"There are infinite worlds both like and unlike this world of ours...We must believe that in all worlds there are living creatures and plants and other things we see in this world"---Epicurus (c. 300 BCE) (died painfully 269 BCE)

"...false and damnable...
G. Galilei (b. 1564)
(life imprisonment 1633)

"There are countless suns and countless earths..."
Giordano Bruno (b. 1584)
in De L'infinito Universo E Mondi
(burned at the stake in Campo dei Fiore, Rome, 1600)
Milestones

- >500 Exoplanets detected, mostly Giant Planets (e.g. Jupiters)
- ~ 70 transiting planets,
- Detection of H$_2$O, CO, Na, maybe CO$_2$, CH$_4$
- Spitzer and NICMOS light curves and secondary eclipse measurements
- Many temperatures measured
- GJ 436b and HAT-P-11b: Neptunes in Transit!
- >70 “Neptunes” and “Super-Earths”
- HD 149026b with a ~80 Earth-mass core
- HD 80606 with high e: light curve and secondary transit!
- ~3.3 Earth-mass object orbiting a brown dwarf; 3 Pulsar planets (Wolszczan and Frail 1992)
- Several > Earth-mass planets by RV and transit techniques (e.g., CoRoT-7bc, GL 581e, GJ 1214b)
- **Discoveries of Fomalhaut b and HR 8799bcd, and perhaps β Pic b**
Our Solar System
Stars and Planets
Giant and Terrestrial Planets

Jupiter

Saturn

Uranus

Neptune

Earth
THE OUTER SOLAR SYSTEM

This animation shows the motion of the outer part of the solar system over a 100-year time period. The sun is at the center and the orbits of the planets Jupiter, Saturn, Uranus and Neptune are shown in light blue (the locations of each planet are shown as large crossed circles).

Comets: blue squares (filled for numbered periodic comets, outline for other comets)
High-e objects: cyan triangles
Centaurs: orange triangles
Plutinos: white circles (Pluto itself is the large white crossed circle)
"Classical" TNOs: red circles
Scattered Disk Objects: magenta circles

The individual frames were generated on an OpenVMS system, using the PGPLOT graphics library. The animation was put together on a RISC OS 4.03 system using !InterGif.
Radial Velocity Technique

“Doppler Shift”
(Radar gun)

Can measure planet mass
0.05 AU!! - 100 times closer than Jupiter-Sun Distance
Astrometry (Wobble Motion) Technique

“See-Saw”
Wobble of Sun
Seen from 33 Light-Years
SIM’s discovery space for planets.
Microlensing Technique

“Einsteinian Bending of Light”

(Light Amplification)
Microlensing: 17 Planets found so far!
Transit Technique

“Primary Eclipse - Partial Eclipse of Star”
(can measure Radius)
Transit

Secondary Eclipse
See thermal radiation and reflected light from planet disappear and reappear

Orbital Phase Variations
See cyclical variations in brightness of planet

Transiting Planets

figure taken from H. Knutson
Venus Transit of 1882:
Transit by HD209458b (with HST/STIS)

Can measure planet radius!

\[ R_p \sim 1.32 \ R_J \]

\~1.5\% dip:

P = 1.4e-05 bars and 3 bars
Central Longitude: -90
High-Z Planet

Earth | Jupiter | 51PegB
--- | --- | ---
300 K 1 bar | ~1600 K 1 bar | ~1200–2000 K
~6000 K 3.6 Mbar | ~17000 K ~70 Mbar | ~2000 Mbar
~17000 K ~70 Mbar | ~22000 K ~30 Mbar | Case a

(T. Guillot)
...70 Planets Are Known to be Transiting.

Some planets appear to be inflated

Massive planets on highly eccentric orbits

Ice/Rock Planets
HD209458b:

Radius is Larger in Na-D!
Na detection: Charbonneau et al. 2003
Transit Radius vs. Wavelength

aka. “transmission spectroscopy”?

Fortney et al. 2003
Statistics/Facts of Exoplanets
They are everywhere!
The Upsilon Andromedae System

- B: 0.06 AU, 4.6 day orbit, 75% Jupiter’s Mass
- C: 0.83 AU, 242 day orbit, Twice Jupiter’s Mass
- D: 2.5 AU, 3.5 year orbit, 4x Jupiter’s Mass

Our Inner Solar System

- Mercury: 0.39 AU, 89 day orbit
- Venus: 0.73 AU, 228 day orbit
- Earth: 1.00 AU, 1 year orbit
- Mars: 1.54 AU, 1.9 year orbit

© Harvard-Smithsonian CfA (A. Contos), 1999
Ups And System
Ongoing Surveys Have Discovered 500+ Planets So Far...

![Diagram showing the relationship between mass and semi-major axis of planets with RV Planets and Transiting Planets indicated.]
HD 80606b Heats Up During Periastron Passage

Laughlin et al. (2009), 8 μm
HD 80606b Heats Up During Periastron Passage

Laughlin et al. (2009), 8 μm

Spitzer will obtain phase curves for several more eccentric planets (HAT-P-2, HD 17156, XO-3) during the warm mission.
51 Peg b
HARPS
An emerging population of Hot Neptunes and Super-Earths

Mayor et al. A&A 2009

HD 40307
K2 V
Dist 12.8 pc
[Fe/H] = -0.31

O-C = 0.85 m/s
135 observations

+ drift = 0.5 m/s/y

$P_1 = 4.31$ days
$e_1 = 0.02$
$m_1 \sin i = 4.3 M_⊕$

$P_2 = 9.62$ days
$e_2 = 0.03$
$m_2 \sin i = 6.9 M_⊕$

$P_3 = 20.5$ days
$e_3 = 0.04$
$m_3 \sin i = 9.7 M_⊕$
Two super-Earth (5-7 $M_{\text{Earth}}$) in a 4-planet system + a very light planet of 1.94 $M_{\text{Earth}}$

Gl 581, M3V star

Mayor et al. 2009

Bonfils et al. 2005

Udry et al. 2007

P1=3.15d M1=1.94$M_{\text{Earth}}$

P2=5.37d M2=15.7$M_{\text{Earth}}$

P3=12.9 d M3=5.4$M_{\text{Earth}}$

P4=66.8 d M4=7.1$M_{\text{Earth}}$

revised in Mayor et al. 2009
transit

microlensing

RV

July 2009
Some properties of close-in low-mass planets

1) Mass distribution

Observations (normalized distribution)

Models (Mordasini et al. 2009)

Prediction of a large population of terrestrial planets

“super-Earths”

Giant planets
Radial Velocity
From the ground
Transits from space
Microlensing
Space Astrometry?
Beyond Hot Jupiters: The Age of Kepler

Kepler will find many new systems, perhaps “Earths”
Transits of terrestrial planets

- Giant planets: 0.01 mag
- Terrestrial planets: 0.0001 mag

Transits from space
Kepler: waiting for results
CoRoT: CoRoT-7b
Planet diversity

CoRoT, M-Dwarf surveys

• Transit $\rightarrow$ fractional radius (relative to host star) $\rightarrow$ inclination.

• RV $\rightarrow$ planetary mass

• 2 solid planets:
  - CoRoT-7b : Period $\sim 0.85$ d
  - MEarth-1b: Period $\sim 1.50$ d

$\Rightarrow$ Diversity
Transit Technique

Secondary Eclipse (eclipse of planet by star)
Transit
See stellar flux decrease (function of wavelength)

Secondary Eclipse
See thermal radiation and reflected light from planet disappear and reappear

Orbital Phase Variations
See cyclical variations in brightness of planet

Transiting Planets

figure taken from H. Knutson
Isolating a Planet’s Spectrum
Spitzer ST:
HD189733b
(At Secondary Eclipse)

Grillmair et al. (this paper)
Charbonneau et al. (2008)

$P_n = 0.1$, Burrows, Budaj, & Hubeny (2008)
$P_n = 0.3$

Water
CO

CH$_4$?

JWST!!
Burrows et al. 2007

Water in Emission!

H$_2$O

IRAC 1 < IRAC 2!
Burrows et al. 2007
Temperature Inversion! IRAC 1 < IRAC 2!

Burrows et al. 2007
Direct Detection and Imaging of planetary systems
Jupiter’s Spectrum

\( \text{Jovian spectrum} \)

\[ \log \sigma (\mu \text{m}) \]

\( \text{B VR I J H K L' M N} \)

- \( H_2 \)
- \( \text{NH}_3 \)
- \( \text{CH}_4 \)
- \( \text{NH}_3 \)
- \( \text{H}_2 \text{O} \)

\( \text{125K; 0.35bar} \)
\( \text{165K; 0.35bar} \)
\( \text{300K; 0.35bar} \)

\( \lambda (\mu \text{m}) \)

(T. Guillot)
Planet/Star Flux ratio versus Orbital Distance

Burrows, Sudarsky, and Hubeny 2004
N.B., Jupiter at 2 AU does not have NH$_3$ clouds, but does have H$_2$O clouds.
Fomalhaut b

Kalas et al. 2008; < 3 M_J

a ~ 115 AU !!
HR 8799bcd

$M_b \sim 7 \, M_J$

$M_c \sim 10 \, M_J$

$M_d \sim 10 \, M_J$

$D = 24, 38, 68 \, \text{AU}$

Marois et al. 2008
Planet/Star **Contrast**: Theory (dashed) versus Capability

(Burrows 2005)

Red: H band (1.6 microns); Purple: Mid-IR; Green: Optical
Habitable Zone

The interesting bit

Mass of star relative to Sun

0 0.1 1 10 40

Radius of orbit relative to Earth's
Planetary (Phase) Light Curves
Phase Functions:

Burrows et al. 2005
Mapping the Day-Night Circulation With Phase Curves

Size of observed variation depends on efficiency of day/night circulation

The HD 189733 system to scale

orbital period = 2.21 d
transit duration = 1.9 hr

9.3 stellar radii

transit
Top down view
View from Earth

Efficient
Inefficient

Image courtesy G. Laughlin
First Longitudinal Temperature Profile for an Exoplanet: HD 189733b’s Warm Night Side

Spitzer 8 μm observations of HD 189733b (Knutson et al. 2007b, Nature 447, 183).

(Knutson slide)
~Same behavior at 24 μm

Hot spot and cold spot on same hemisphere!

Transiting
Planet/Star Flux Ratio vs. Wavelength and Phase

F_p/F_* vs. λ
Every 30° in Phase

Burrows, Rauscher, Spiegel, & Menou 2010
J band HD 209458b Map (model a00)
IRAC3 band
HD 209458b
Map (model a03)
I band HD 209458b Map (model a03)
Methane Map: w/o U/A heating
Methane Map: with U/A heating
The Future?
Today's Lesson: \( W_D \) or "Witten's Dog"

\[
\begin{align*}
\text{Neutron Encrusted} & \\
\text{Steaming Hot} & \\
\text{Dark Matter} & \\
\end{align*}
\]

\[
\begin{align*}
e^- + p & \rightarrow \Omega + \nu \\
\Omega \nu & = \sum_{i=1}^{\Omega_n} \left( \frac{m_n}{93\text{eV}} \right) x \Omega_b W_0^2 \left( \frac{Z+1}{9} \right) \end{align*}
\]

"Superdupsymmetric String Theory"

Any questions?