# The Crowded Universe: The Search for Living Planets

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DTM, Carnegie Institution

Planets Beyond the Solar System:
The New Astronomical Revolution
UC Santa Barbara, California
March 27, 2010

FEBRUARY 5, 1996 $2.95

# TIME

Dole Drops, Clinton Rises

# IS ANYBODY OUT THERE?

How the discovery of two planets brings us closer to solving the most profound mystery in the cosmos

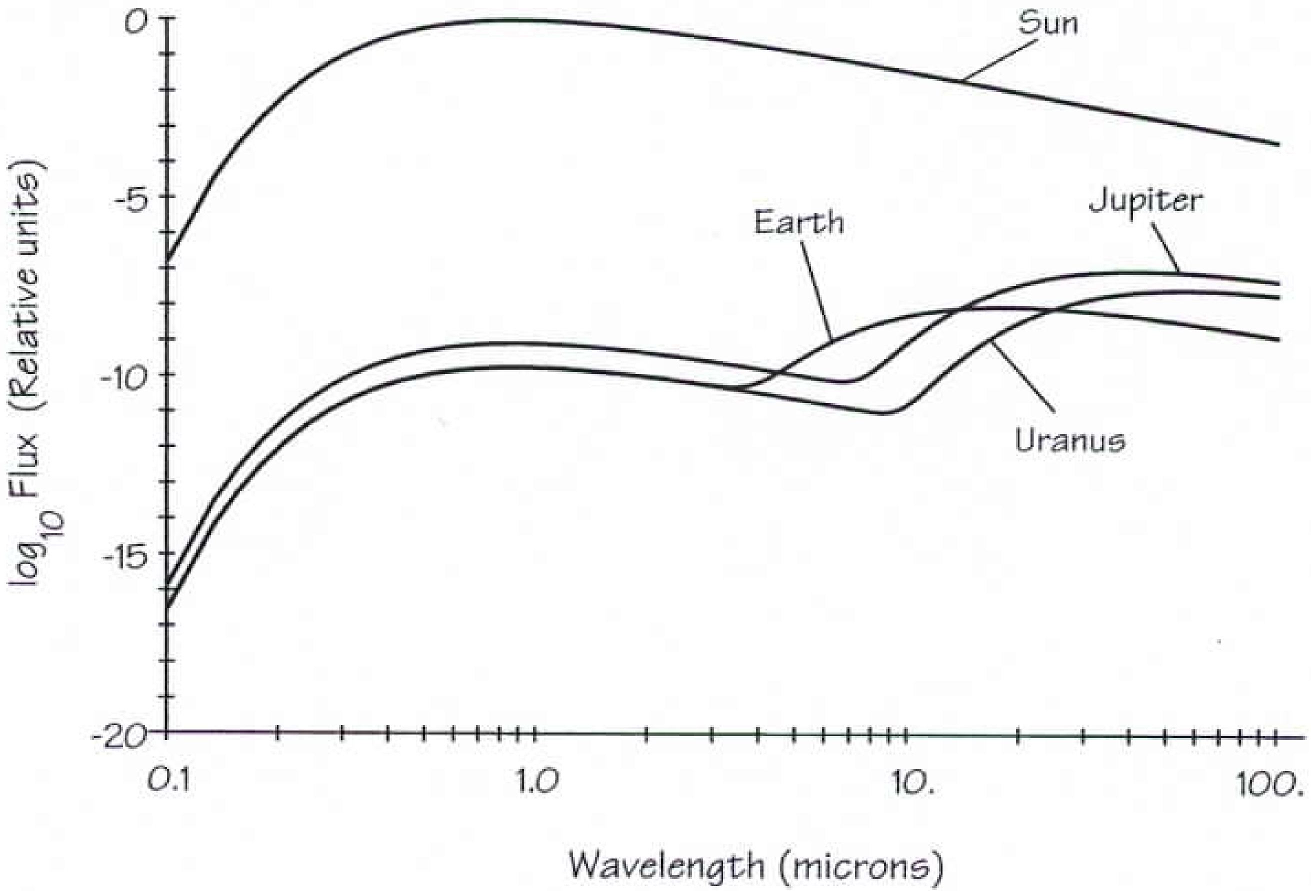
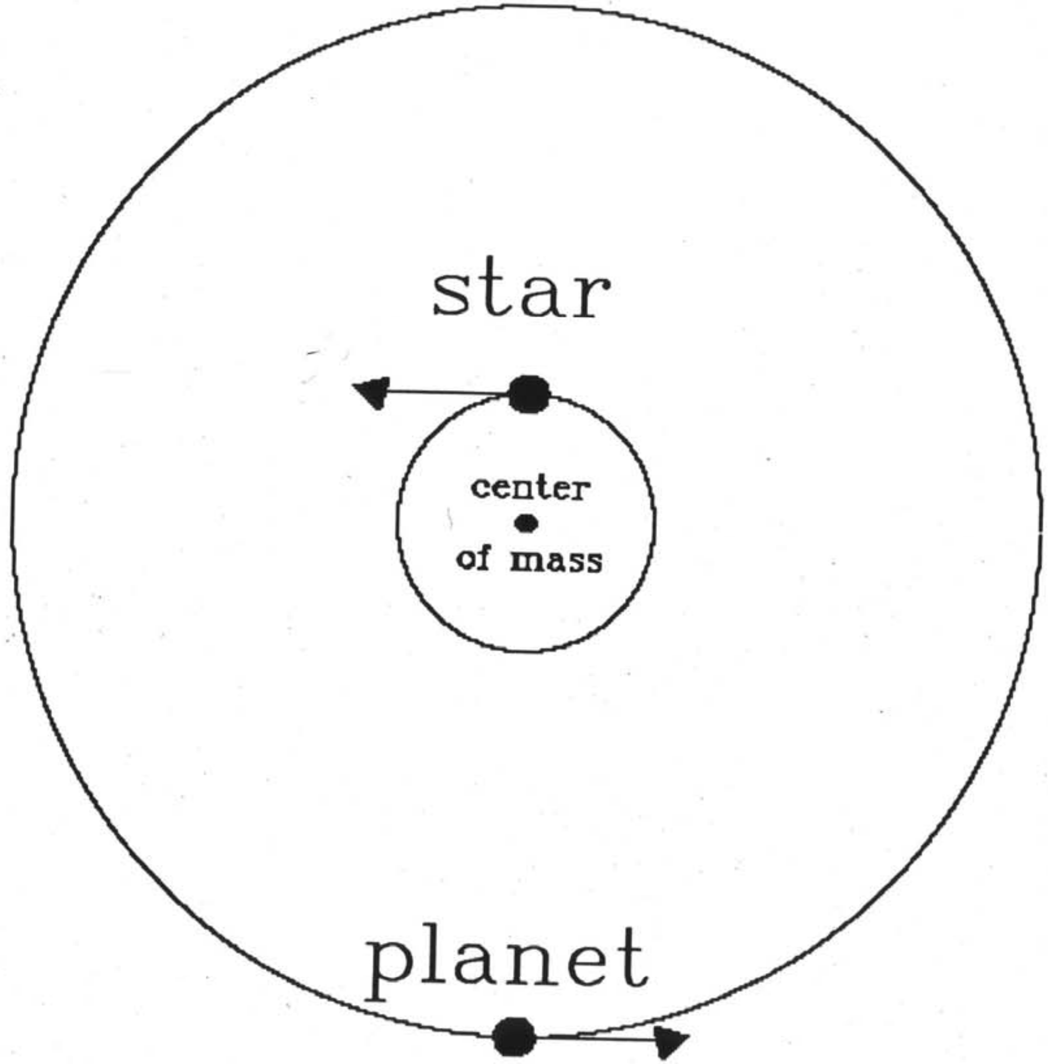



*Figure 4-1. The spectral energy distributions of the Sun, Jupiter, Earth, and Uranus as they would appear at 5 pc, averaged over a 10% spectral bandpass. Note the decreased ratio of solar to planetary flux in the thermal infrared, compared to visible wavelengths.*


star
center
of mass
planet

VAN DE KAMP (1963)

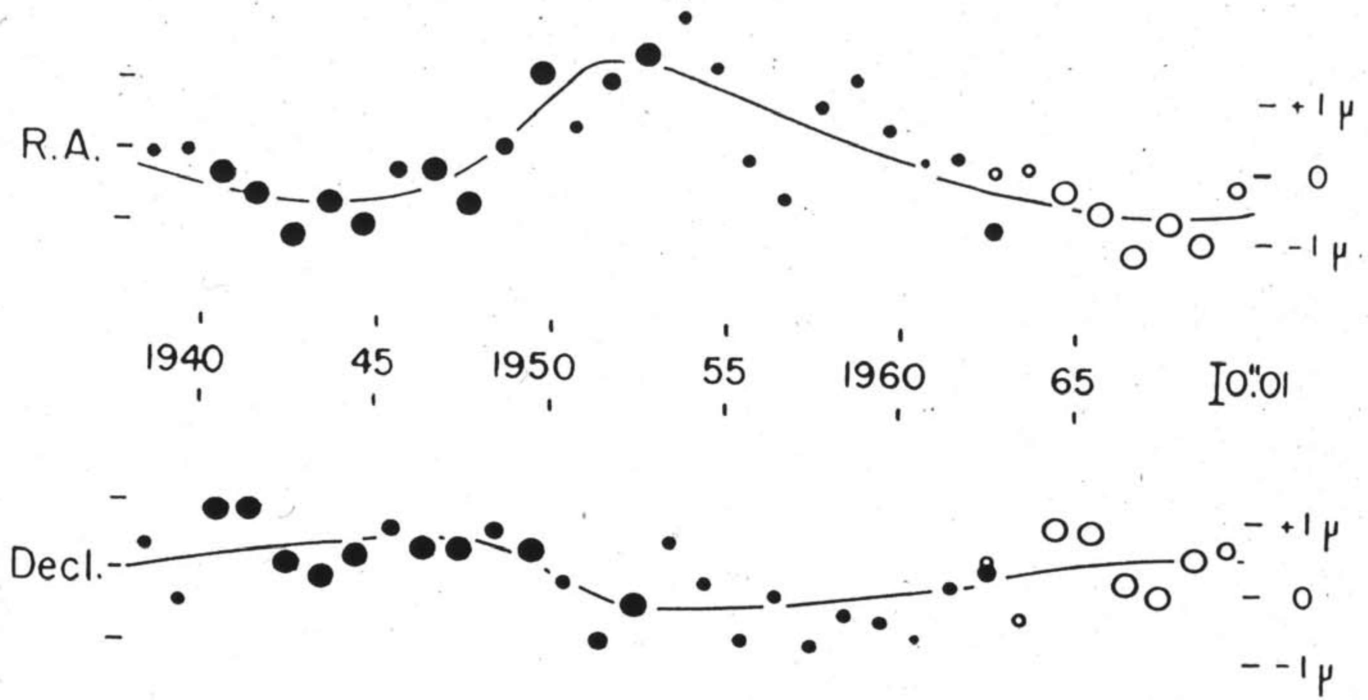



FIG. 5. Barnard's star—yearly means, averaging 96 plates and weight 64. Time displacement curves for $P=24$ yr, $e=0.6$, $T=1950$. Circles are early means transferred 24 yr forward. The scale of the displacements is shown both in terms of 0."01 and of $1\mu$ (.001 mm) on the Sproul plates.

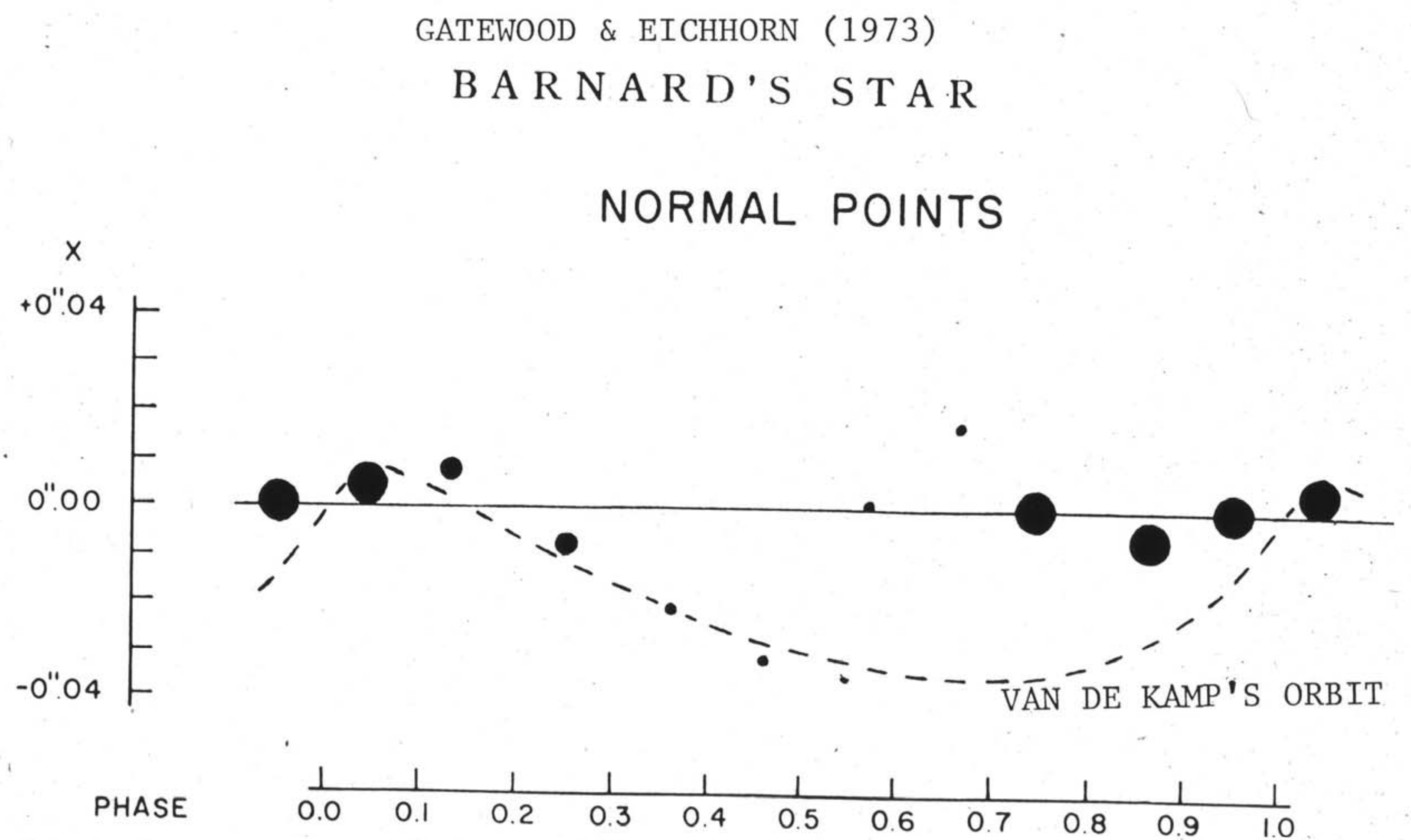
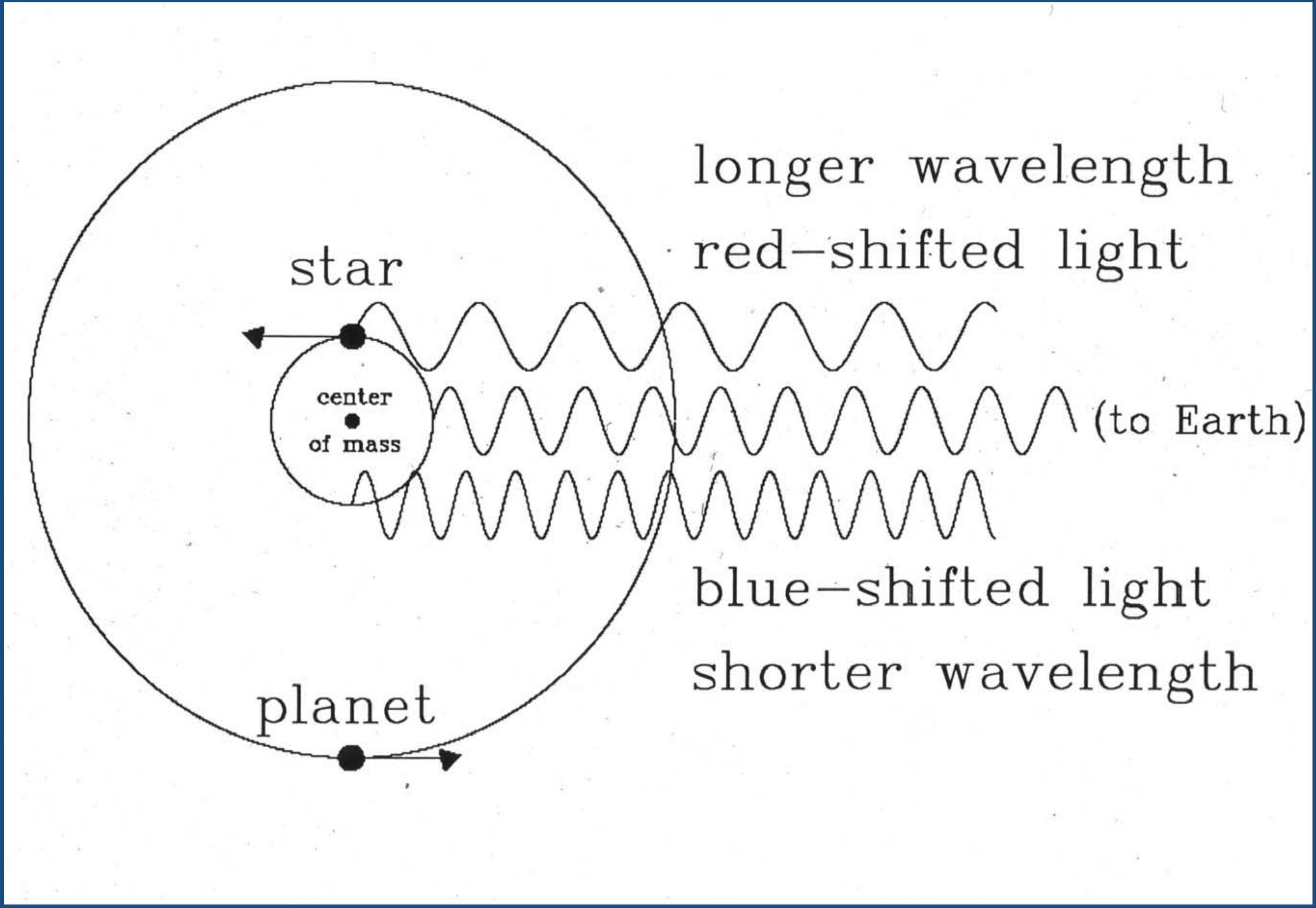
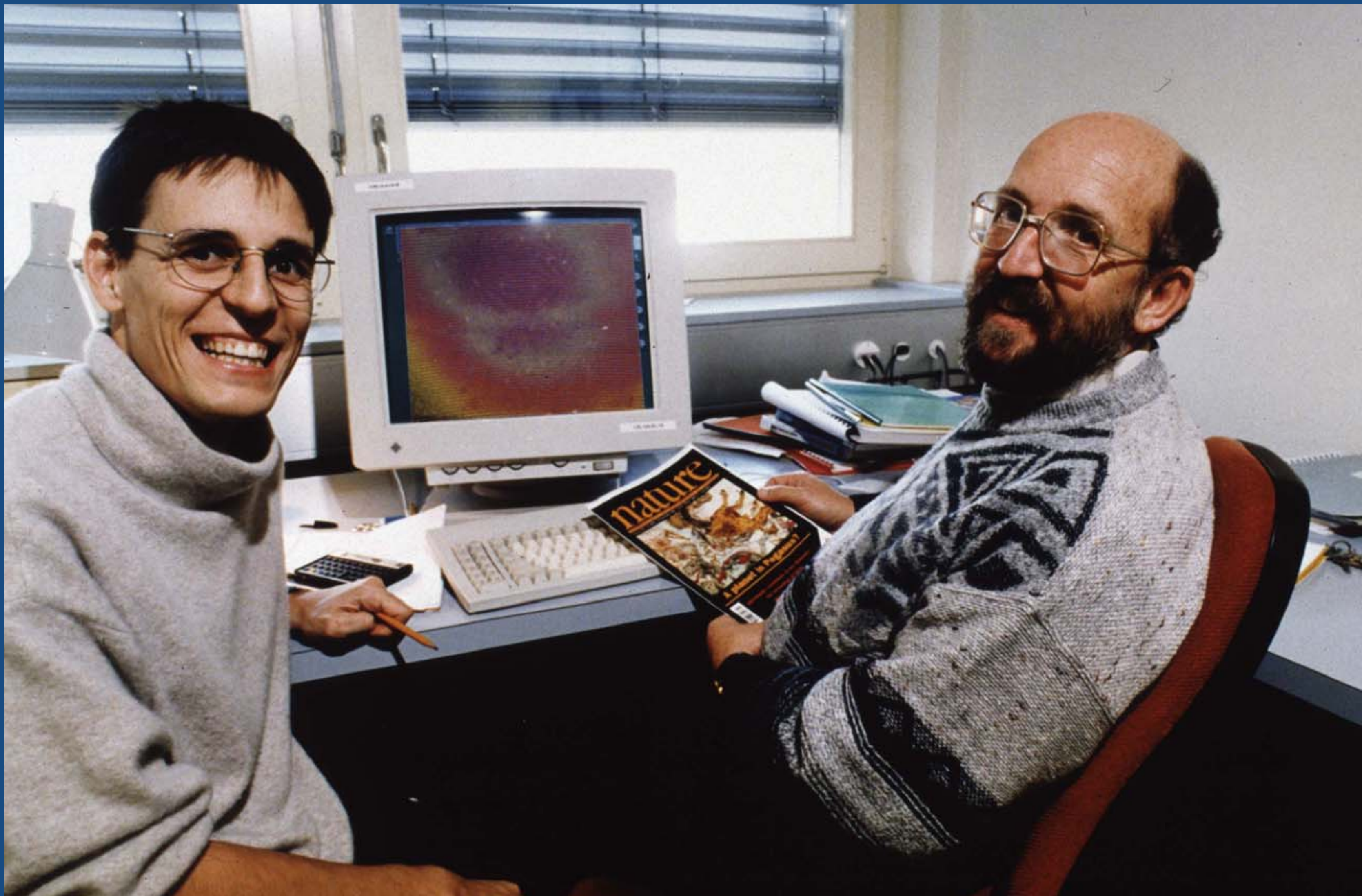



FIG. 1. Normal points.


longer wavelength
red-shifted light
star
center
of mass
(to Earth)
blue-shifted light
shorter wavelength
planet


nature

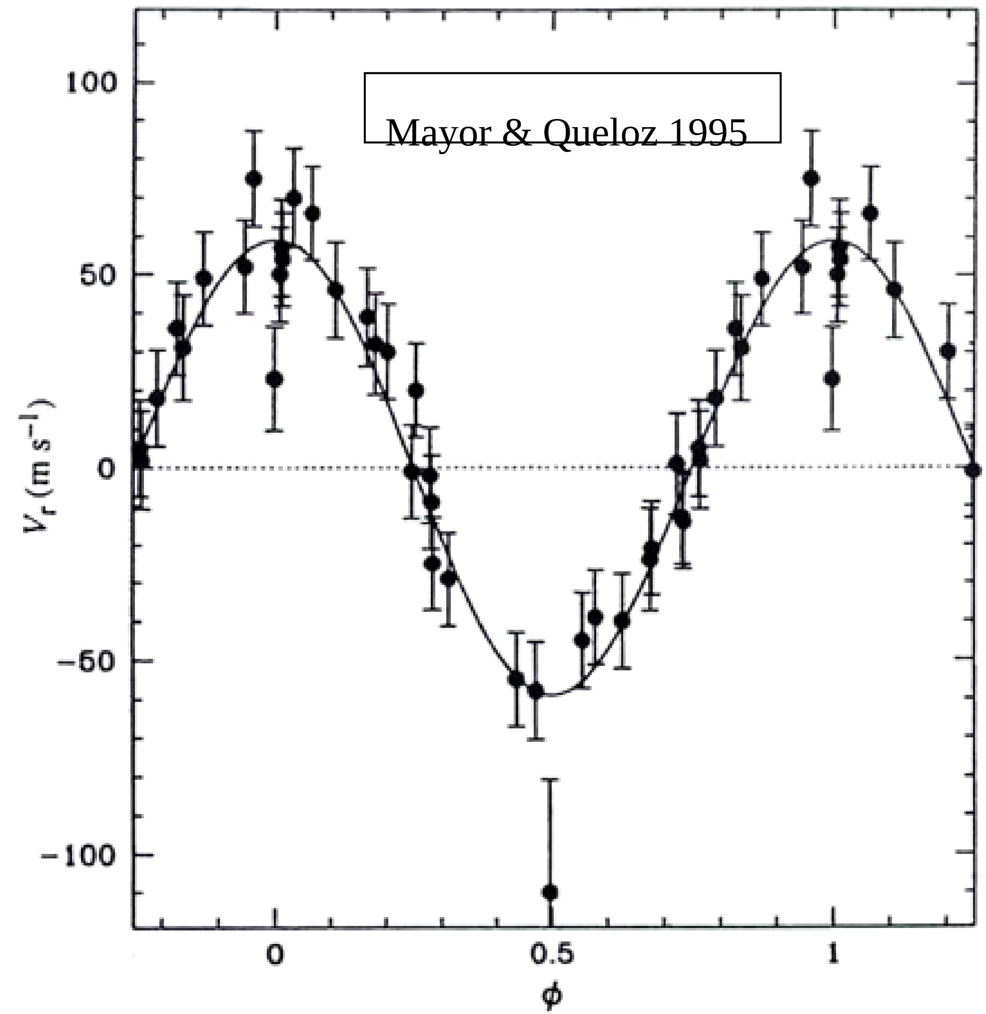
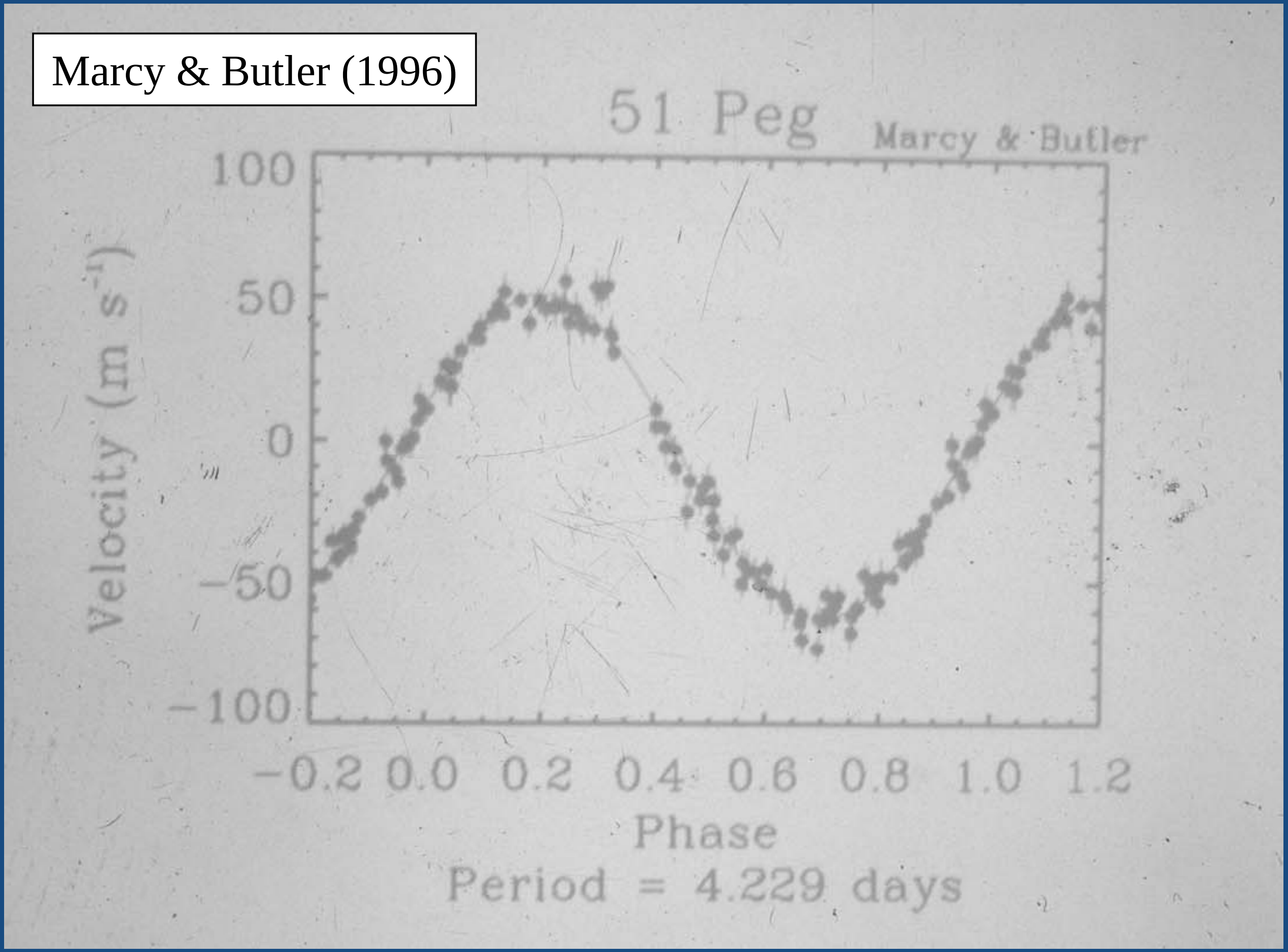
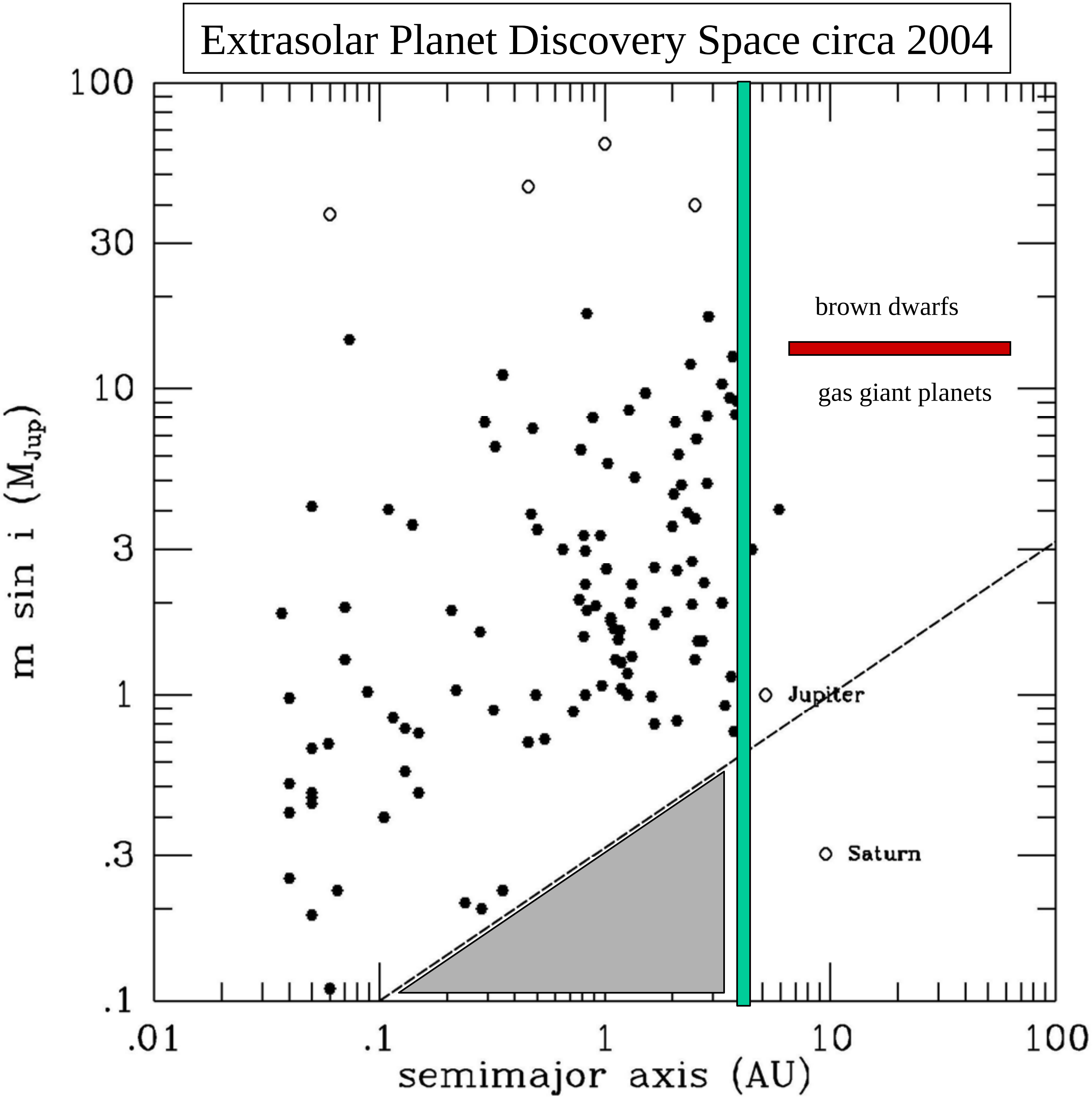



FIG. 4 Orbital motion of 51 Peg corrected from the long-term variation of the $\gamma$-velocity. The solid line represents the orbital motion computed from the parameters of Table 1.

Marcy & Butler (1996)

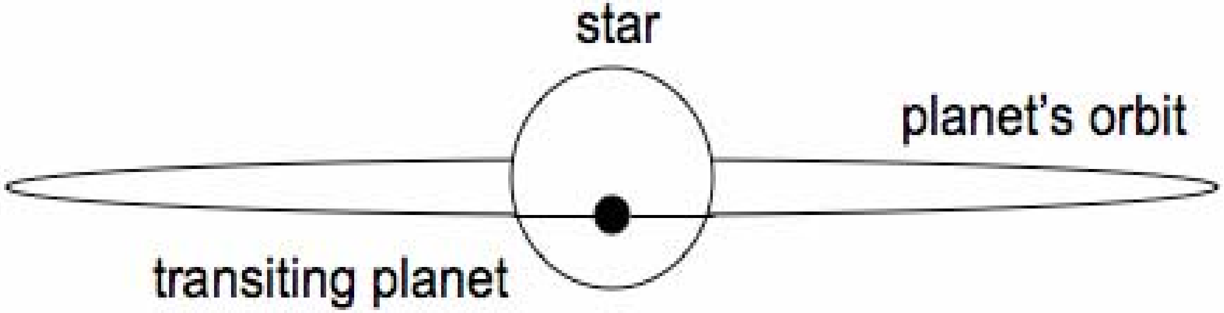



<unregistered>



Extrasolar Planet Discovery Space circa 2004
100
30
10
3
1
.3
.1
m sin i ($M_{Jup}$)
.01
.1
1
10
100
semimajor axis (AU)
brown dwarfs
gas giant planets
Jupiter
Saturn

# Planetary transits



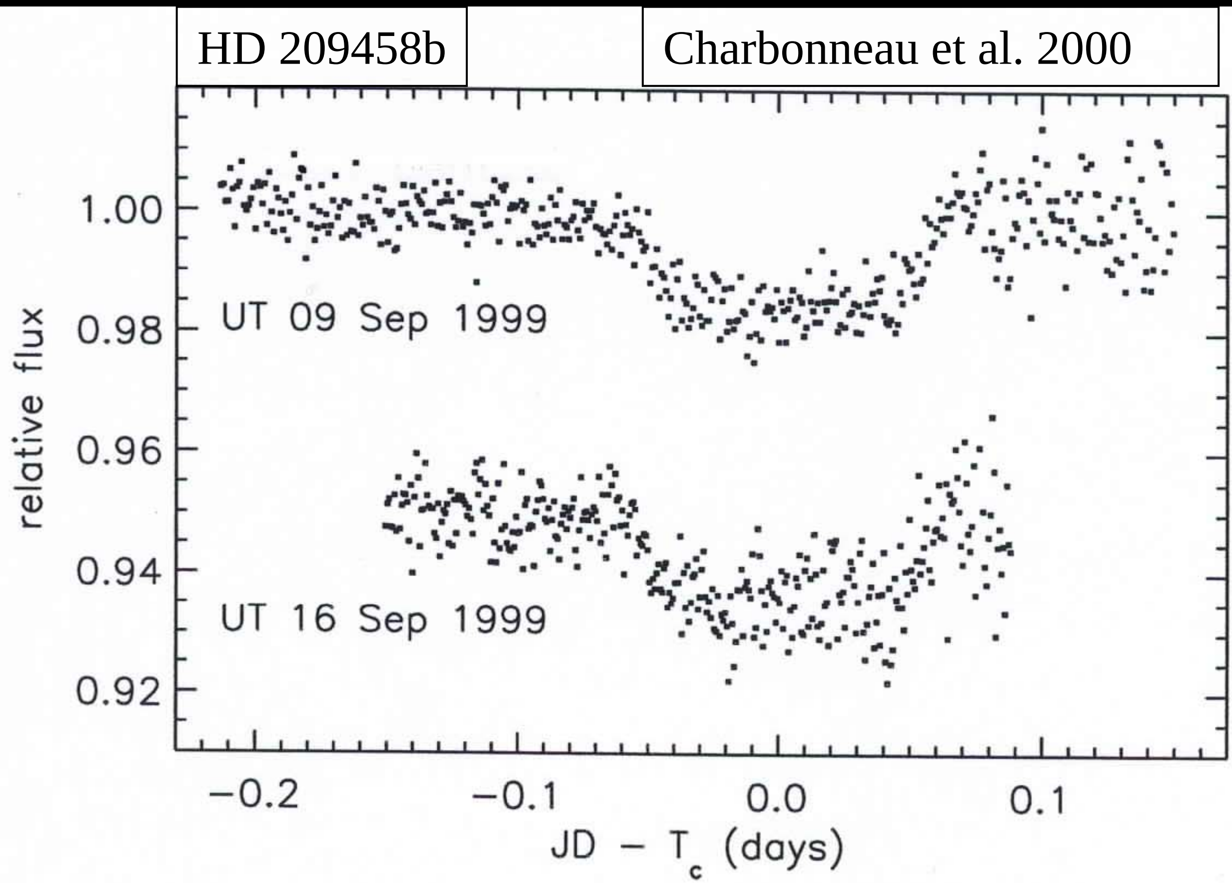
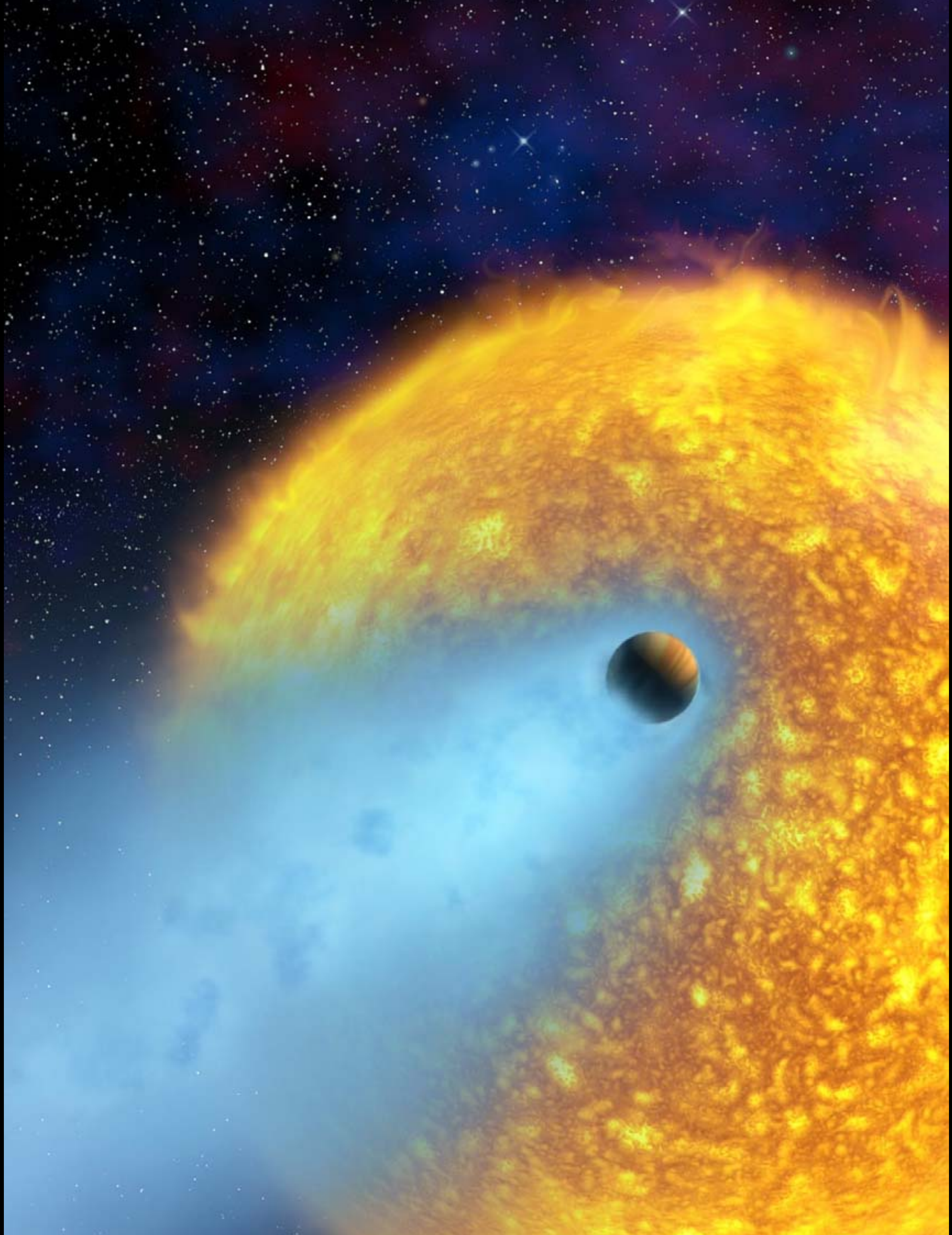
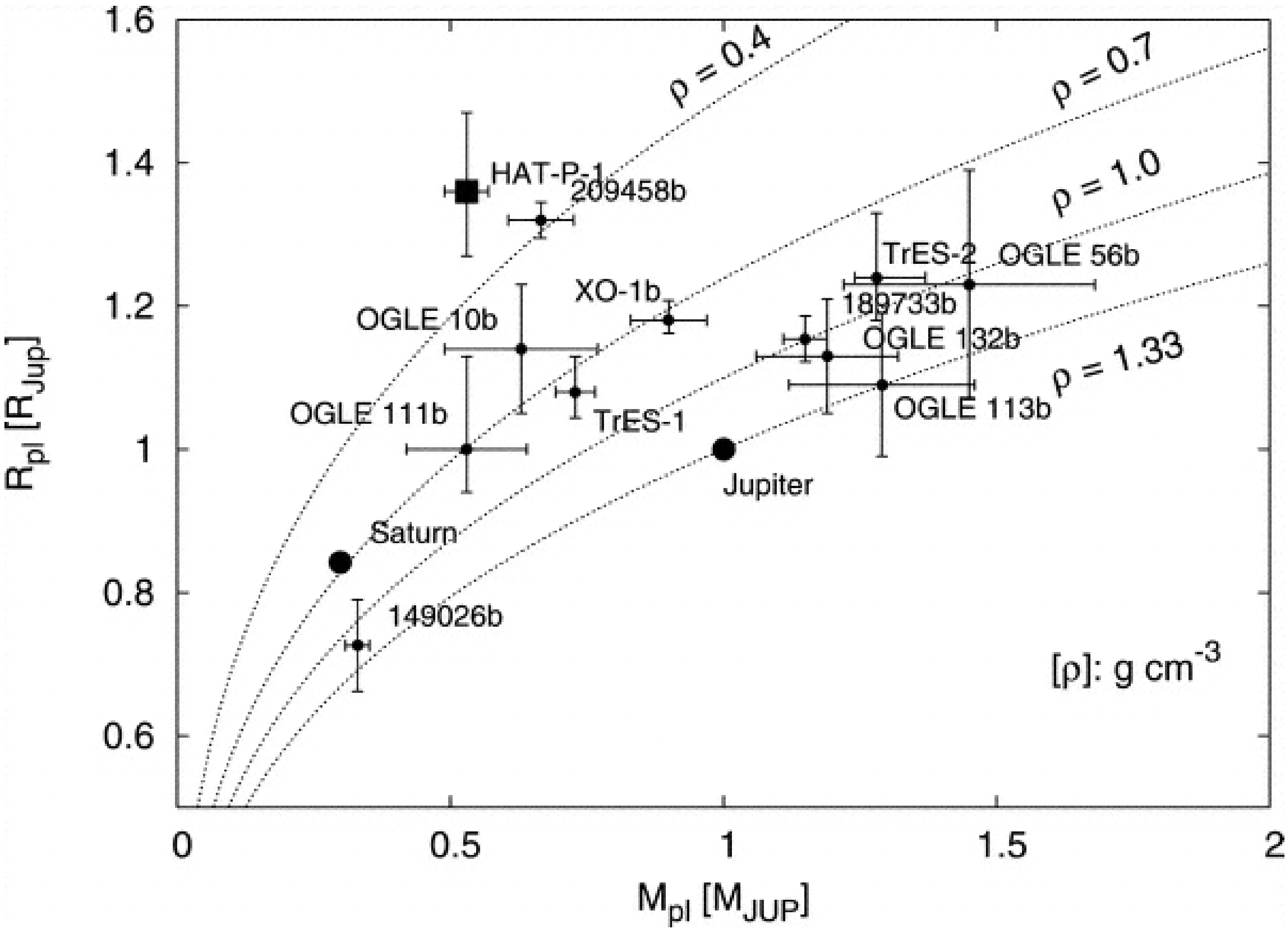
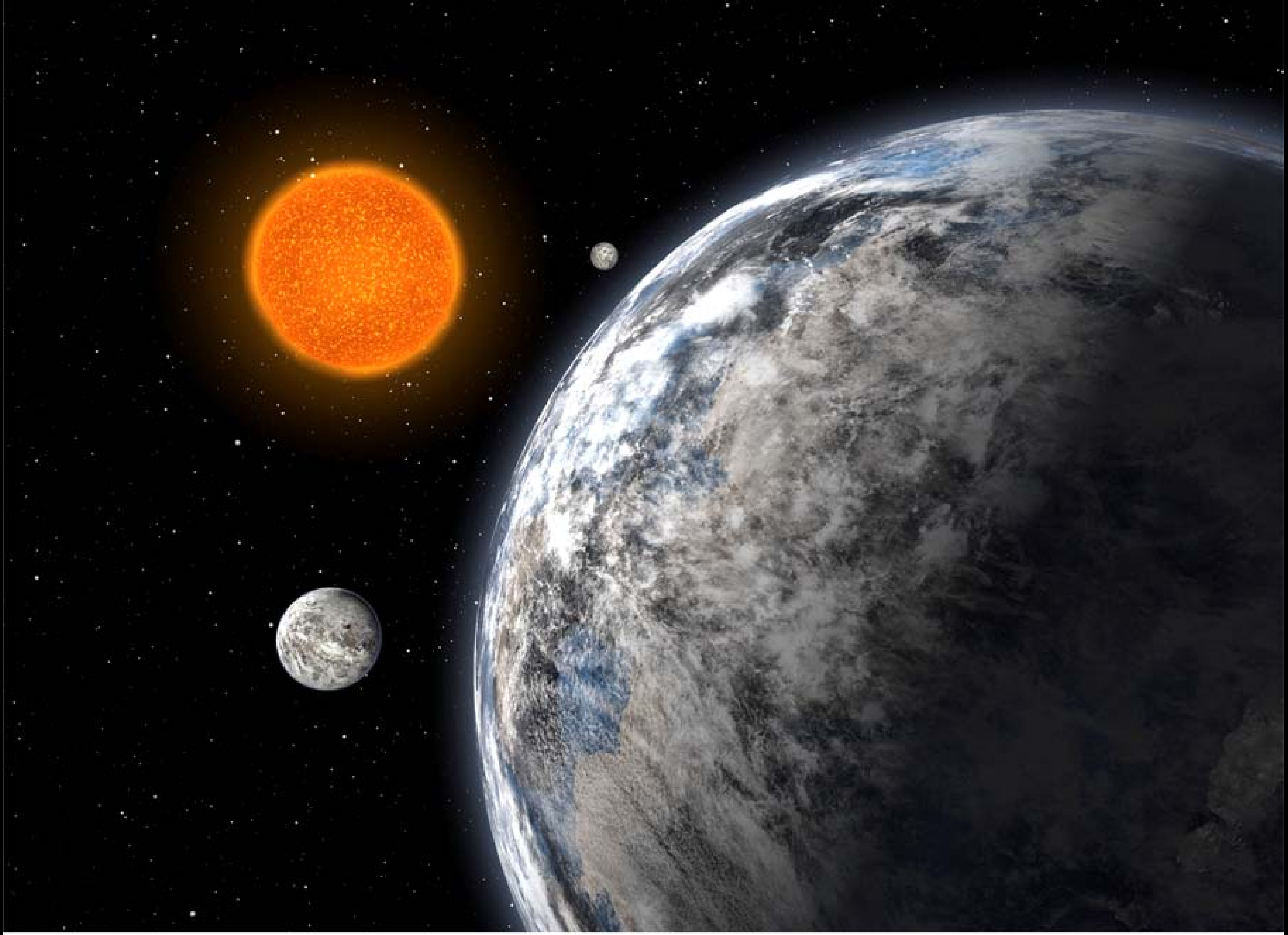



Fig. 1.— Shown are the photometric time series, corrected for gray and color-dependent extinction, for 9 & 16 Sep 1999, plotted as a function of time from $T_c$. The RMS of the time series at the beginning of the night on 9 Sep is roughly 4 mmag. The increased scatter in the 16 Sep data relative to the 9 Sep data is due to the shorter exposure times. The data from 16 Sep are offset by -.05 relative to those from 9 Sep.



Bakos et al. 2007

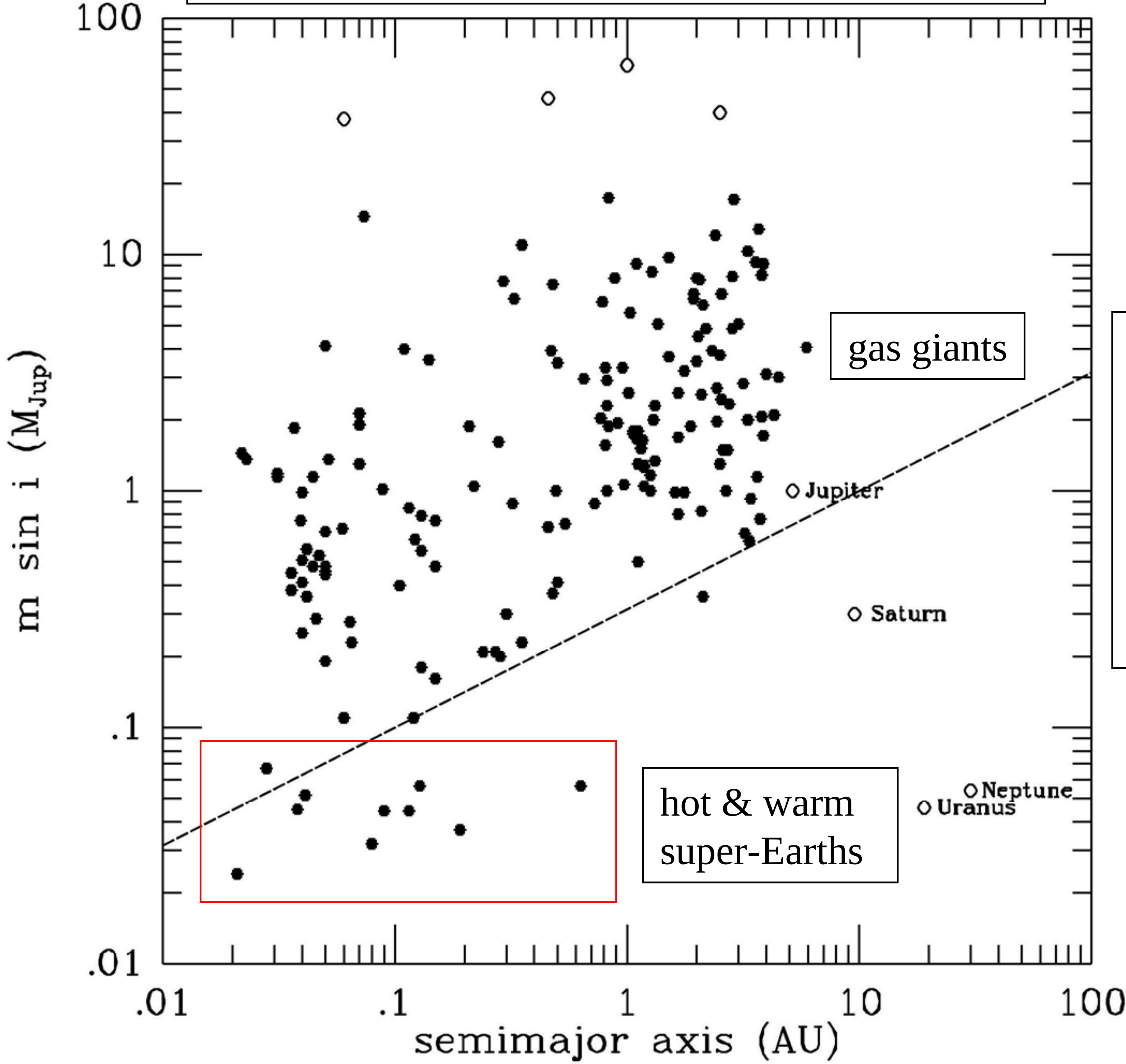




# A Trio of Super-Earths
# (Artist's Impression)

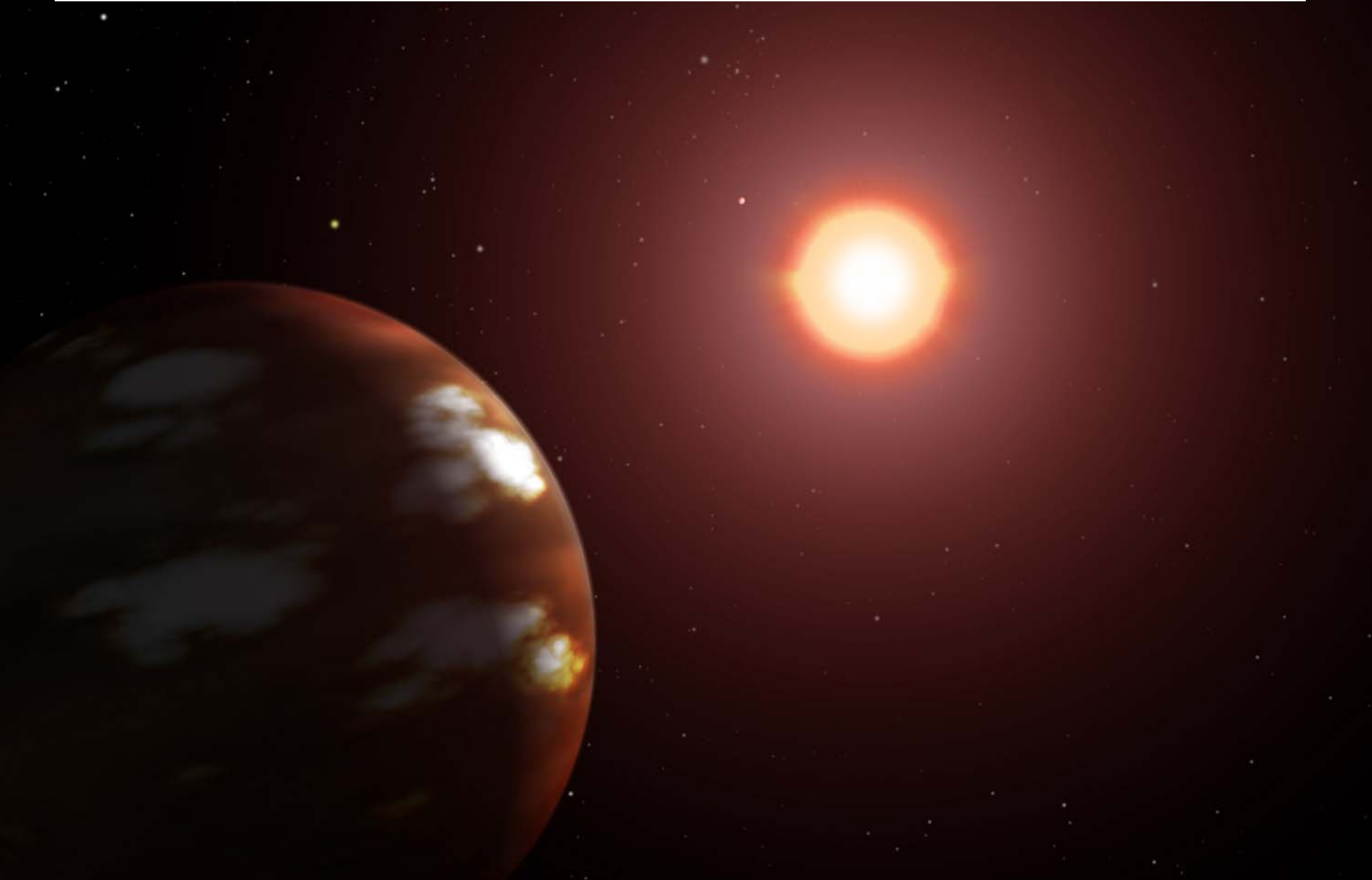
ESO Press Photo 19a/08 (16 June 2008)

# Discovery space with hot and warm super-Earths

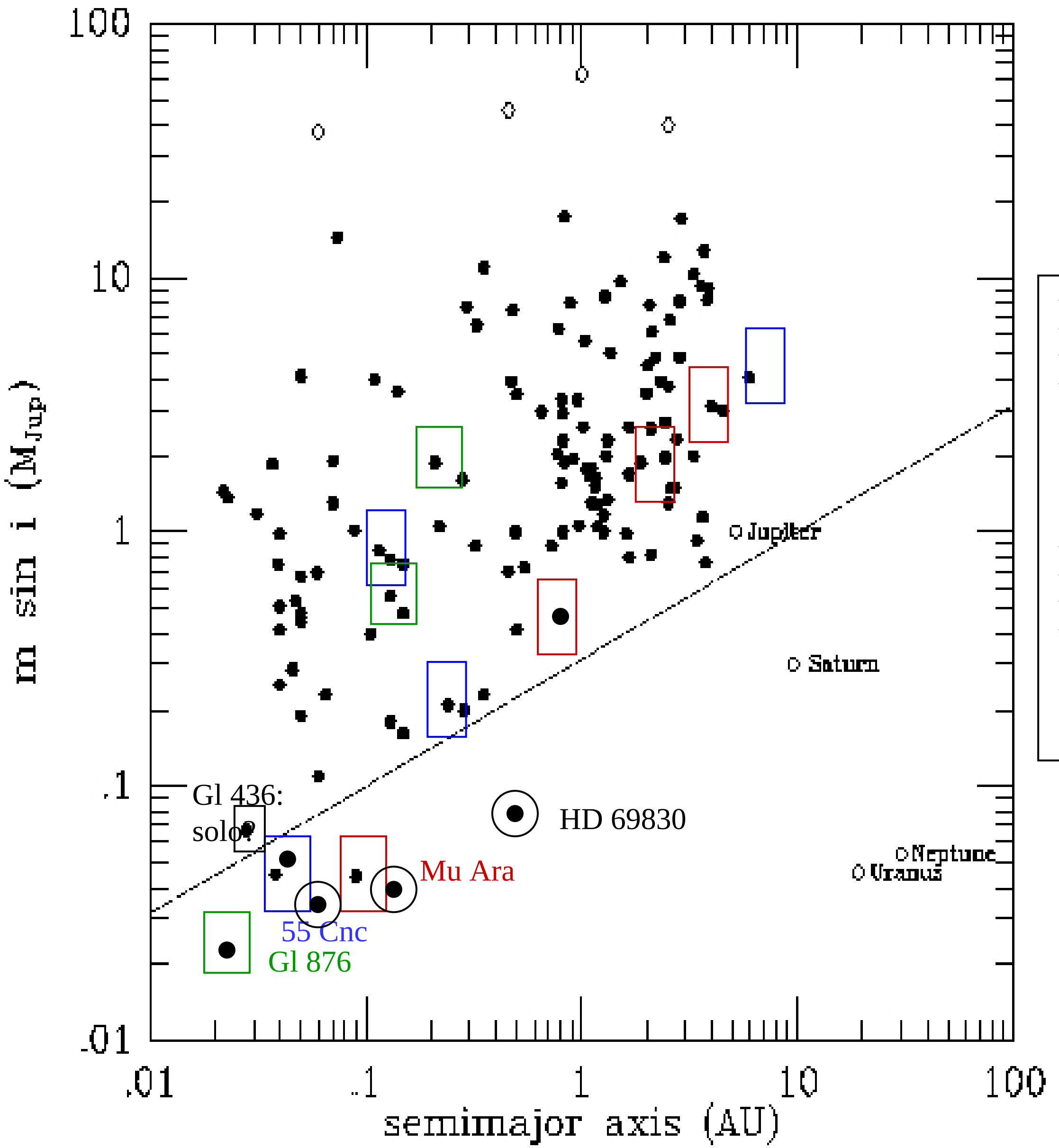



HD 40307: 3 hot super-Earths with 4.2, 6.9, and 9.2 Earth-masses and a longer-period companion (Mayor et al. 2008)

# Gliese 436 b - first transiting hot super-Earth (Gillon et al. 2007)



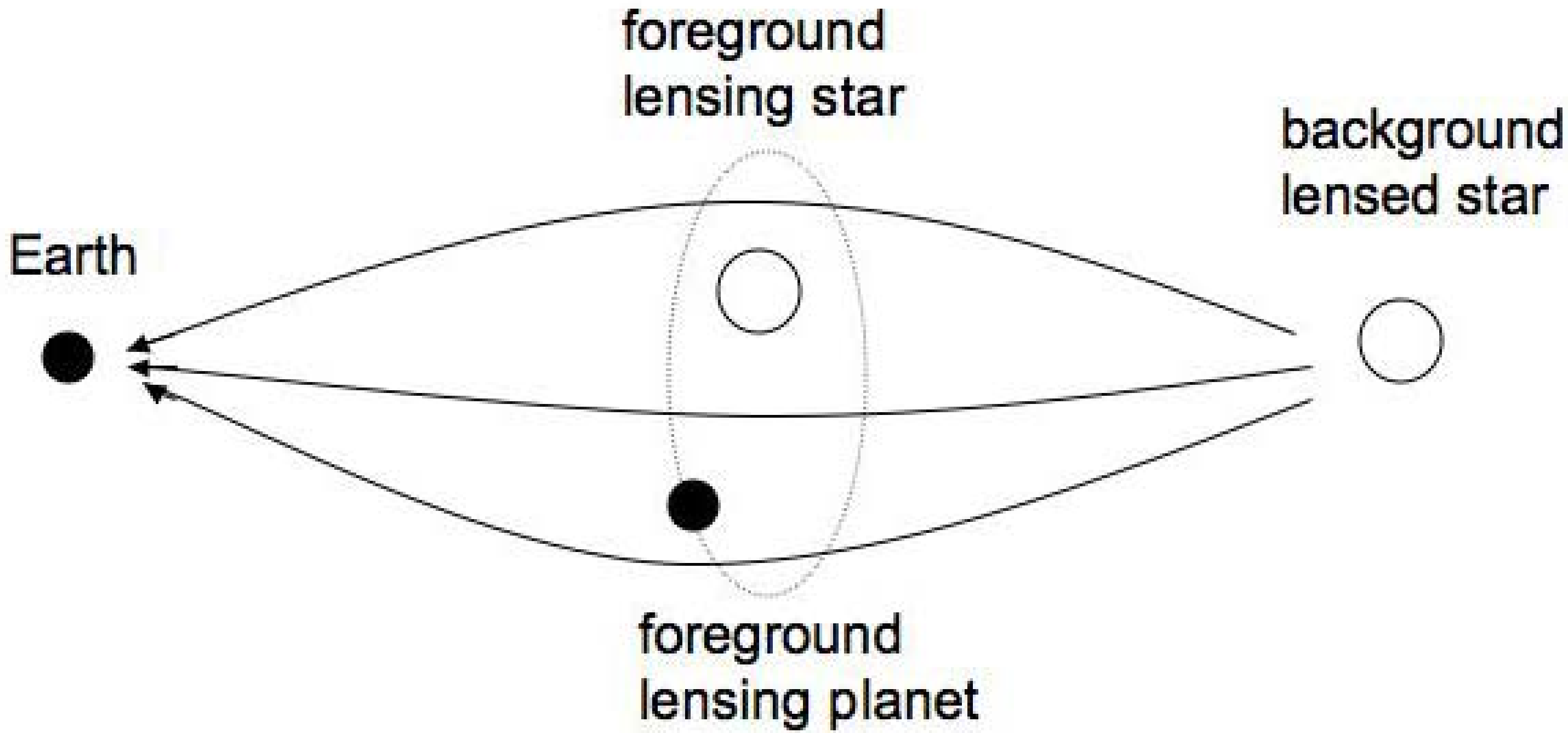
Discovery space with hot and warm super-Earths and their gas giant planet siblings



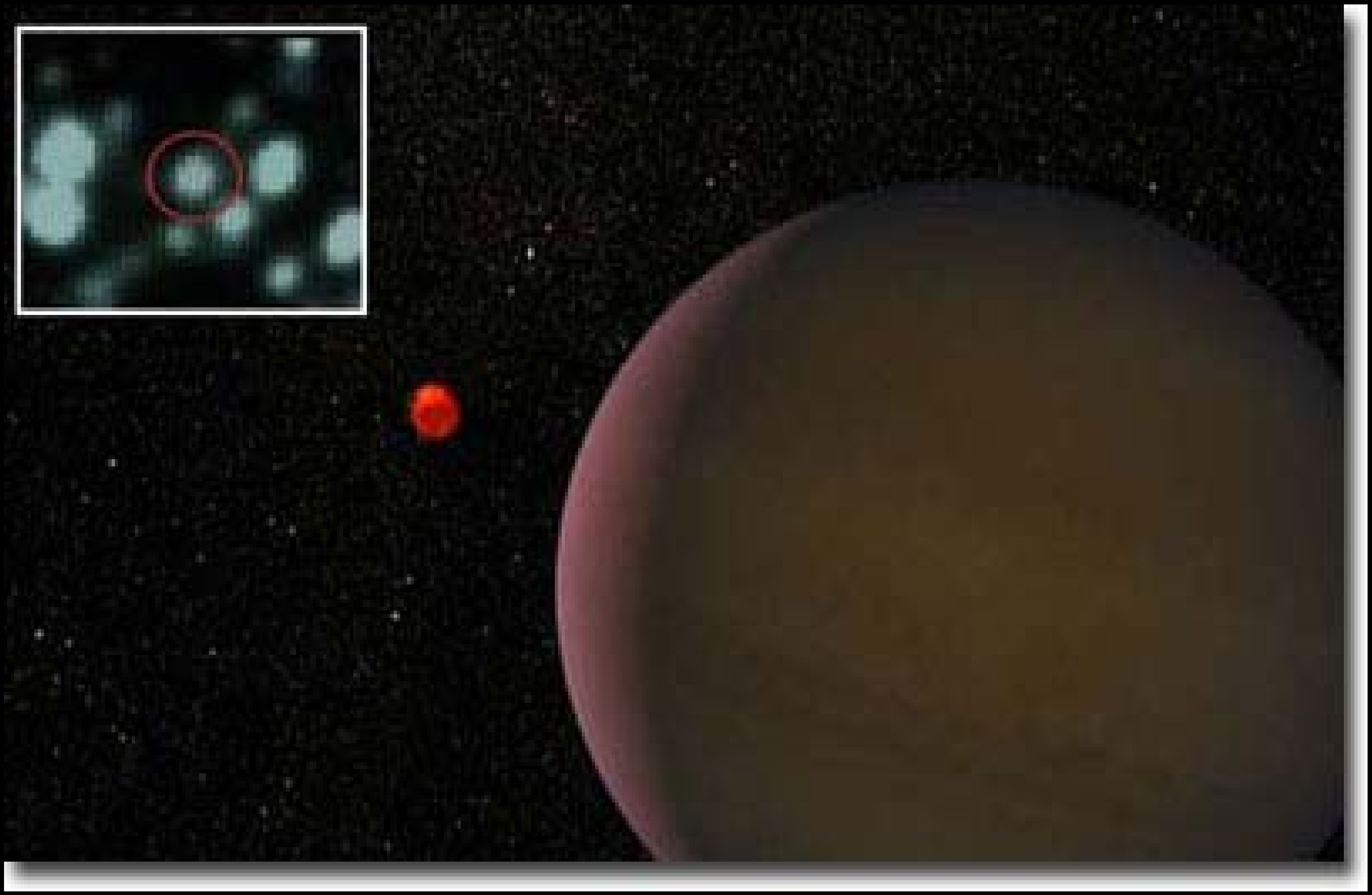

HD 181433: inner 7.5 Earth-mass and two outer Jupiters (Bouchy et al. 2009)

HD 47186: inner 22 Earth-mass and outer Saturn (Bouchy et al. 2009)

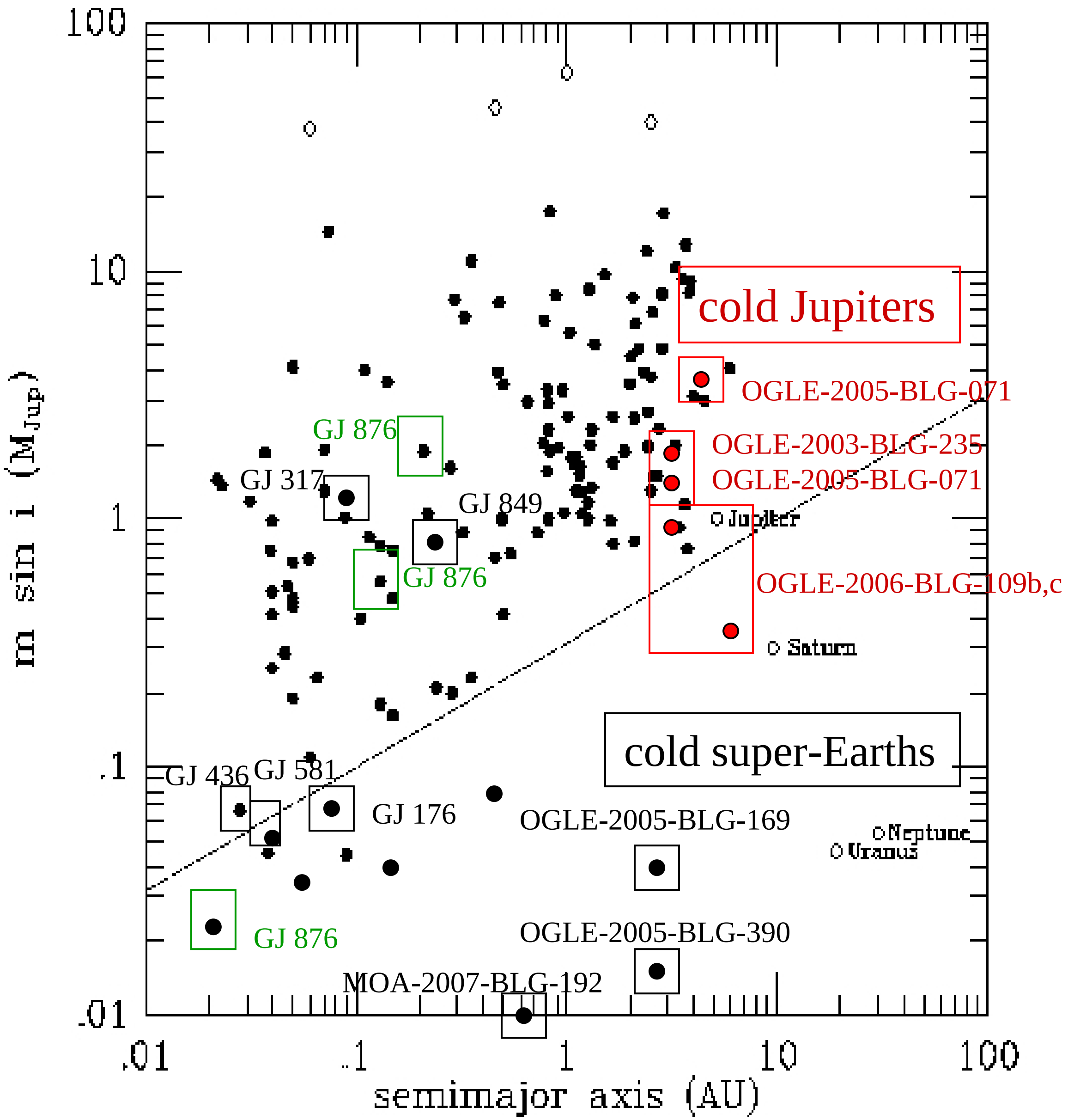
# Gravitational microlensing

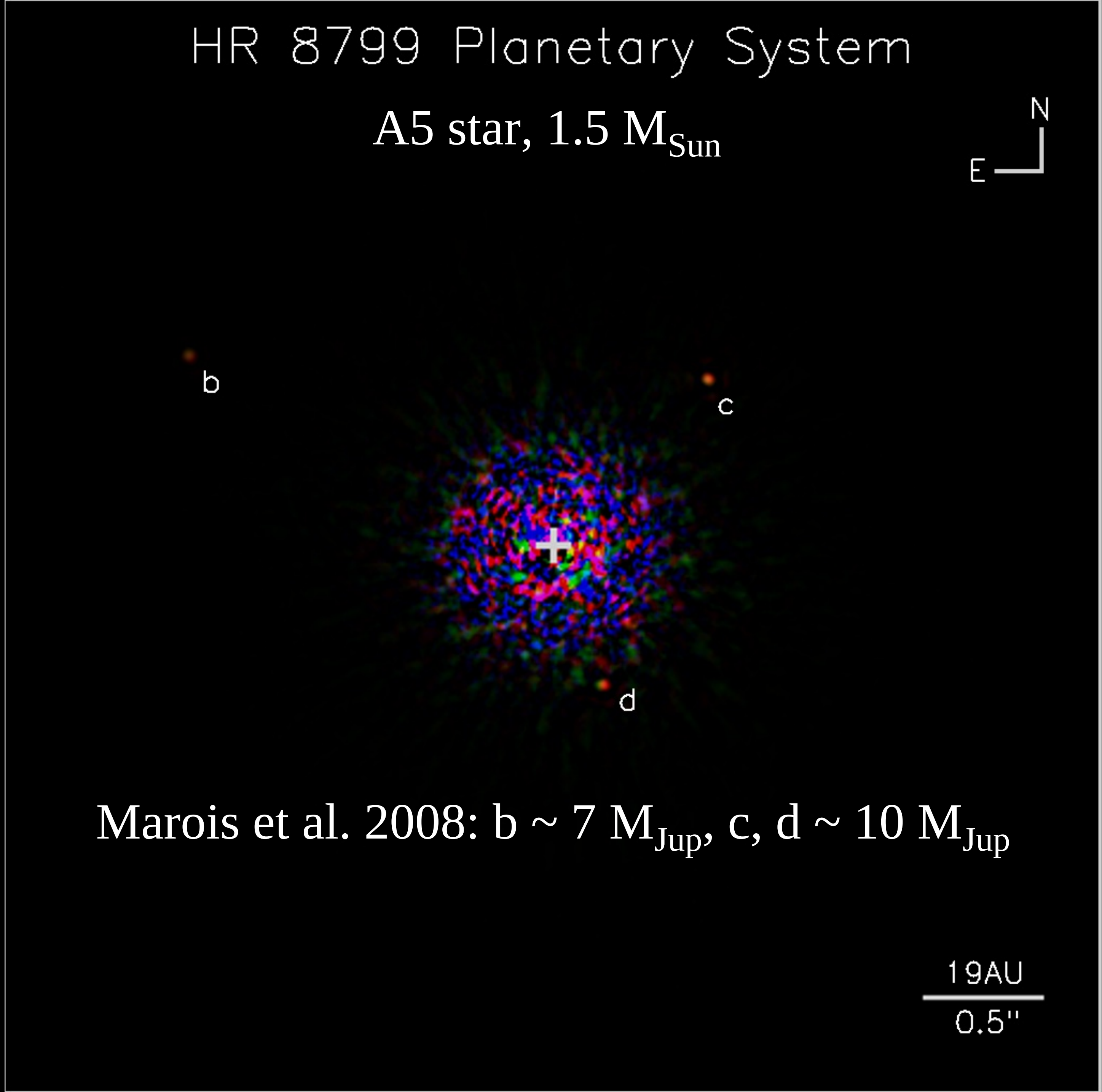


Microlensing detection with Warsaw 1.3m telescope, Las Campanas - 2004



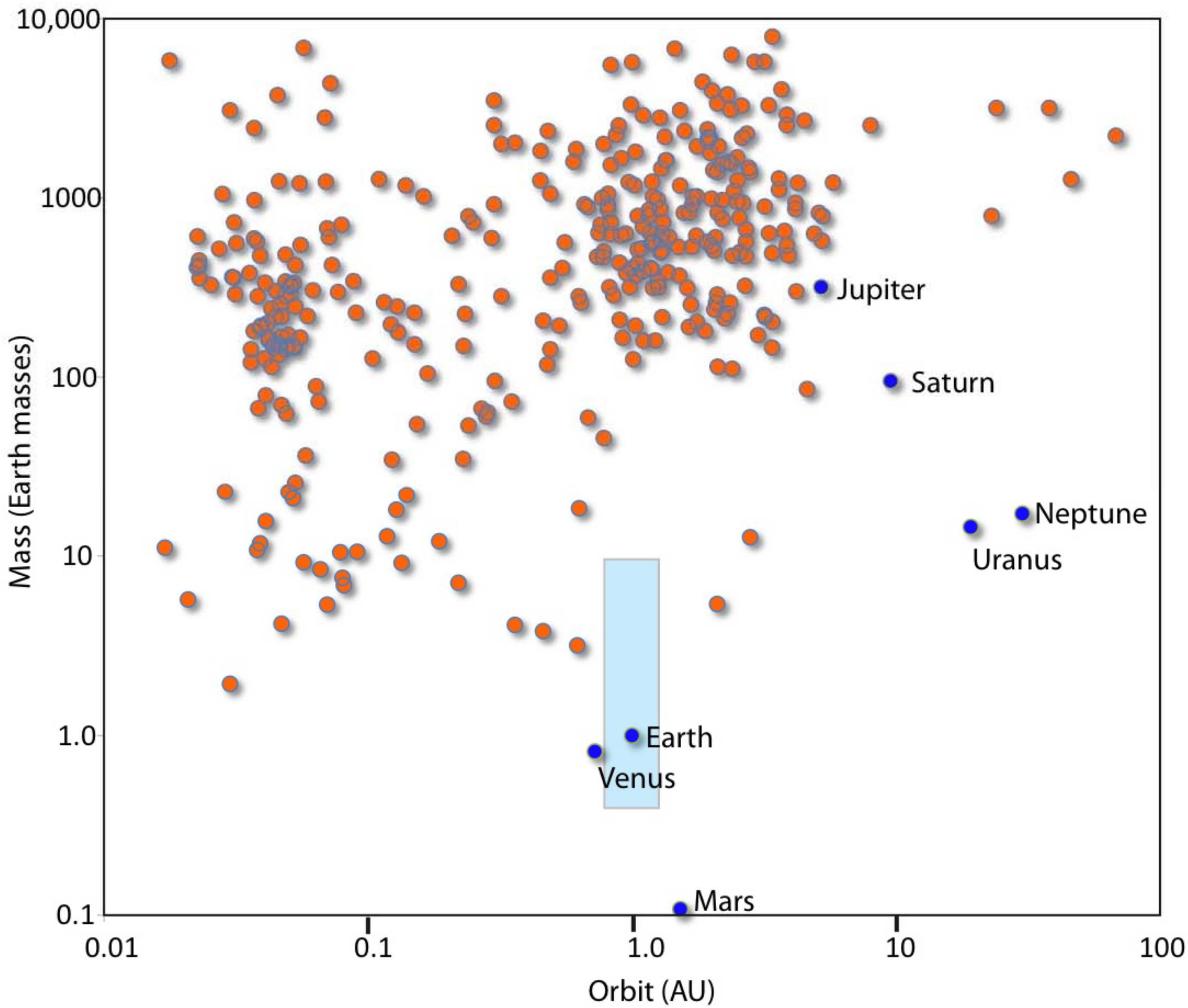
# Discovery space with planets around M dwarf stars highlighted





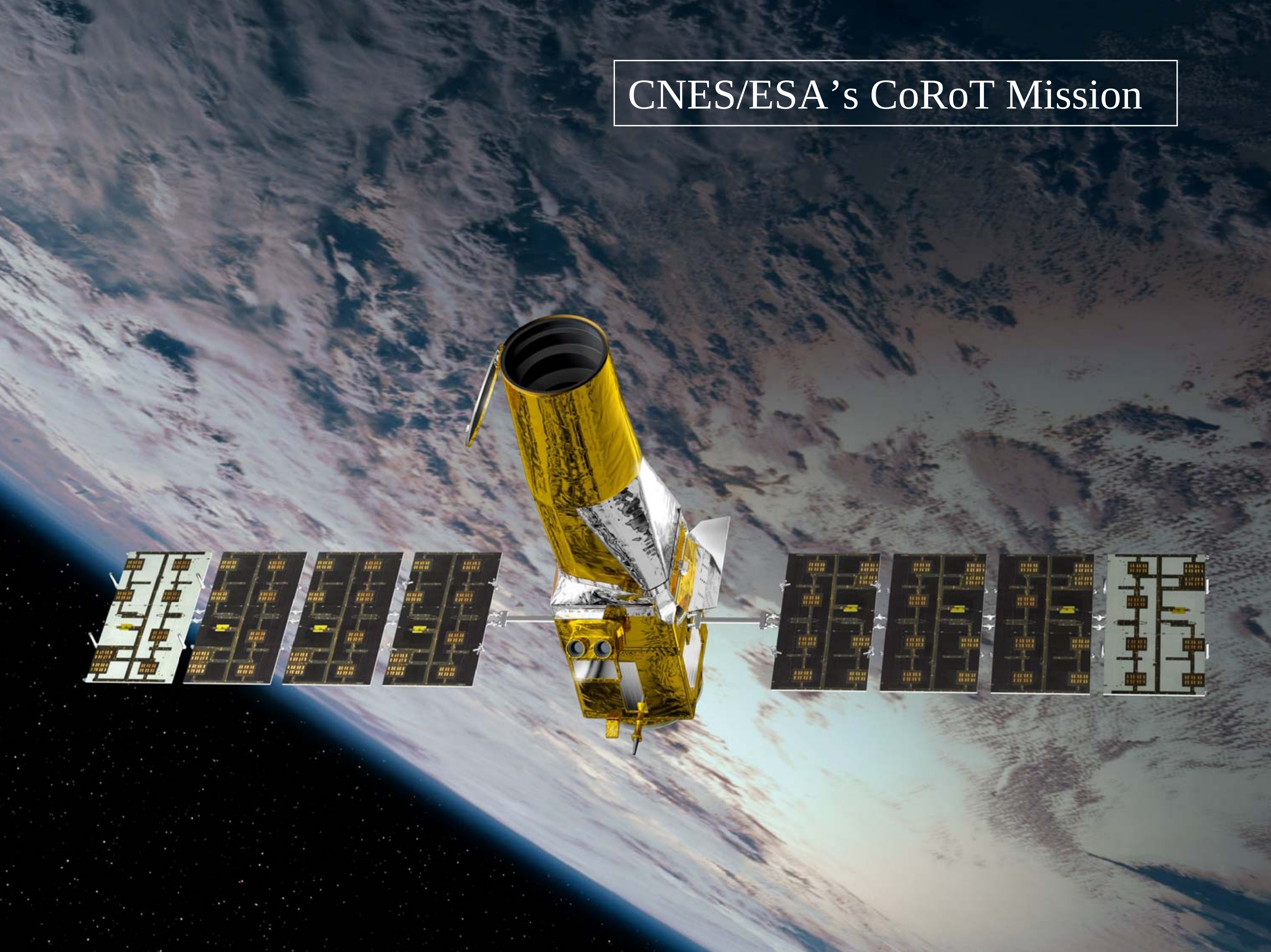

A5 star, 1.5 $M_{Sun}$

Marois et al. 2008: b ~ 7 $M_{Jup}$, c, d ~ 10 $M_{Jup}$

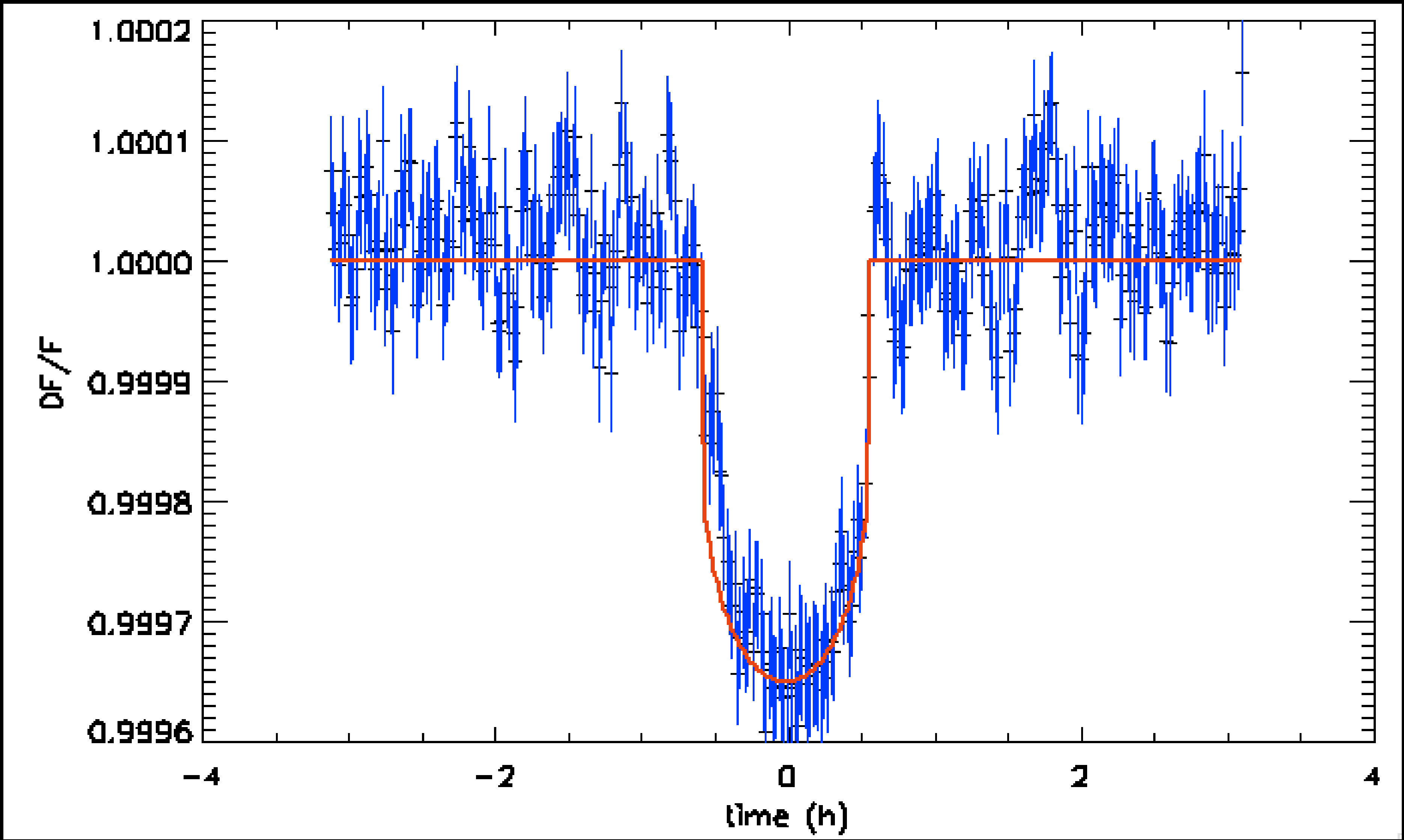


10,000
1000
100
10
1.0
0.1
Mass (Earth masses)
0.01
0.1
1.0
10
100
Orbit (AU)
Jupiter
Saturn
Neptune
Uranus
Earth
Venus
Mars

CNES/ESA’s CoRoT Mission

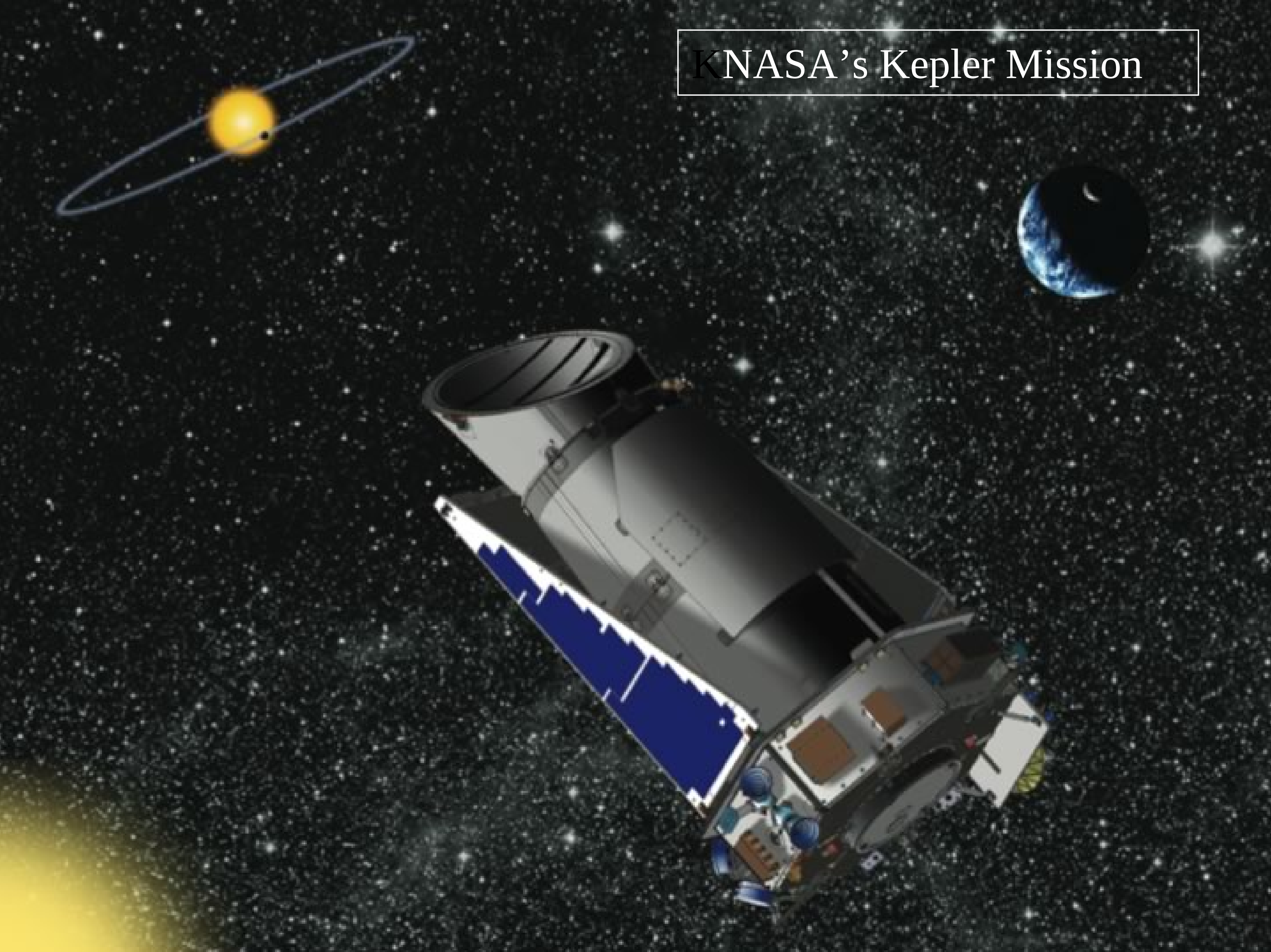


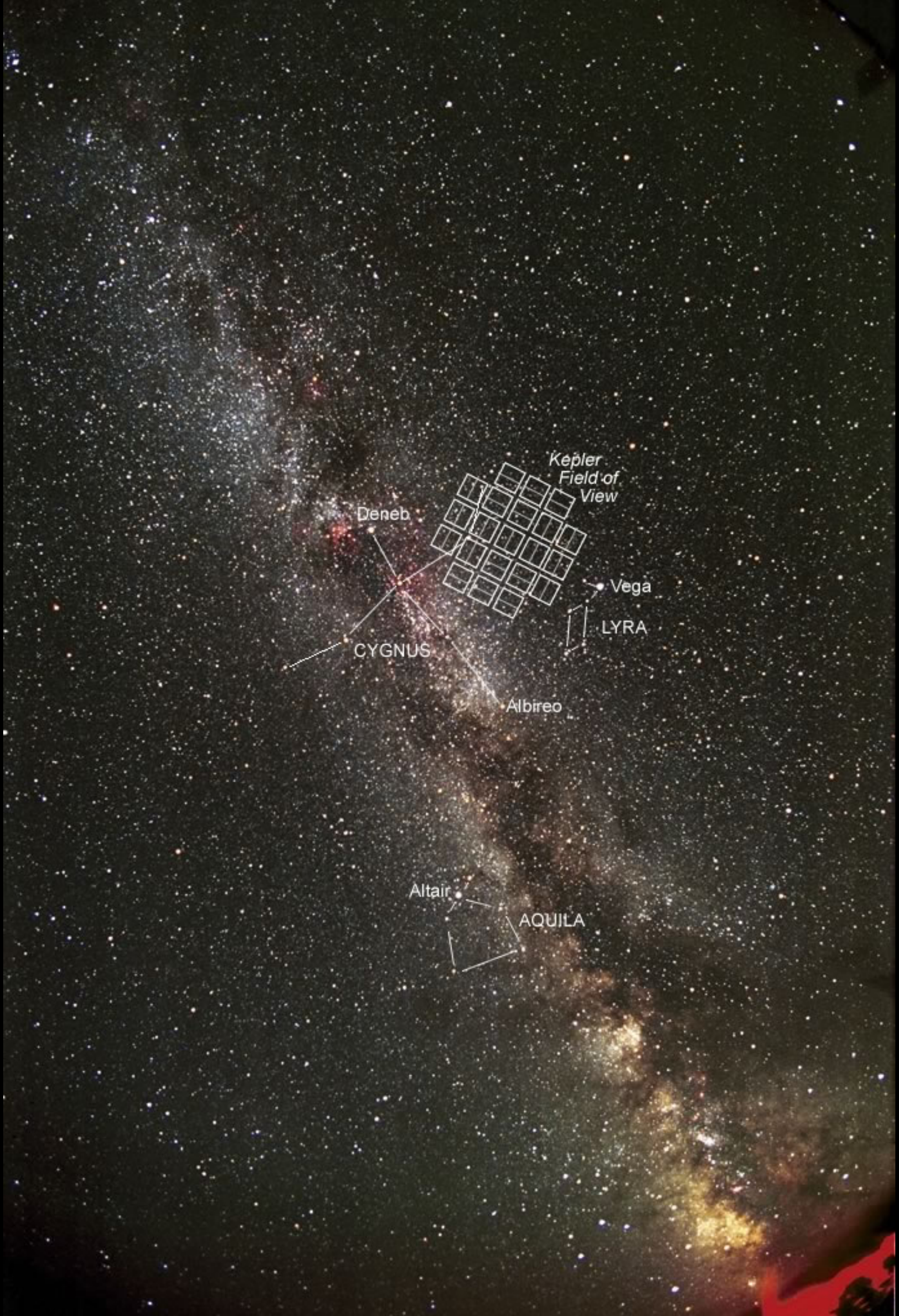
CoRoT- Exo-7 b, the smallest radius transiting planet found to date: radius = 1.68 Earth-radii, mass = 4.8 Earth-masses, and a density = 5.6 g/cc, close to that of Earth (5.5 g/cc)



# Kepler Mission launch - March 6, 2009

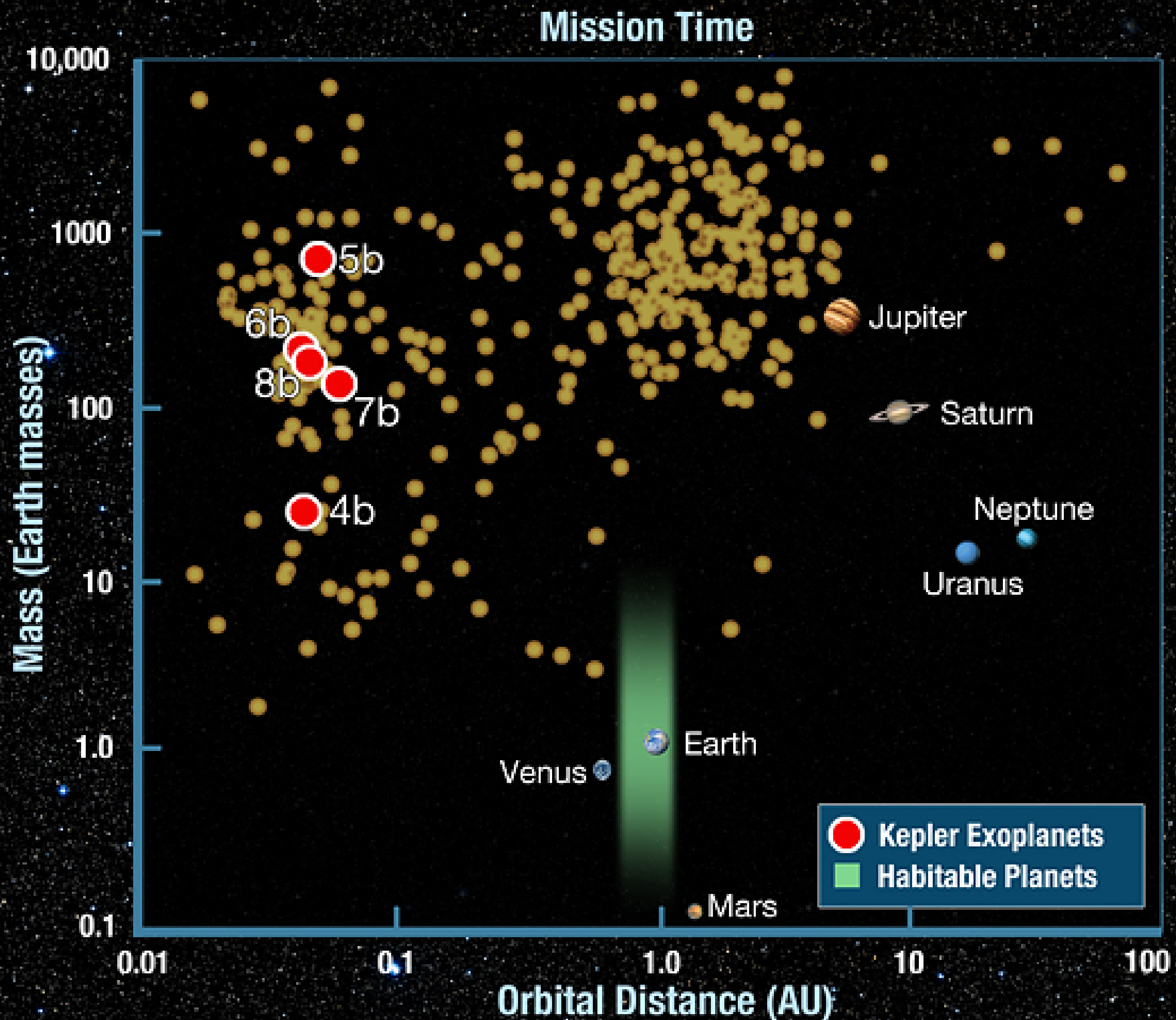
Venus transiting the Sun on June 8, 2004 (Robert Traube image)

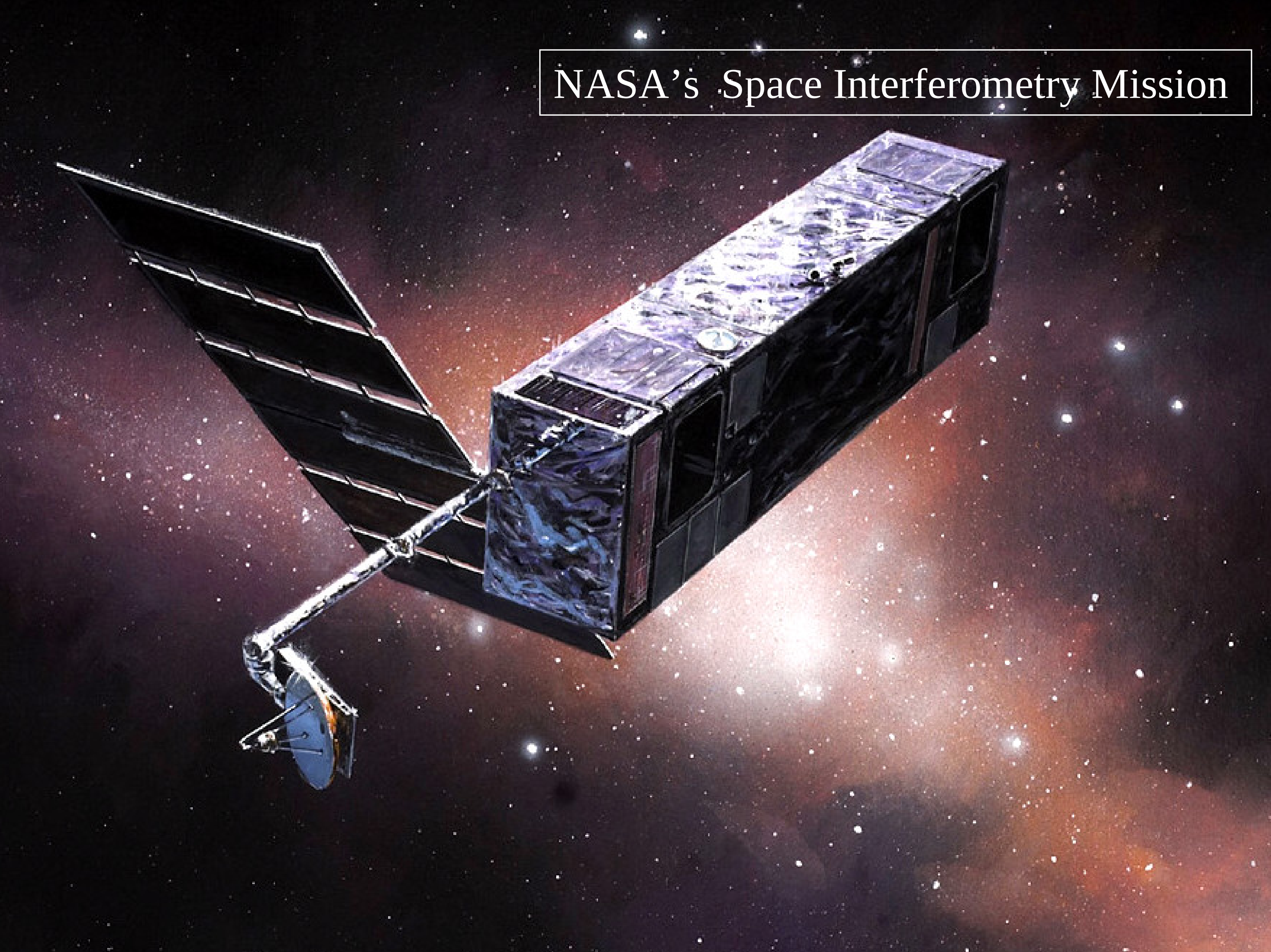

KNASA’s Kepler Mission


Kepler
Field of
View
Deneb
Vega
LYRA
CYGNUS
Albireo
Altair
AQUILA

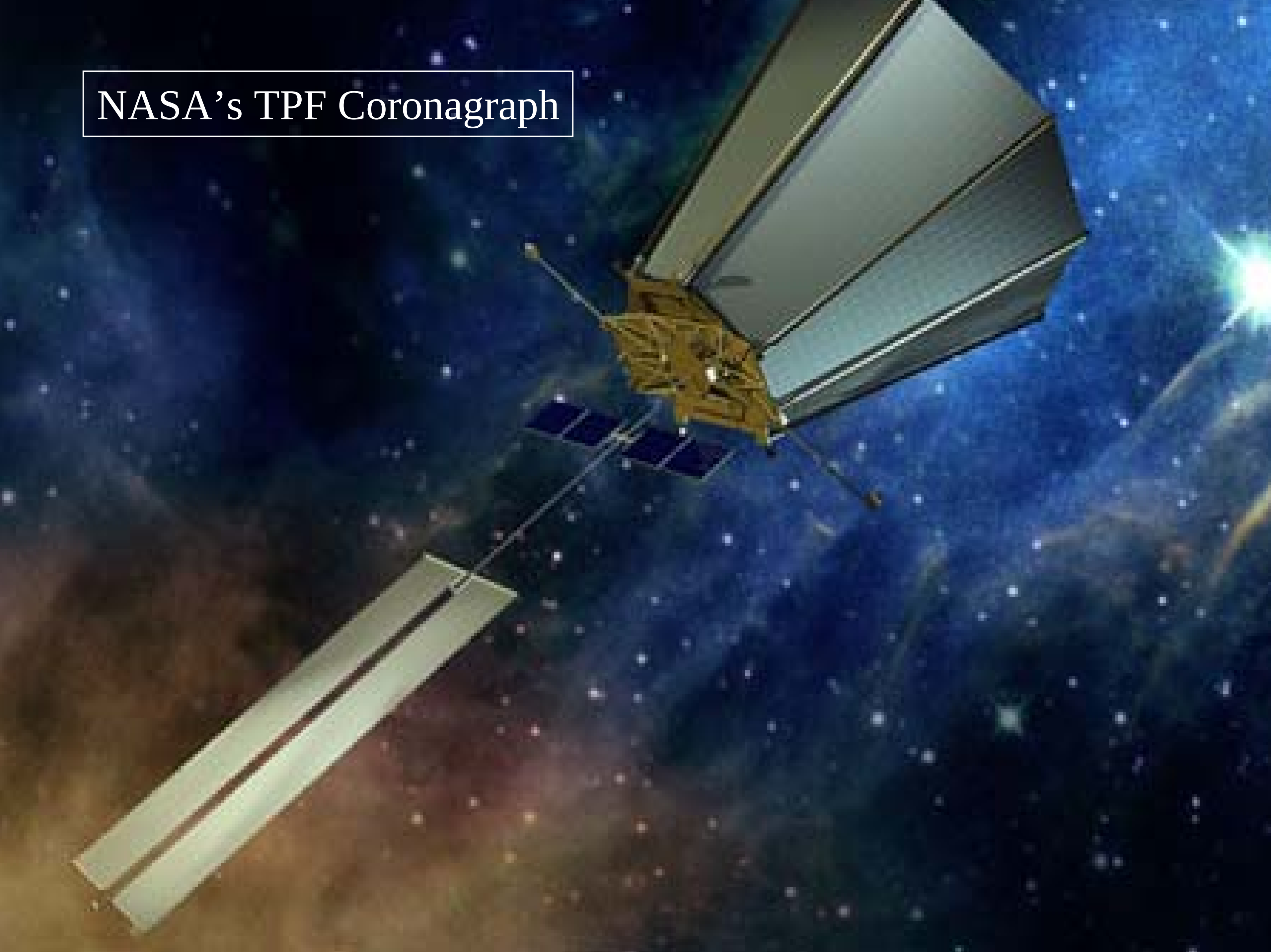
# First Five Planet Discoveries

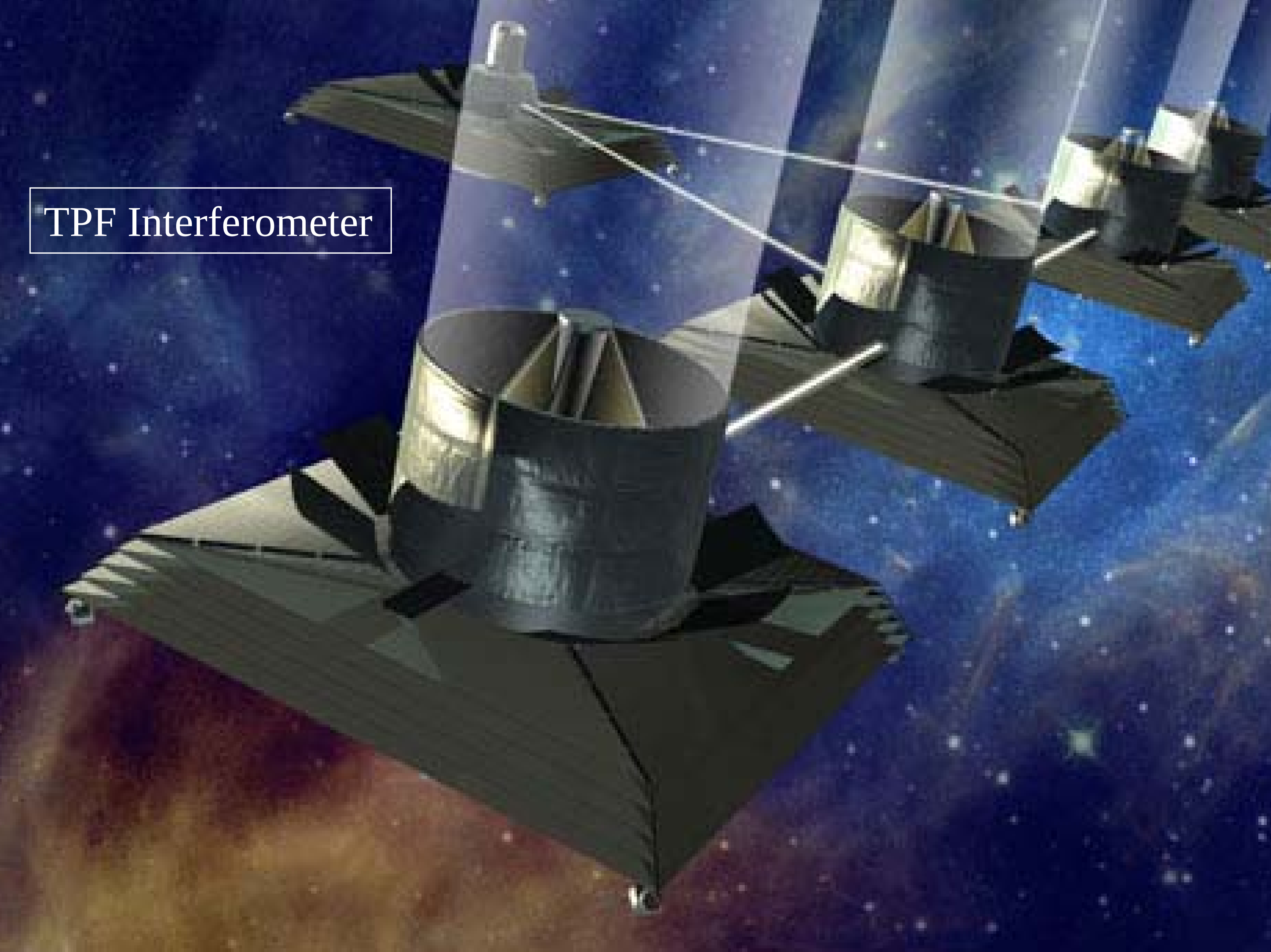
## Made with First 43 Days of Data




NASA's Space Interferometry Mission


QUICK & EASY DIRECTIONS
MIX SOUP + 1 OCEAN WATER
RADIATION : HEAT, UNCOVERED IN MICROWAVABLE OCEAN ON HIGH ABOUT 100 MILLION YEARS. CAREFULLY LEAVE IN OCEAN FOR 3 BILLION YEARS, ALLOWING OXYGEN TO ACCUMULATE.
SMOKER: HEAT, CIRCULATING OCCASIONALLY
REG. U.S. PAT. & TM. OFF.
PROMPTLY REFRIGERATE UNUSED PORTION ON A SEPARATE PLANET.
RECOMMEND USE BY DATE ON END OF CAN.
STORE UNOPENED CAN IN INTERSTELLAR SPACE.
Nutrition Facts
Serv. Size 1 mole serves one planet
Calories 0.0
Fat Calories 0.0
Serving size based on a 99% chance of a successful Origin of Life.
Amount/serving %DV Amount/serving %DV
Protein 0% Metal sulfides 100%
Fat 0% Hydrogen 100%
Carbohydrate 0% Ammonia 100%
Fiber 0% Methane 100%
Vitamins 0% Carbon monoxide 100%
L-amino acids 1% Formaldehyde 100%
D-amino acids 1% High MW PAHs 100%
Nucleic acid 0% NP-40 100%
Rich in reducing power, low in toxic oxygen and reactive oxygen products. High in heavy and transition metals. Great for the hottest, most radioactive watery planets!
Satisfaction guaranteed. For questions or comments, please email arthur_dent@zz9.plural.z.alpha
Allow 5-6 x 10^24 years for refund or reply.
0 51000 01251 7
LABELS FOR EVOLUTION
Save Label
TM
1251-108-10
CARBON
Please RECYCLE
WHERE ENZYMES AVAILABLE
Campbell's®
CONDENSED
PARIS INTERNATIONAL EXPOSITION 1900
Primordial
SOUP
NET WT. 10 3/4 OZ. (305g)
INSPECTED FOR WHOLESOMENESS BY U.S. DEPARTMENT OF CHEMISTRY
A QUICK MEAL IN 4.5 BILLION YEARS!
PRIMORDIAL SOUP; FOR THE PRIMITIVE... AND THE PRIMITIVE AT HEART!
A SIMPLE, SELF-ORGANIZING MEAL WITH EVERYTHING YOU NEED TO GET YOUR LIFE STARTED BEFORE THE ARCHAEAN PASSES BY. GREAT FOR ALL WATERY PLANETS, SERVE HOT WITH LOTS OF REDUCING POWER AND A GOOD DOSE OF IONIZING RADIATION FOR THAT UNIQUE MICROBIAL FLAVOR!
INGREDIENTS: WATER, SILICA, IRON SULFIDE, HYDROGEN SULFIDE, CARBON DIOXIDE, HYDROGEN, POTASSIUM CYANIDE, POTASSIUM ACETATE, FORMALDEHYDE, ADENINE, PROLINE, ALANINE, METHANE, CARBON MONOXIDE, AMMONIA, SODIUM ARSENITE, GLYCEROL PHOSPHATE, ACETYLENE, ACETALDEHYDE, HIGH MOLECULAR-WEIGHT PAH'S, PYRENE, MAGNETITE, PHOSPHORIC ACID, WOLF'S TRACE MINERALS. AND NP-40.
JWB MOCK SOUP COMPANY, RALEIGH, NORTH CAROLINA JAMES_W_BROWN@EARTHLINK.NET


NASA’s TPF Coronagraph


TPF Interferometer

# ESA's Emma Darwin x-array

# Swain et al. (2008) - HD 189733 b with HST Nicmos

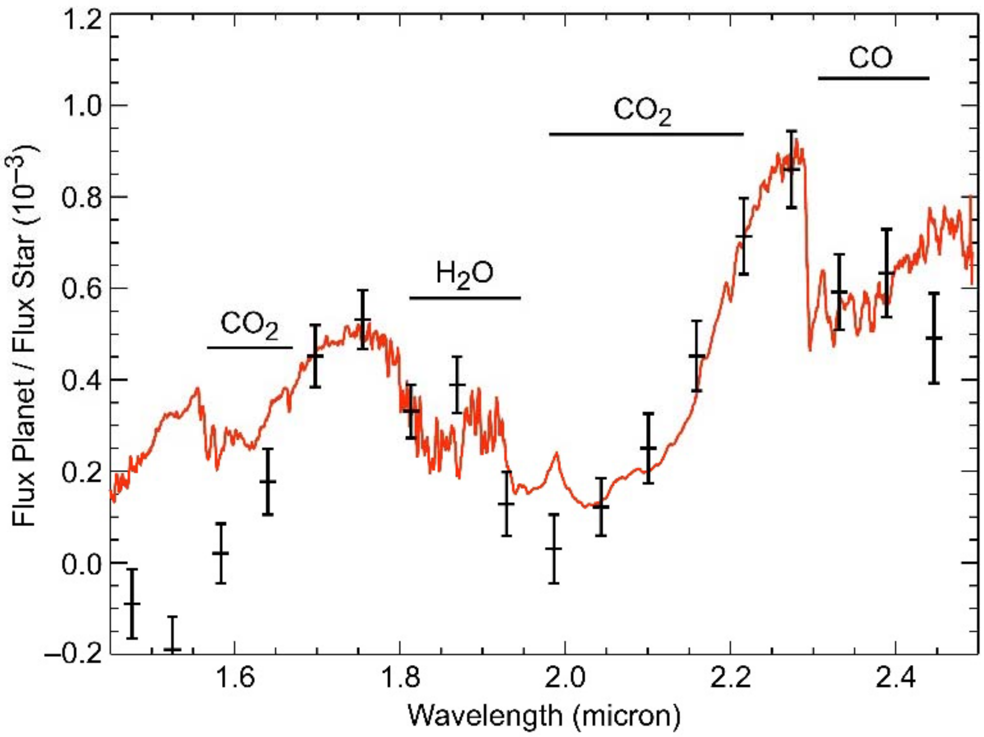
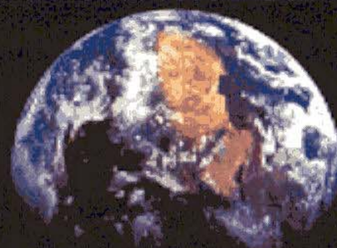
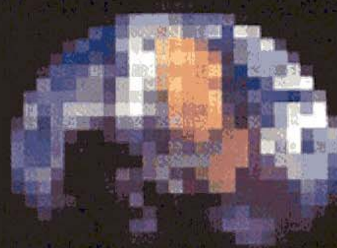
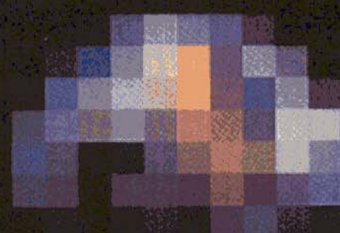



Fig. 3.— The near-IR dayside emergent spectrum used in our analysis with $\pm 1 - \sigma$ errors shown (black), together with a model spectrum (orange) containing the molecules $H_2O$, CO, $CH_4$ and $CO_2$, which are responsible for the absorption features (the strongest of which are identified above). The fit residuals suggest that one or more additional molecular species may be present. Although the fit is improved slightly by including $C_2H_2$, $C_2H_6$, or $NH_3$, additional data is required to make a strong case for the presence of additional molecular species.

| Pixel / Diameter | Pixel size @ planet (km) | Image | Interferometer Requirements | Collecting Area | Baseline |
|---|---|---|---|---|---|
| 400 | 32 |  | IR<br>Visible | 144 km²<br>1,296 km² | 100,000 km<br>5,000 km |
| 100 | 128 |  | IR<br>Visible | 0.64 km²<br>5.76 km² | 24,000 km<br>1,200 km |

# Terrestrial Planet Imager?

| Pixel / Diameter | Pixel size @ planet (km) | Image | Interferometer Requirements | Collecting Area | Baseline |
|---|---|---|---|---|---|
| 25 | 510 |  | IR<br>Visible | 1,024 m²<br>9,216 m² | 6,000 km<br>303 km |
| 10 | 1276 |  | IR<br>Visible | 64 m²<br>576 m² | 2,4km<br>120 km |

# THE CROWDED UNIVERSE

ALAN BOSS

THE SEARCH FOR LIVING PLANETS