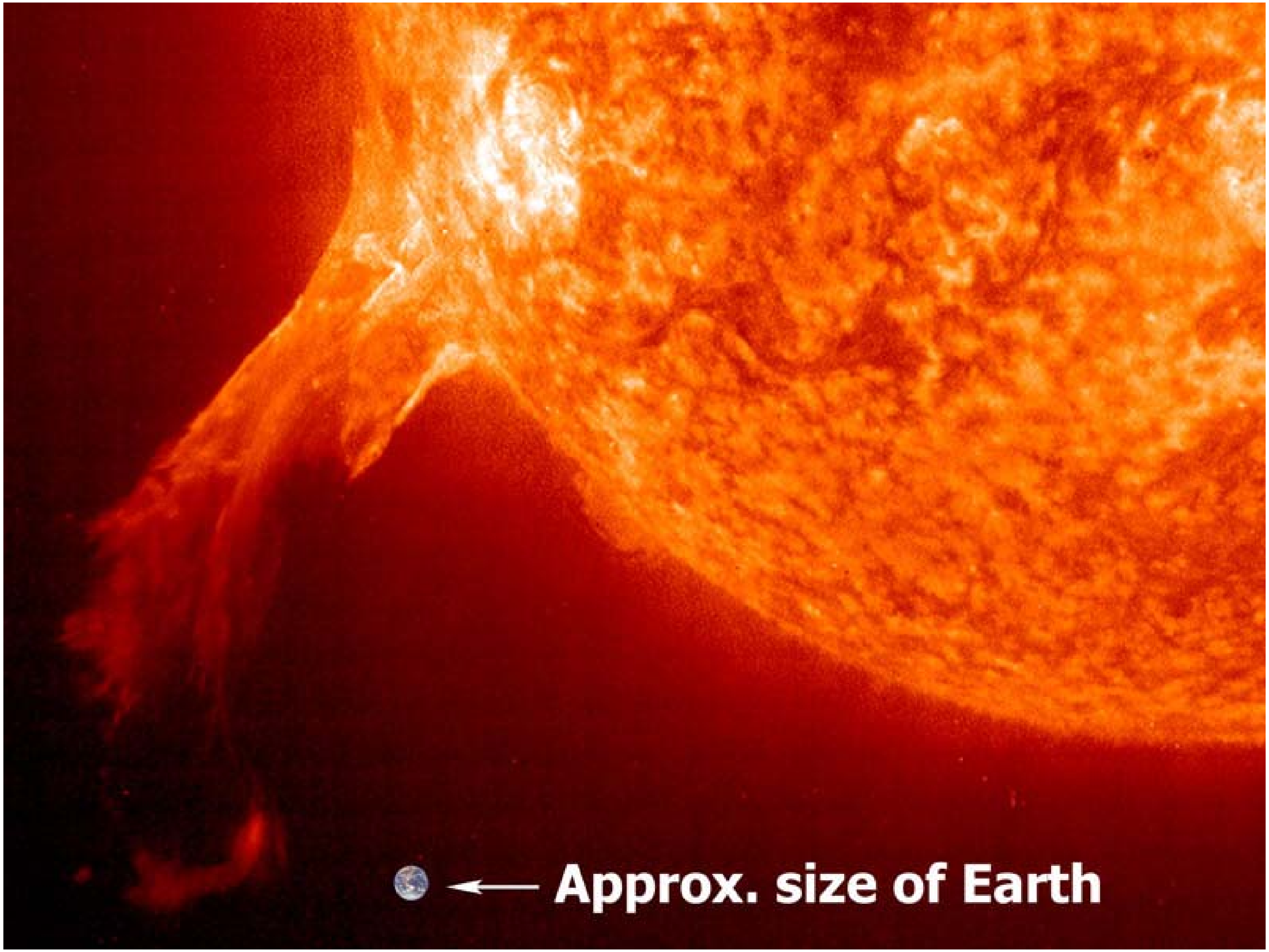
BRIEF HISTORY OF TRANSIT PHOTOMETRY
W. J. Borucki, NASA Ames

A Search for Habitable Planets



SELECTION OF EARLY PAPERS

Kepler
A Search for Habitable Planets

- Rosenblatt, F. (1971).. Icarus 14, 71-93. First thorough discussion of requirements necessary to detect planets by transit photometry.
- Borucki & Summers (1984), Icarus 58, 121-134. Discussed the need for high precision detectors, out-of-atmosphere observations, & monitoring thousands of stars.
- Borucki, Scargle, & Hudson (1985). ApJ 291, 852-854. First discussion of photometric limitations due to stellar variability & the possibility of detecting Earths in the presence of solar variability.
- Borucki et al (1987). NASA CP 10015, p47. Tests of silicon diode detectors for transit photometry.
- Borucki et al (1988). Proc.Fiber Optics in Astron Conf. Tests of a multichannel photometer based on optical fibers.
- Schneider and Chevreton (1990) A&A 232, 251. Discussed the possibility of finding Earth-sized planets around 8 luminous binary systems with a 30 cm spaceborne photometer.
- Schneider (1994) compared the detection of oxygen in planetary atmospheres and concluded that the transit method was more efficient than the integration of the reflected light from the planet.
- Robinson et al (1995). Test of CCD limits for differential photometry. PASP 107,1094-1098. First demonstration of detectors with precision to detect Earth-size planets.
- Wolszczan & Frail (1992);Nature 355, 145. First discovery of an extrasolar planetary system
- Mayor & Queloz (1995). Nature 378, 355. First discovery (RV) of exoplanet around a main-sequence star
- Charbonneau et al (2000). ApJ 529, L45; First observation by transit photometry of an exoplanet
- Charbonneau et al (2002)ApJ 568, 377; Transit spectroscopy used to find species in exoplanet atmosphere
- Gilliland et al (2000). ApJ 545, L45-47. HST transit search of 47 Tuc that found 0 instead of 17.
- Brown (2003). ApJ 593, L125. Expected detection and false alarm rates
- Horne (2003). Sci. Front. Res. Extrasolar Planets. Scaling laws to compare grd-based transit approaches.
- Sahu and Gilliland (2003). ApJ 584, 1042-1052. Calculations show that a transit by a white dwarf causes an increase in star brightness rather than a decrease.

GROUND-BASED PHOTOMETERS

A Search for Habitable Planets

- Robotic systems

- Narrow field systems; large telescopes
  - Monitor star clusters
  - Monitor single stars; often to follow up radial velocity discoveries
  - Example: STEPSS

- Wide field systems;
  - Monitor very large number of stars to discover planets
  - Example: Vulcan at Lick Observatory

- ~20 Systems in operation:
- ASP, BEST, GITPO, HATnetwork, MONET, OGLE III, PASS, PISCES, STARE, STELLA, Super WASP, STEPSS, Tenn Auto Photo Tel, Transitsearch.org, TrES, USTAPS, UNSWEPS, Vulcan, WHAT, XO project.

NARROW FOV, LARGE APERTURE TELESCOPE

Appalachian State University
Dark Sky Observatory

Search for Trojan Planets

Observe eclipsing binary stars

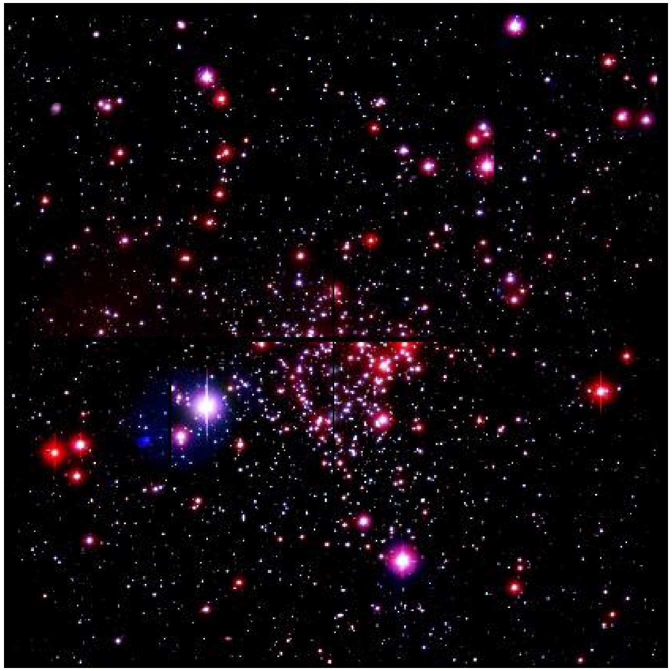
80 cm telescope

Survey for Transiting Extrasolar Planets in Stellar Systems (STEPSS)

Instrumentation: Apertures: 2.4m & 1.3m - Kitt Peak
Field of view: 25x25 46x46 arcmin; 0.17& 0.6 sq deg
Instrument: MDM 8K CCD Mosaic Imager
Pixel size: 0.36 arcsec

Project Members: Christopher Burke, Scott Gaudi, Joshua Pepper, Darren DePoy, Jennifer Marshall, Richard Pogge

Synopsis: Our goal is to assess the frequency of close-in extrasolar planets around main-sequence stars in several open clusters. By concentrating on main-sequence stars in open clusters of known (and varied) age, metallicity, and stellar density, we will gain insight into how these properties affect planet formation, migration, and survival.



WIDE FOV, SMALL APERTURE

Kepler
A Search for Habitable Planets

Vulcan photometer; Lick Observatory; First observations 1997

TELESCOPE:

- Aperture: 10 cm
- Focal length: 30 cm
- Field of View: 7x 7 degrees
- Detector: 4096x4096 CCD with 9 μ pixels

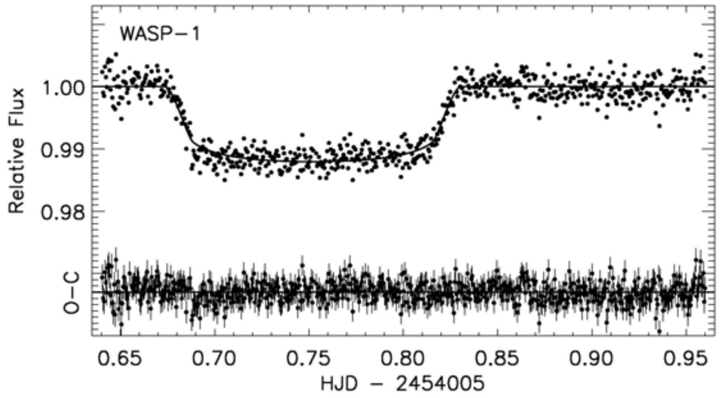
OBJECTIVES:

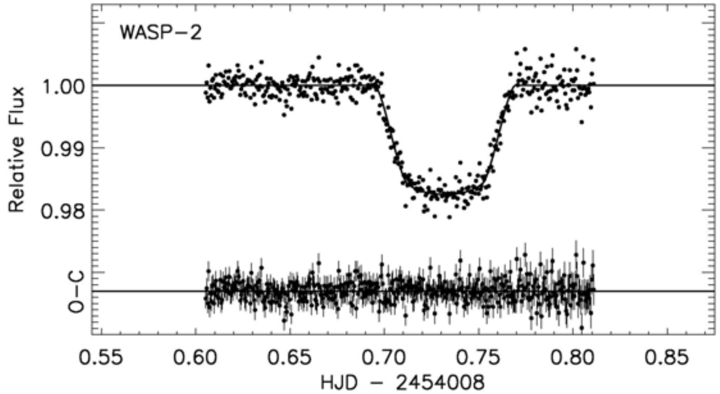
- Monitor 10000 stars "continuously" for periods of at least 6 weeks
- Detect jovian-size planets in short period orbits
- Use Doppler-velocity measurements to determine mass and density

SPACE-BASED VS. GROUND-BASED OBSERVATIONS

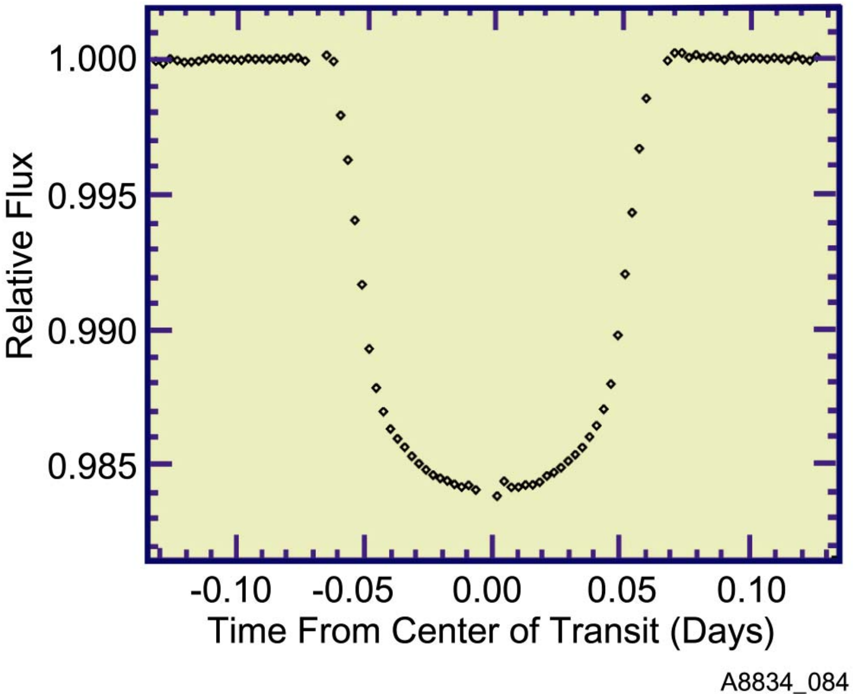
A Search for Habitable Planets

Ground-based





Space-based



Ten-minute to ten-minute binned data from several orbits have a precision of 60 ppm (Brown et al. 2001).

SPACE BASED PHOTOMETERS

A Search for Habitable Planets

- HST
  - 47 Tuc ; Gilliland et al 2000; 17 planets expected of 34,000 stars, none found.→ Planets rare in globular clusters
  - Atmospheres of HD.., Brown, Charbonneau
- MOST; Jaymie Mathews et al. 2003
- Spitzer; 2003
- Corot; Baglin et al. 2006
- Kepler; Borucki et al. 2009

- TABLE OF COMPARISONS

BRIEF HISTORY OF THE MOST MISSION

Kepler
A Search for Habitable Planets

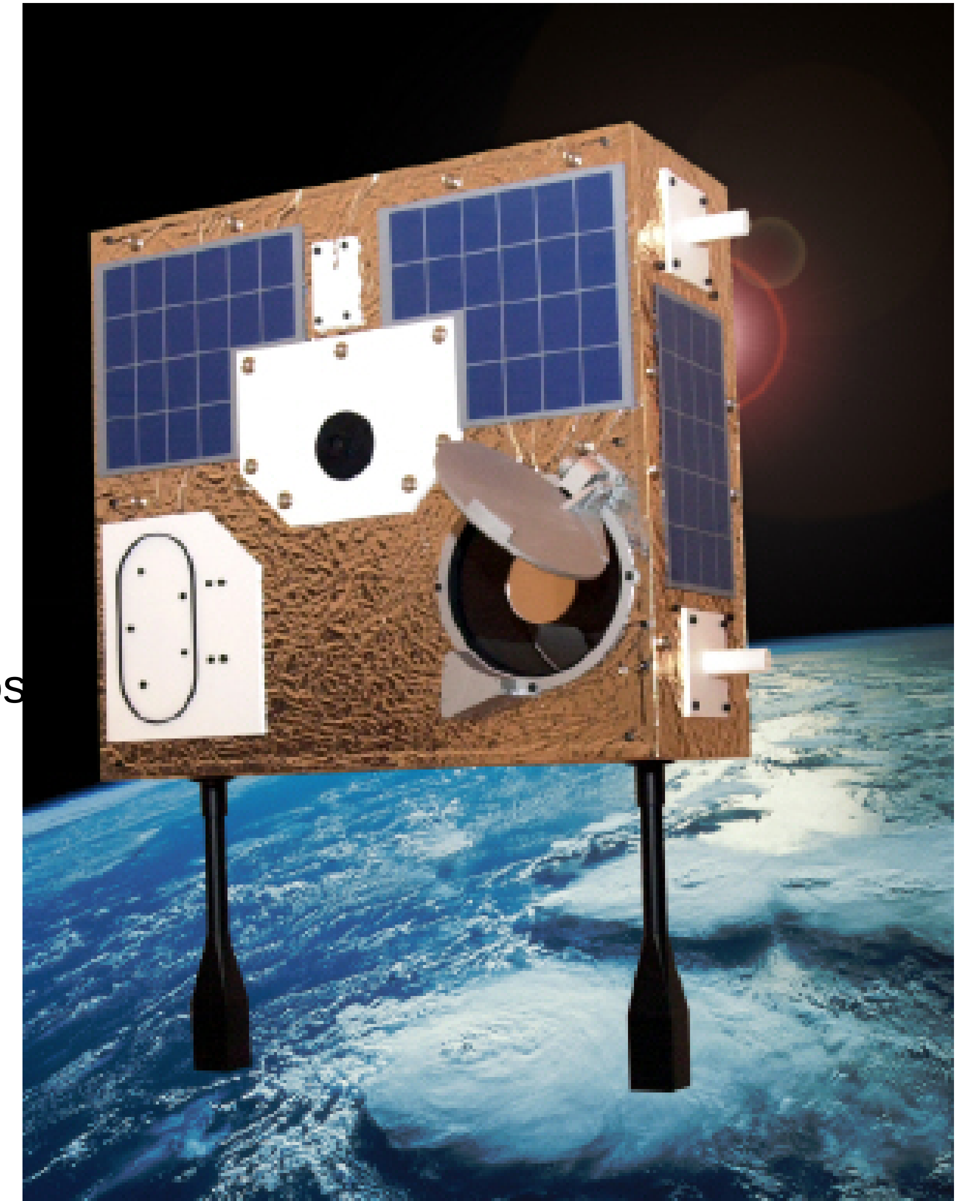
MOST = Microvariability & Oscillations of Stars

PI Name:
Jaymie Matthews

Launch 2003

Science Results

- Search for Earths
- “Ultrasound” of stellar embyos
- Measured surface rotation of a young Sun
- Discovered new classes of pulsating hot star



BRIEF HISTORY OF THE MOST MISSION

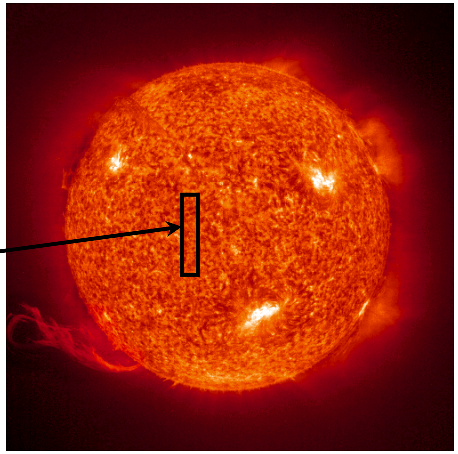
A Search for Habitable Planets

- The original MOST proposal was one of 54 submissions in 1997 in response to a Canadian Space Agency AO for Small Payload science and was chosen as Canada's first microsatellite mission in 1998.
- The MOST mission was funded based solely for asteroseismology and studying turbulence in winds of massive stars. Exoplanet science was added to the MOST objectives, without changing the design, the planned operation, or the cost of the mission.
- MOST was launched on 30 June 2003 aboard a Russian Rockot, a former Soviet SS-19 "Stiletto" ICBM, from the Plesetsk Cosmodrome and began science operations on 1 Jan. 2004.
- Upwards of 40 targets can be monitored in a single field – including stars as faint as V ~ 13. MOST is also able to observe targets outside its Continuous Viewing Zone and to observe multiple fields per 101-min satellite orbit.
- MOST was originally planned and funded as a 1-year mission. It has no consumables, so it is difficult to estimate its lifespan. The power output of the solar panels degrades with time will provide power above the nominal spacecraft operating budget for another 3.5 – 4 years.
- MOST has now monitored 35 Primary Science Targets, 5 Commissioning Targets, and about 650 Direct Imaging and Guide Star Targets.
- Science Results
  - Search for Earths
  - "Ultrasound" of stellar embyos
  - Measured surface rotation of a young Sun
  - Discovered new classes of pulsating hot star

BRIEF HISTORY OF COROT

A l'origine……

En 1962, un peu par hasard,
Lloyd Evans et Raymond Michard (OPM)
observent le Soleil pour étudier le phénomène
des éruptions
Détectent en plus de curieux mouvements….
Semblent à peu près périodiques (5 minutes)
Leighton (USA) confirme quelques mois plus tard.



Dans les années 70, une équipe franco-américaine
(E. Fossat, Université de Nice et J.Pomerantz)
organise une expédition au pôle Sud,
Observer le Soleil **plusieurs jours (5)**
sans interruption pendant le jour polaire

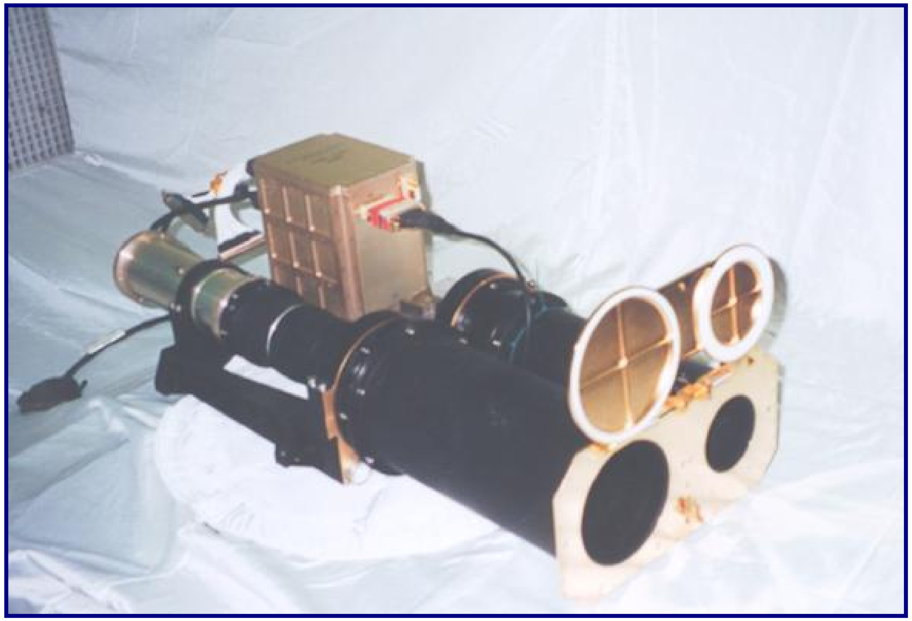
Confirmation de la périodicité entre 3 et 5 minutes
et de la multipériodicité

De quoi s'agit-il?

Premier projet: EVRIS

A Search for Habitable Planets

Première proposition retenue…… en 89
Telescope de 9 cm,
construit à Meudon et Marseille (+Autriche)
Grande avance Française

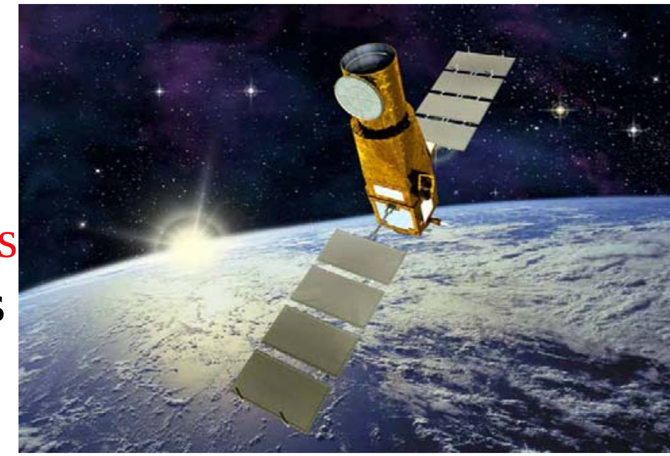


Etude de la
Variabilité et de la
Rotation des
Intérieurs
Stellaires

A bord de la sonde Russe Mars 94/96

Observation de 10 étoiles très brillantes Pendant la croisière Terre Mars

Le nouveau COROT



Nouvelle proposition en 1997

filière "petites missions" du CNES

Programme scientifique beaucoup plus ambitieux

- plus d'étoiles en sismologie
- détection de quelques dizaines de petites planètes

COnvection, ROtation et Transits planétaires

Préselection fin 98

Mais…..pas de décision finale….

difficultés politiques financières….

Sélection en Octobre 2000

3ème mission de la filière PROTEUS

pour un lancement en 2004 !

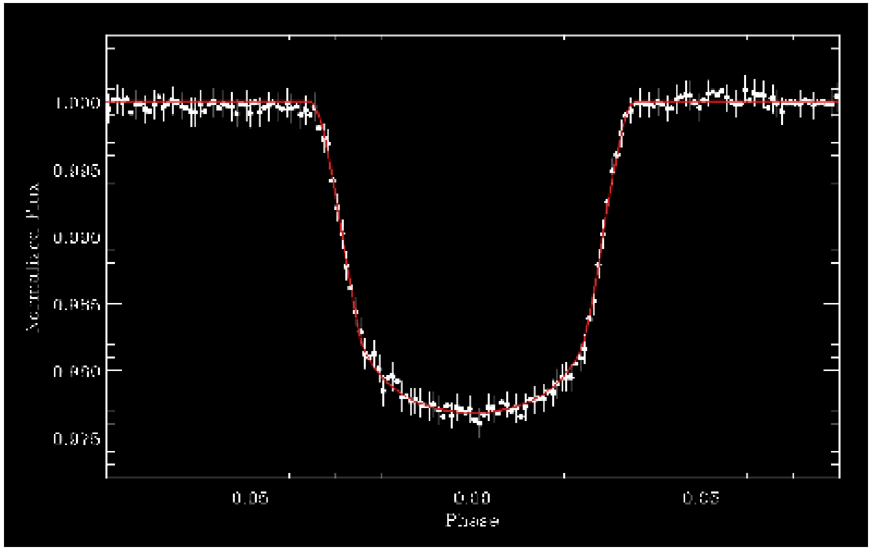
Arrêt d'un an en 2002

pour raison financières(!)

Lancement 2006

Une planète extrasolaire

A Search for Habitable Planets



Précision: 3 dix-millièmes en 1 heure !
Observé 40 fois!, durée 2h

CoRoT-EXO-1b

Periode: 1.5 Jour
Rayon 1.5 à 1.8 R Jupiter
Distance a l’etoile: 0.04 UA

Suivie depuis le sol
Masse 1.3 M Jupiter

QuickTime™ et un
décompresseur GIF
sont requis pour visionner cette image.

Etoile naine mv=13
analogue au Soleil

Brief History of the Kepler Mission

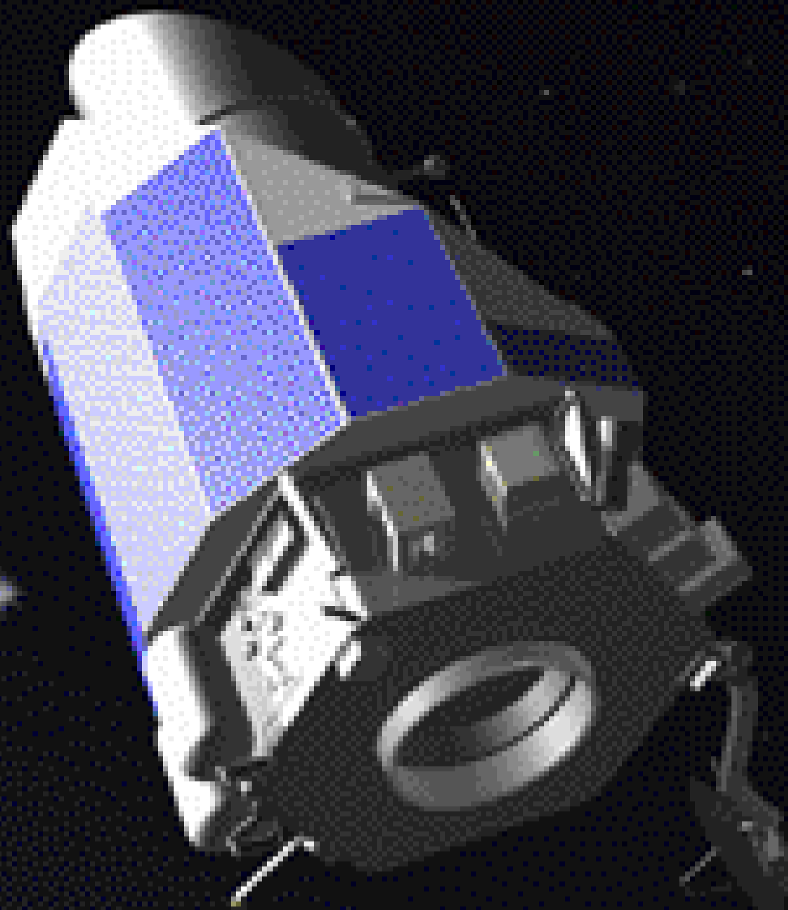
Critical Questions:

Are terrestrial planets common or rare?

What are their sizes & distances?

How often are they in the Habitable Zone?

What are their dependencies on stellar properties?



SAO

STSc

BRIEF HISTORY OF KEPLER MISSION

A Search for Habitable Planets

1971: Rosenblatt publishes first paper on transit detection of extrasolar planets
1984: Borucki and Summers publish paper on methods needed to detect transits of extrasolar planets
- **Ames sponsors the first workshop on high precision photometry**

1985: Borucki, Scargle, & Hudson publish paper on the detectability of transits of Earth-sized extrasolar planets
1987: Second workshop on high precision photometry sponsored by Ames & NBS (NIST)
- **Operation of a robotic telescope to determine precision from ground based observations**
- **Test of CCD photometry at Lick Observatory**
- **Tests of silicon diodes, collaboration with NIST**
- **Mission exploration funded by HQ**

1992: Discovery Program starts & requests concepts for funding
- **FRESIP (Frequency of Earth-size Inner Planets) proposed to Discovery Program**
- **Great science but rejected because no suitable detectors believed to exist → No funding**

1993: Ames sponsors a workshop to explore the astrophysics that could be accomplished by FRESIP
1994: Announcement of Opportunity (AO) for first Discovery Class Mission
- **FRESIP proposes photometer in Lagrange orbit, CCD detectors,**
- **Rejected as too costly based on HST costs**

1995: Ames/Lick group publishes a paper showing lab measurements of CCDs that have the required precision
1996: Second AO for Discovery Class Missions
- **Carl Sagan, Jill Tarter, & Dave Koch advocate changing name from FRESIP to Kepler**
- **Mission cost estimated 3 ways, solar orbit, CCD detectors proved & results published**
- **Rejected because automated photometry of thousands of stars not proven**

1997: Ames team builds an observatory at Lick & demonstrated automated photometry of thousands of stars
1998: Third AO for Discovery Class Missions
- **Rev panel accepted science, detector capability, and automated photometry**
- **Rejected because ability to handle on-orbit noise not demonstrated**
- **HQ funds a lab testbed to demonstrate the ability to handle on-orbit noise**

1999: Kepler testbed designed, built, & operational. It demonstrates the ability to handle on orbit noise.
2000: Fourth AO for Discovery Class Missions
- ***Kepler* selected as one of three candidates**

2001: *Kepler* accepted as Discovery Mission #10 to launch in 2006

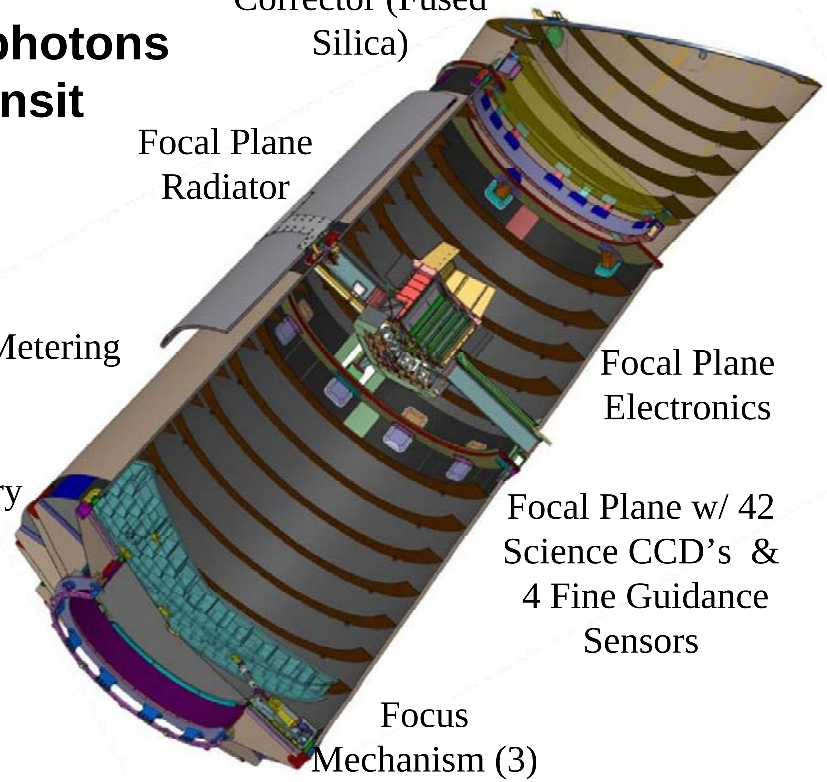
INSTRUMENT

A Search for Habitable Planets

KEPLER: A Wide FOV Photometer that Monitors 100,000 Stars for 4 years with Enough Precision to Find Earth-size Planets in the HZ

Use transit photometry to detect Earth-size planets

- **0.95 meter aperture provides enough photons**
- **Observe for several years to detect transit patterns**
- **Monitor a single FOV continuously to avoid missing transits**
- **Use heliocentric orbit**

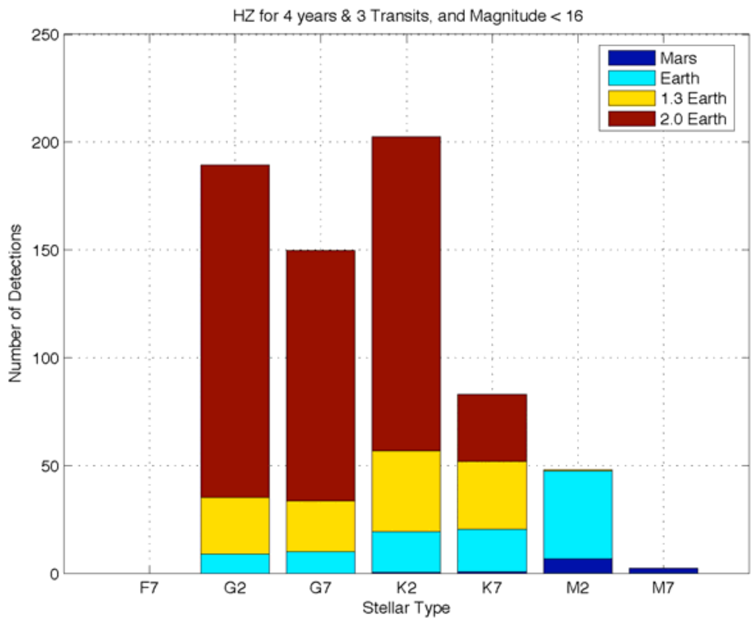


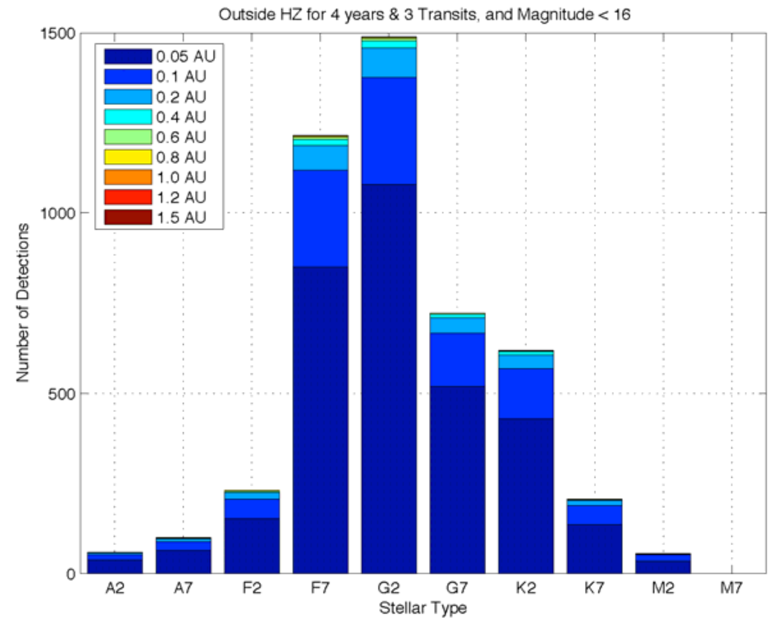
Get statistically valid results by monitoring 100,000 stars

- **Wide FOV telescope**
- **Large array of CCD detectors**

KEPLER SHOULD DETECT THOUSANDS OF TERRESTRIALPLANETS

A Search for Habitable Planets





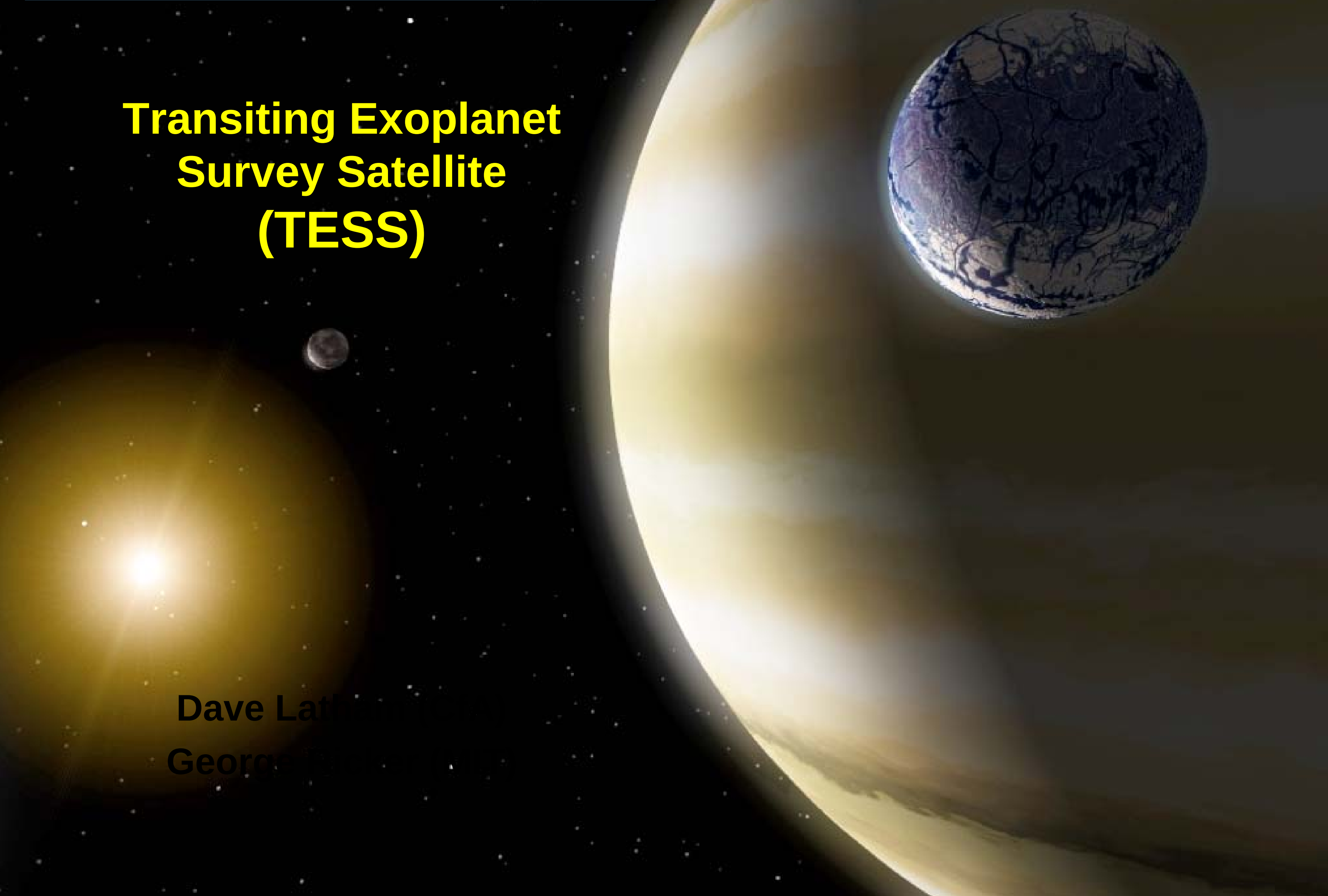
- Several hundred terrestrial planets are expected in the HZ if they are common. A null result would mean Earths in the HZ are rare in our galaxy.
- Several thousand Earth-size planets should be detected outside the HZ. The actual occurrence frequency will dramatically affect theories of planet formation.

COMPARISON OF CAPABILITIES FOR SPACE-BASED SYSTEMS

Kepler
A Search for Habitable Planets

SYSTEM	FOV (sq deg)	Aperture Start of Science Ops	Mass & Pointing precision	Photo-metric precision	Results
HST	1.7×10^{-3}	2.4 m 1993	11,100 kg $\pm$ 0.1”	60 ppm/ 10 min	47 Tuc; none (Gilliland) Atmosphere Comp.
MOST	~ 0.2 plus lenslets	0.15 m 1 Jan 2004	54 kg $\pm$ 1”	60 ppm/hr 7.5 mag	Ruled out terrestrial planets around
Spitzer	8×10^{-3} MIPS Imaging 24-180 μ	0.85 m 2003	950 kg $\pm$1”		Occultations; Atmosphere temp & distribution
COROT	~ 6	0.27 m Feb 2007	630 kg $\pm$ 0.5”	300 ppm/hr (press report)	Short period planet with dia ~1.4 Jupiter
Kepler	105	0.95 m ~Mar 2010	1900 kg $\pm$ 0.1”	45 ppm/hr 12^{th} mag	
TESS					

Transiting Exoplanet Survey Satellite (TESS)



Dave Lat

Georg

TESS Scientific Goals

- Survey entire sky for transiting planets
  - Identify all the nearby bright systems (>1000)
  - Reach planets as small as the Earth
  - Reach periods as long as two months
  - Provide best systems for follow-up
    - Infrared by JWST
    - Radial velocities by HARPS (North and South)
    - A legacy for future follow-up experiments

TESS Approach

A Search for Habitable Planets

- Small university-style experiment
  - MIT: instrument, operations
  - CfA: optics, follow-up observations
  - Ames: spacecraft, launch
- Low Earth equatorial orbit
  - Avoid radiation damage, use commercial parts
  - Utilize HETE-2 ground stations