For there is a single general space, a single vast immensity which we may freely call Void; in it are innumerable globes like this one on which we live and grow. This space we declare to be infinite, since neither reason, convenience, possibility, sense-perception nor nature assign to it a limit.

In it are an infinity of worlds of the same kind as our own.

Giordano Bruno
On the Infinite Universe and Worlds (1584)
Detecting Extra-Solar Planets

METHODS

Astrometry
Radial velocity
Pulsar timing
Transit method
Gravitational microlensing
Circumstellar disks
Contamination of stellar atmospheres
Direct imaging
Astrometry

One method of detecting planets consists of carefully Measuring the position of a star in the sky.

Orbiting planets can make the star wobble slightly. Unfortunately, this effect is too small to consistently detect planets orbiting other stars.

This plot shows the center of mass of our solar system with respect the center of our Sun from 1945 through 1996.
Radial Velocity or the Doppler Method

Doppler Shift due to Stellar Wobble
Radial Velocity or the Doppler Method

Stellar absorption lines are Doppler shifted as the star moves toward and away from us.

In this situation, the star moves in a plane perpendicular to our line-of-sight. We don’t detect a Doppler shift.
<table>
<thead>
<tr>
<th><strong>51 Peg</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constellation</strong></td>
<td>Pegasus</td>
</tr>
<tr>
<td><strong>Right ascension</strong></td>
<td>22h 57m 28.0s</td>
</tr>
<tr>
<td><strong>Declination</strong></td>
<td>+20° 46′ 08″</td>
</tr>
<tr>
<td><strong>Apparent magnitude (V)</strong></td>
<td>5.49</td>
</tr>
<tr>
<td><strong>Spectral type</strong></td>
<td>G2.5Iva or G4-5Va</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>1.06 Solar Masses</td>
</tr>
<tr>
<td><strong>Luminosity</strong></td>
<td>1.30 Solar Lumins.</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>5,665 K</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td>7.5–8.5 × 10⁹ years</td>
</tr>
<tr>
<td><strong>Distance</strong></td>
<td>50.1 ly (15.4 pc)</td>
</tr>
</tbody>
</table>
51 Pegasi b

Michel Mayor and Didier Queloz
Discovery of 51 Pegasi in 1995

Radial Velocity of 51 Peg
60 m/s variation
Unofficially named Bellerophon, after the Greek Hero who tamed Pegasus

**Semimajor axis** 0.0527 ± 0.0030 AU  
**Periastron** 0.0520 AU  
**Apastron** 0.0534 AU  
**Eccentricity** 0.013 ± 0.012  
**Orbital period** 4.23 days (0.0116 years)

Bellerophon is thought to be a Gas Giant of a class now called **Hot Jupiters**. It is probably tidal-locked to the star.
As of 21 April 2015, a total of 1915 confirmed exoplanets are listed in the Extrasolar Planets Encyclopaedia. This includes 1210 planetary systems, of which 481 are multiple planetary systems (source: Wikipedia on 28 April 2015)
Kepler Mission

The Kepler mission launched on March 7, 2009.

Its objective was to explore the structure and diversity of extrasolar planetary systems.
Transit Method

Sequence of images of Venus transiting the Sun in June 2004.
(Jordano Bruno University, Dimitrovgrad Bulgaria)
Detecting Planetary Atmospheres

Moreover, if the planet has an atmosphere, changes in the spectral absorption lines can indicate the presence of particular chemical species.

This is a photo of Venus transiting the Sun.

One can even see sunlight refracting through its atmosphere!
Video at: https://www.youtube.com/watch?v=8GMoBfHXKnw
Star blocks light from planet sinusoidally-varying light from planet
Shift in baseline flux due to thermal light emission from planet

HAT-P-7b

Knuth and Placek ERCIM 2014

HAT-P-7b
HAT-P-7b

HAT-P-7b orbits an F8-type star in a circular orbit at 0.0377 AU with a period of 2.2 days.

We estimate HAT-P-7b to a Hot Jupiter that is 1.66 times more massive than Jupiter with 1.634 times the radius.

Its day-side temperature is 2859 ± 33 K whereas the night-side is 1332 ± 756 K.

Placek & Knuth 2014
arxiv:1409.4152
HD 209458 b orbits the star HD 209458 in the constellation Pegasus, about 150 LY from Earth. The orbital radius is about 0.047 AU and it revolves about its star every 3.5 Earth days. It has an estimated surface temperature of about 1,000°C (about 1,800°F). It is a gas giant with a mass is 220 times that of Earth (0.69 Jupiter masses) and its volume is some 146% greater than that of Jupiter.

First transiting extrasolar planet discovered.
First extrasolar planet known to have an atmosphere
Its atmosphere has Carbon, Oxygen and Water and has evaporating Hydrogen.
PSR B1620-26 resides in the Globular cluster of stars called M4 12,400 ly (3,800 pc) from Sol.

Pulsar PSR B1620-26 is a binary star system with a white dwarf WD B1620-26. The two stars share at least one planet.
History of PSR 1620-26 System

Jovian planet in Globular Cluster M4: Calm bystander in stellar drama

- Jovian planet forms around Sun-like star in outskirts of M4 13 billion years ago.
- Planet system travels to core of Globular Cluster M4
- Sun-like star swells to a red giant, spilling matter onto neutron star.
- Neutron star "spins up," becoming a pulsar that spins 100 times a second (PSR B1620-26). Red giant becomes a helium white dwarf.
- Jovian planet continues to orbit, relatively undisturbed, around new binary system.
- Slowly spinning neutron star captures star and planet; its original partner is ejected into space.
PSR B1620-26 b orbits a pair of stars. One, the pulsar, is a neutron star spinning at 100 revolutions per second. The second is a white dwarf with a mass of 0.34 solar masses. These stars orbit each other at a distance of 1 AU about once every six months.

The planet has a mass of 2.5 times that of Jupiter, and orbits at a distance of 23 AU (3,400 million km) with a period of about 100 years.

(source: wikipedia)

The triple system is just outside the core of the globular cluster Messier 4. The age of the cluster has been estimated to be about 12.7 billion years, and because all stars in a cluster form at about the same time, and planets form together with their host stars, it is likely that PSR B1620-26 b is also about 12.7 billion years old. This is much older than any other known planet, and nearly three times as old as Earth.
**55 Cancri: 5 Planets!!**

**Our Solar System**

**55 Cancri System**

---

### The 55 Cancri A system (Keplerian fit)[16]

<table>
<thead>
<tr>
<th>Companion (in order from star)</th>
<th>Mass</th>
<th>Semimajor axis (AU)</th>
<th>Orbital period (days)</th>
<th>Eccentricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>&gt;0.034 ± 0.0036 $M_J$</td>
<td>0.038 ± 10^−6</td>
<td>2.81705 ± 0.0001</td>
<td>0.07 ± 0.06</td>
</tr>
<tr>
<td>b</td>
<td>&gt;0.824 ± 0.007 $M_J$</td>
<td>0.115 ± 0.000011</td>
<td>14.65162 ± 0.0007</td>
<td>0.014 ± 0.008</td>
</tr>
<tr>
<td>c</td>
<td>&gt;0.169 ± 0.008 $M_J$</td>
<td>0.240 ± 0.00005</td>
<td>43.93 ± 0.021</td>
<td>0.086 ± 0.052</td>
</tr>
<tr>
<td>f</td>
<td>&gt;0.144 ± 0.04 $M_J$</td>
<td>0.781 ± 0.007</td>
<td>260.00 ± 1.1</td>
<td>0.2 ± 0.2</td>
</tr>
<tr>
<td>d</td>
<td>&gt;3.835 ± 0.08 $M_J$</td>
<td>5.77 ± 0.11</td>
<td>5218 ± 230</td>
<td>0.025 ± 0.03</td>
</tr>
</tbody>
</table>
Not All Systems are Nice
A Tour of 2000 Extrasolar Systems
An infrared image of 2M1207 (bluish) and 2M1207b (reddish).

These objects are separated by less than one arc second in the sky.

Credit: European Southern Observatory's 8.2 m Yepun Very Large Telescope
Iota Draconis B (2001)

The first planet found to be orbiting a giant star. Discovered using the Doppler method despite the tremendous oscillations of its parent star’s surface.

This is proof that planets can survive the cataclysmic changes that stars experience in their lifecycle.

This system originated in the Hyades cluster of stars along with Epsilon Tauri.

http://www.extrasolar.net/planettour.asp?PlanetID=189
HD 69830 (May 2006)

HD 69830 is an orange dwarf KO7 star aged About 7 billion years.

It is located 41 LY from Earth in the constellation of Puppis.

In addition to 3 Neptune sized planets orbiting within 1 AU of the star, the Spitzer Space telescope has detected a debris field or asteroid belt around the distance of Earth’s orbit that is shepherded by the three large planets!

<table>
<thead>
<tr>
<th>Companion</th>
<th>Mass</th>
<th>Semimajor axis (AU)</th>
<th>Orbital period (days)</th>
<th>Eccentricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>$&gt;0.033 M_J$</td>
<td>0.0785</td>
<td>$8.667 \pm 0.003$</td>
<td>0.1 $\pm$ 0.04</td>
</tr>
<tr>
<td>c</td>
<td>$&gt;0.038 M_J$</td>
<td>0.186</td>
<td>$31.56 \pm 0.04$</td>
<td>0.13 $\pm$ 0.06</td>
</tr>
<tr>
<td>d</td>
<td>$&gt;0.058 M_J$</td>
<td>0.63</td>
<td>197 $\pm$ 3</td>
<td>0.07 $\pm$ 0.07</td>
</tr>
<tr>
<td>Debris disk</td>
<td></td>
<td>0.93 — 1.16 AU</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fomalhaut is an A class star on the Main Sequence about 25 LY from Earth.

It is a young star (100–300 MY) surrounded by a dense dust cloud, which has a well-defined inner edge.

This led to the prediction that there must be a planet focusing the dust.

This was directly observed in visible light in 2008.
The Fomalhaut system[^11]

<table>
<thead>
<tr>
<th>Companion (in order from star)</th>
<th>Mass</th>
<th>Semimajor axis (AU)</th>
<th>Orbital period (years)</th>
<th>Eccentricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>0.054 - 3.0 $M_J$</td>
<td>~115</td>
<td>~872</td>
<td>~0.11</td>
</tr>
<tr>
<td>Dust disk</td>
<td></td>
<td>133 — 158 AU</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[^11]: Source reference for the Fomalhaut system data.
Fomalhaut b  (Nov 2008)

Artist’s rendition of Fomalhaut b
HD 189733 is a K class star located about 69 LY from Earth.

It has a Hot-Jupiter orbiting close to the star at 0.03 AU with a mass of 1.13 Jupiter masses.

Spectral measurements reveal water vapor in the planet’s atmosphere as well as methane! This is the first time organic molecules have been found on an extrasolar planet.
The same day that the planet Fomalhaut b was announced in 2008, we saw the first photograph of a triple planetary system.

HR 8799 is a young (60 MY) K class star located 129 LY from Earth. The orbits of its three planets are 2–2.5 times the distance from the star as Saturn, Uranus and Neptune are from the Sun. Further out HR8799 has an extensive dust disk.
Gliese 436 is an M class star located 33.4 LY from Earth in the constellation of Leo.

Gliese 436 b is 22 times more massive than Earth and orbits at 0.03 AU, extremely close to the parent star, which means it revolves every 2 days and 15.5 hours.

Its surface temperature is extremely high at 439 C and its radius and mass suggests an ice core. At this temperature and pressure, the water would be in a rare state---hot and solid!
Note: Artist Renditions

Potentially Habitable Exoplanets

Earth

Kepler-62 e
Gliese 667C c
Gliese 581 g*
Tau Ceti e*
Gliese 667C f
Kepler-22 b

Gliese 163 c
Kepler-61 b
HD 40307 g*
Kepler-62 f
Gliese 667C e
Gliese 581 d

*planet candidates

http://phl.upr.edu/projects/habitable-exoplanets-catalog/results

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) July 29, 2013
4,229 NASA Kepler Exoplanet Candidates

The Periodic Table of Exoplanets

<table>
<thead>
<tr>
<th>Stellar Systems</th>
<th>Gas Giants</th>
<th>Jovians</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,598</td>
<td>430</td>
<td>147</td>
</tr>
<tr>
<td>147</td>
<td>54</td>
<td>18</td>
</tr>
<tr>
<td>54</td>
<td>18</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mercurians</th>
<th>Subterrans</th>
<th>Terrans</th>
<th>Superterrans</th>
<th>Neptunians</th>
<th>Jovians</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03 → 0.4 (R_e)</td>
<td>0.4 → 0.8 (R_e)</td>
<td>0.8 → 1.25 (R_e)</td>
<td>1.25 → 2.5 (R_e)</td>
<td>2.5 → 6 (R_e)</td>
<td>&gt; 6 (R_e)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Hot Zone</th>
<th>Hot Subterrans</th>
<th>Hot Terrans</th>
<th>Hot Superterrans</th>
<th>Hot Neptunians</th>
<th>Hot Jovians</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>148</td>
<td>599</td>
<td>1,847</td>
<td>939</td>
<td>457</td>
</tr>
<tr>
<td>0.1%</td>
<td>3.5%</td>
<td>14.2%</td>
<td>43.7%</td>
<td>22.2%</td>
<td>10.8%</td>
</tr>
<tr>
<td>Confirmed 1</td>
<td>Confirmed 14</td>
<td>Confirmed 112</td>
<td>Confirmed 467</td>
<td>Confirmed 290</td>
<td>Confirmed 55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Warm 'Habitable' Zone</th>
<th>Warm Subterrans</th>
<th>Warm Terrans</th>
<th>Warm Superterrans</th>
<th>Warm Neptunians</th>
<th>Warm Jovians</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>91</td>
<td>72</td>
<td>44</td>
<td>1</td>
</tr>
<tr>
<td>&lt;0.1%</td>
<td>0.2%</td>
<td>2.2%</td>
<td>1.7%</td>
<td>1.0%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Confirmed 0</td>
<td>Confirmed 1</td>
<td>Confirmed 7</td>
<td>Confirmed 3</td>
<td>Confirmed 3</td>
<td>Confirmed 0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cold Zone</th>
<th>Cold Subterrans</th>
<th>Cold Terrans</th>
<th>Cold Superterrans</th>
<th>Cold Neptunians</th>
<th>Cold Jovians</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>3</td>
<td>6</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>0%</td>
<td>0%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>0.1%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Confirmed 0</td>
<td>Confirmed 0</td>
<td>Confirmed 0</td>
<td>Confirmed 0</td>
<td>Confirmed 0</td>
<td>Confirmed 0</td>
</tr>
</tbody>
</table>

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) Sep 2014
Planet Sizes

Kepler-7b: 16.52 $R_E$
Kepler-5b: 16.00 $R_E$
Kepler-8b: 15.86 $R_E$
Kepler-6b: 14.79 $R_E$
Jupiter: 11.2 $R_E$

Kepler-9b: 9.4 $R_E$
Kepler-9c: 9.2 $R_E$
Kepler-4b: 3.99 $R_E$
Kepler-9d: 1.64 $R_E$
Kepler-10b: 1.42 $R_E$
Earth: 1 $R_E$

Kepler-11b: 1.97 $R_E$
Kepler-11c: 3.15 $R_E$
Kepler-11d: 3.43 $R_E$
Kepler-11e: 4.52 $R_E$
Kepler-11f: 2.61 $R_E$
Kepler-11g: 3.66 $R_E$
Planet Habitability Chart

Habitable Zone

Mass of star relative to Sun

Radius of orbit relative to Earth's
The Sirius System

The Sirius System is 8.6 LY from Earth.
Sirius A and B orbit one another with a period of 50.9 years
Sirius B is slightly smaller than Earth.
The gravity on its surface is 350,000 times that of Earth’s.
A 150 lb person would weigh 50 million pounds on Sirius B!
Gliese 581 System
Gliese 581 System
Kepler 11

Kepler-11 System

Venus

Mercury

Solar System

Kepler-11b 1.97 $R_E$
Kepler-11c 3.15 $R_E$
Kepler-11d 3.43 $R_E$
Kepler-11e 4.52 $R_E$
Kepler-11f 2.61 $R_E$
Kepler-11g 3.66 $R_E$
Centauri System (Triple Star System)

Possible planets at Alpha Centauri

α Centauri A

11 AU distance at closest approach

Proxima (α Centauri C)
(13,000 astronomical units away from A and B)

2 AU limit for stable orbits

α Centauri B

Life zone

The Sun and its terrestrial planets (on the same scale)

In true relative scale

Sun
α Centauri A
α Centauri B
Proxima
Alpha Centauri B b

Type: Hot Terran
Habitability: non habitable
Mass: $\geq 1.13 \, M_E$
Radius: $\sim 1 \, R_E$
Period: 3.24 days
Dist. to Star: 0.04 AU
Temperature: $\sim 870^\circ C$

Earth Similarity Index = 0.27

CREDIT: PHL @ UPR Arecibo
Artist’s Conception of a Sunset in a Binary Star System
Our Stellar Neighborhood

There are 2000 stars within 50 LY of Earth.

133 (shown here) are G-type stars like the Sun

Most of the others are red dwarves

One out of 5 of these stars has a planet in the Habitable Zone.

There are potentially 400 habitable planets within 50 LY
3200 habitable planets within 100 LY
3,200,000 habitable planets within 1000 LY
(This does not include habitable moons!)
Search for Life

"I believe we are going to have strong indications of life beyond Earth in the next decade and definitive evidence in the next 10 to 20 years"
- Dr. Ellen Stofan
Chief Scientist for NASA

"Either we will find Extraterrestrial life in the next 20 years or I will buy you a cup of coffee."
- Dr. Seth Shostak
SETI

"It's definitely not an if, it's a when"
- Dr. Jeffery Newmark
NASA Interim Director Heliophysics Division

"The questions of life's origins and of whether life exists elsewhere in the universe are very suitable and deserve serious consideration,"
- Rev. Jose Gabriel Funes,
Astronomer and Director of the Vatican Observatory.

"I think in the next 20 years we will find out we are not alone in the universe."
- Dr. Kevin Hand
NASA Astrobiologist
I cleave the heavens and soar to the infinite.  
And while I rise from my own globe to others  
And penetrate ever further through the eternal field,  
That which others saw from afar, I leave far behind me.  

I pray you, magnificent Sir,  
do not trouble yourself to return to us,  
but await our coming to you.  

Giordano Bruno (1584)