Is the solar system unique? How did it form?

Pluto demoted in 2006

Images by NASA
Is our sun unique?

There are too \( \sim 170 \) billion galaxies in the Universe

Milky Way contains \( \sim 400 \) billion stars

Some giant spiral galaxies contain \( \sim 100 \) trillion stars

About \( 10^{24} \) stars are contained in 13.8 billion light-years of the Universe

Located on the main sequence

Spectrum is similar to many other stars

An average mass

Probably, there other planetary systems out there

How do we search for them?

Hertzsprung–Russell diagram.
Planet detection

Direct (best):
- Pictures or spectra of the planets reveal their existence

Indirect (most exoplanets detected this way):
- Precise measurements of some properties of a star can indicate that planet(s) are orbiting it
Sun’s motion around solar system’s center of mass depends on tugs from all the planets.

Can determine masses and orbits of all the planets.
Detect planets by measuring the change in a star’s position in the sky.

Motions are difficult to measure ~0.0015 arcsecond from 30 light-year distance

It is about 100 smaller than Hubble Space Telescope angular resolution
Detect oscillation of a star's absorption line

Doppler Shift due to Stellar Wobble

Note: measuring the star’s spectrum not the planet’s

Figure credit: NASA/JPL-Caltech
First extrasolar planet detected: 51 Pegasi

Main sequence star (burns hydrogen)
Surface temperature 5570K
6-8 billion years old
About 25\% larger and
10\% heavier than the sun

Swiss astronomers Michel Mayor and Didier Queloz announced the discovery of an exoplanet orbiting 51 Pegasi on October 6, 1995

What is wrong with the photo?
First extrasolar planet detected: 51 Pegasi

Doppler shifts of the star indirectly reveal a planet with a 4-day orbital period.

Short period means small orbital distance.

Most of planet discoveries were done using Doppler technique.

Best to find massive planets close to their stars:
- stronger the gravitational tug => faster star’s orbital speed
- difficult to find Earth-like planets

Identify if more than one planet are in the system.

Since April 1994 we have monitored the radial velocity of 142 G and K dwarf stars with a precision of 13 m s⁻¹. The stars in our survey are selected for their apparent constant radial velocity (at lower precision) from a larger sample of stars monitored for 15 years. After 18 months of measurements, a small number of stars show significant velocity variations.
Range 389.5 nm to 681.5 nm in a single exposure
Split into 67 spectral orders
Fed with optical fibers from the Cassegrain focus

Located in a temperature controlled room
Integrated data reduction pipeline
34286 spectra in the archive (17676 are public)
7476 distinct identifiers (6173 are public)
Quick tutorial: http://www.obs-hp.fr/archive/elodie-for-dummies.html
Decommissioned in mid-August 2006
A transit is when a planet crosses in front of a star.

The resulting eclipse reduces the star’s apparent brightness and tells us the planet’s radius.

When there is no orbital tilt, an accurate measurement of planet mass can be obtained.

Venis transit June 7, 2012. Photo NASA H-alpha filter
If the orbit of a planet around another star happens to be edge-on, then once during every revolution, the planet will pass in front of its star in what is called a transit.

Since it blocks a small portion of the star's photosphere, it will decrease the light from the star for a brief period -- typically a few hours. The size of the dimming depends on the relative sizes of the star and planet:

**Big star, small planet**  -->  **small dip**

**small star, big planet**  -->  **big dip**

Works best for finding big planets.
Detection of a transit of TrES-1 at RIT Observatory
The green points: measurements from each image
Red points: moving averages of 10 consecutive frames
1-2% effect, but detectable by a small telescope (only 5” mirror in this case)
Note the asymmetry of the curve. Is it a binary system?
New (Seventh) Transiting OGLE Planet: Inflated Hot Jupiter

Light and radial velocity curves of OGLE-TR-211.

Light curve: black points - OGLE photometry, red dots - VLT photometry. Orbital period of OGLE-TR-211b is 3.6772 days, its mass $1.03 \pm 0.20 \, M_{\text{Jup}}$ and radius $1.36 \, (\pm 0.18 - 0.09) \, R_{\text{Jup}}$.

Eclipses

We measure the combined light from the planet and the star

Eclipse - when planet passes behind the star

Planets emit in the infrared

Brightness drop is visible in infrared only and is very small

Transits and eclipses

Con: Only work for a small fraction of the planets with orbits edge-on.

Pro: Can measure the spectrum of the starlight transmitted through planet’s atmosphere – learn about chemical composition of the planet’s atmosphere:

- HD 209458b and HD 189733b planets: water, methane and carbon dioxide are found (Hubble data)
- “Detecting organic compounds in two exoplanets now raises the possibility that it will become commonplace to find planets with molecules that may be tied to life” - Mark Swain, JPL
Gravity affects the motion of ordinary objects:

- the gravitational force of the Sun, causes the Earth to move around it in a roughly circular orbit

Gravity can also alter the path of a beam of light

Gravitational microlensing is very rare: requires that the source of light, massive lensing object, and observer all be lined up nearly perfectly.

However, there are many systems known, and new ones discovered every year
The five bright white points near the cluster center are actually images of a single distant quasar SDSS J1004+4112 cluster of galaxy acts as a gravitational lens ~7 billion light years distant toward the constellation of Leo Minor.

2006 May 24. Credit: K. Sharon (Tel Aviv U.) and E. Ofek (Caltech), ESA, NASA
Gravitational microlensing concept

Separate images are not resolved, but the brightness of a lensed object is greatly enhanced

Red – foreground massive star
Blue – background source star
X – exoplanet that can cause additional light disturbance
+ – exoplanet that can not cause additional light disturbance
Source star is a red giant

The planet OGLE-2012-BLG-0406Lb is a 3.9 $M_{\text{Jup}}$ mass object orbiting 0.6 $M_{\text{Sun}}$ mass star

Separation of the planet from the star was 3.9 AU i.e., much larger than the snow line distance.

Challenges the core accretion planetary formation theory, which does not predict super-Jupiters to form beyond the snow line of low-mass stars
Direct detection

Simplest way to find planets is to look for them with a big telescope

Con:
In the visible part of the spectrum, for example, Jupiter is about 8 orders of magnitude fainter than the Sun

Techniques:
Block most of a star's light by placing bars, disks, or other opaque objects in the optical path from telescope to camera
Select a very, very feeble star - only about 25 times more massive than Jupiter
Observe in the near-infrared (wavelengths between 1000 nm and 3500 nm), where the star/planet contrast is minimal
Use an adaptive-optics system to compensate for atmospheric blurring

1RXS J160929.1-210524 planetary system. Credit David Lafrenière and Gemini Observatory
Most of the planets are found by transit technique

Join the data mining!
## Summary

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<th>found any planets yet?</th>
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<td>big planets far from star</td>
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<td>six suspects remain</td>
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<td>Radial velocity</td>
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<td>yes, many</td>
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<tr>
<td>Photometry</td>
<td>big planets close to star</td>
<td>many confirmed,</td>
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<td>lots of candidates</td>
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<tr>
<td>Gravitational lensing</td>
<td>(no strong bias)</td>
<td>several suspects</td>
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</table>
Extrasolar planet properties

Orbital period, distance, and shape

Planet mass, size, and density

Composition
Only few have orbital distance $> 5$ AU (Jupiter)
Many orbit closer than Mercury
Many orbits are elliptical instead of nearly circular
Solar system is unique or there is a detection bias?

Doppler technique tends to detect massive planets close to the stars

Orbital resonances ($R_2=2xR_1$) in multi-planetary systems. Resonances help to shape the overall layout of the planetary systems
Most planets detected are more massive than Jupiter. Only few planets have mass close to Earth (\( \sim 0.003 \, M_{\text{Jup}} \)). Reality of observational bias?
Chemical composition

We detected the planets that contain:
- hydrogen
- water
- organic molecules (methane)

Data is very limited
Sizes and densities

Size information is available from transits.
Doppler technique allows to estimate mass.
Need both measurements to calculate density.
Most planets where density is measured are consistent with jovian planets.
Some are “Hot Jupiters” with lower density orbiting very close to the star.

Plot by Tahir Yaqoob
Discovered Oct 30, 2013
Mass ~ 1.75 that of Earth
Density 5.57 g/cm³ (vs 5.52 g/cm³ for Earth)
Circles a Sun-like star at 0.01 AU (40 times closer than Mercury)
Even rock is liquid at such a temperature (2300-3100K)
About 10% of the stars examined are found to have a planetary system. Technology is not advanced to find planets around the other 90%.

“Hot Jupiters” so prevalent today might be actually quite rare as technology catches up and more Neptune-like planets are discovered.

Terrestrial planets can be very common:

there is a correlation between “metallicity” in the star and a probability to find a planet(s) circling around it – in agreement with nebular theory.

Geoffrey Marcy et al., Progress of Theoretical Physics Supplement No. 158, 2005
Is the theory of solar system formation correct?

Nebular theory: jovian planets should form in cold outer regions and have nearly circular orbits.

Observations: “Hot Jupiters” and highly elliptical orbits.

The theory is wrong or another mechanism is involved?

- Planetary migration theory
- Gravitational encounter

Nebular theory is incomplete.

As many more planetary systems discovered we can tune our models of the solar system creation and predict its future.
Summary

Our solar system is not a random collection of objects moving chaotically. There are families of objects that move according to clear laws (we can predict existence of invisible objects).

The theory of the solar system formation from a gravitational collapse of an interstellar gas is generally correct, but is incomplete.

The system was formed ~4.6 billion years ago when it emerged in the shape we observe today.

Planetary system formation process is probably universal. Minor perturbations can explain the diversity of the planetary systems we observe today.

Once we learn about other planetary systems, we will be able to say more about the solar system past and predict its future.