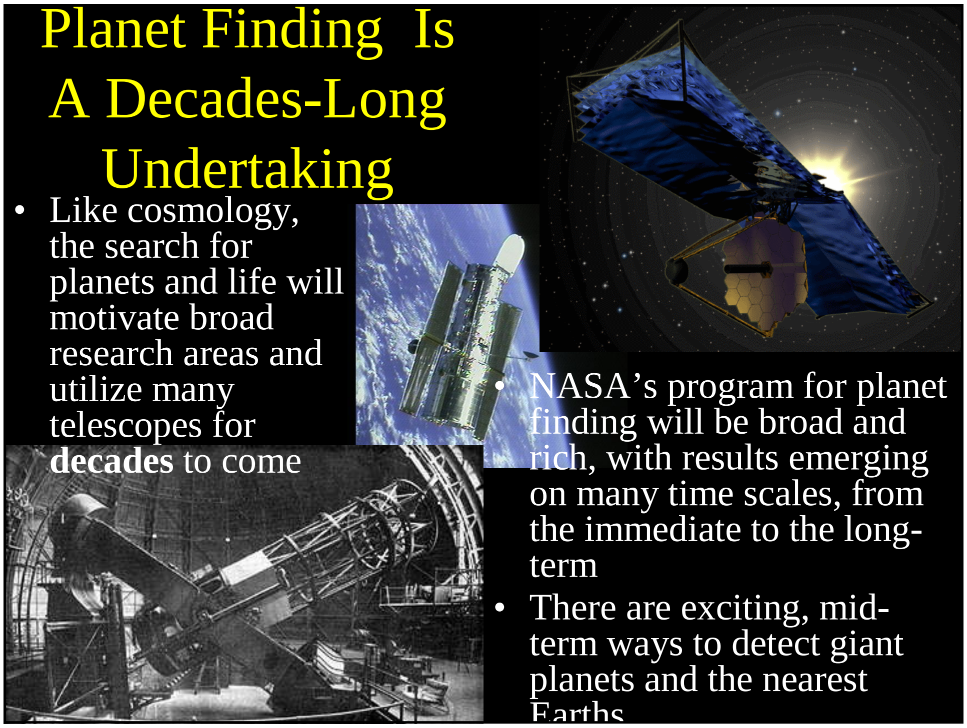
- Marc Kuchner is leading TPF-SWG effort on ancillary astrophysics with meeting at Princeton on April 13-14 to prepare briefing package for CAA meeting in May with White Paper by mid-summer



Collaboration on TPF/Darwin

- Strong ESA/NASA interest in joint planet-finding mission
  - Collaborative architecture studies
  - Discussions on technology planning and development
- Joint project leading to launch ~2015
  - Scientific and/or technological precursors as required and feasible




Planet Finding Is A Decades-Long Undertaking
• Like cosmology, the search for planets and life will motivate broad research areas and utilize many telescopes for decades to come
• NASA's program for planet finding will be broad and rich, with results emerging on many time scales, from the immediate to the long-term
• There are exciting, mid-term ways to detect giant planets and the nearest Earths