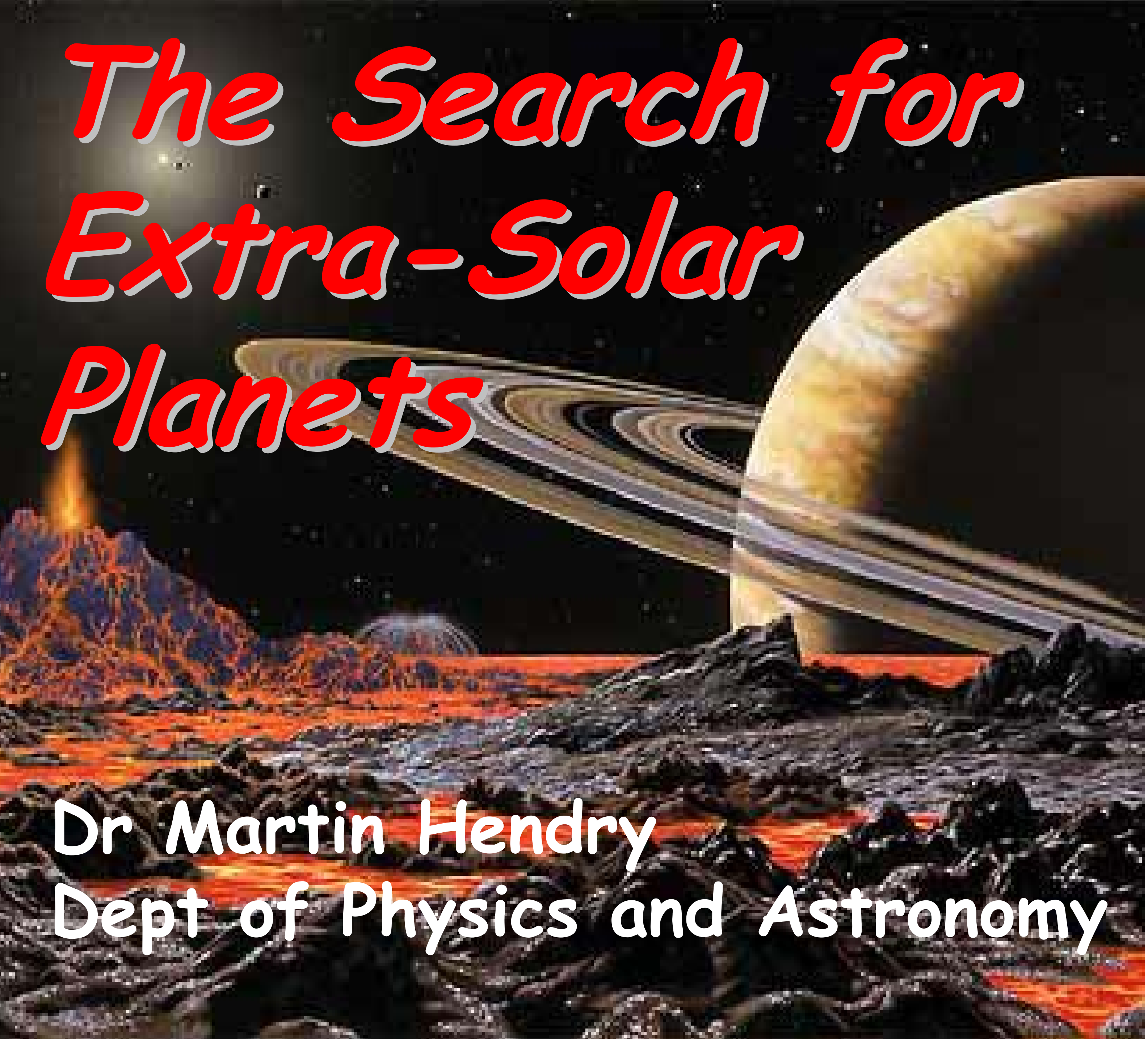

The Search for Extra-Solar Planets

Dr Martin Hendry
Dept of Physics and Astronomy

UNIVERSITY of GLASGOW

PPARC

Life in the Cosmos: Jan 2006

Extra-Solar Planets

- *One of the most active and exciting areas of astrophysics*
- **More than 170 exoplanets discovered since 1995**

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Some important questions

- How common are planets?
- How did planets form?
- Can we find Earth-like planets?
- Do they harbour life?

Extra-Solar Planets

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- **More than 170 exoplanets discovered since 1995**

What we are going to cover

- **How can we detect extra-solar planets?**
- **What can we learn about them?**

1. How can we detect extra-solar planets?

- Planets don't shine by themselves; they just reflect light from their parent star

$\Rightarrow$ Exoplanets are very *faint*

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$\Rightarrow$ Exoplanets are very *faint*

- We measure the intrinsic brightness of a planet or star by its **luminosity**

$$\boxed{\text{Luminosity, } L \ \textit{(watts)}}$$

Luminosity varies with colour (see later)

e.g. consider Rigel *and* Betelgeuse in Orion

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Adding up (integrating) L over all colours

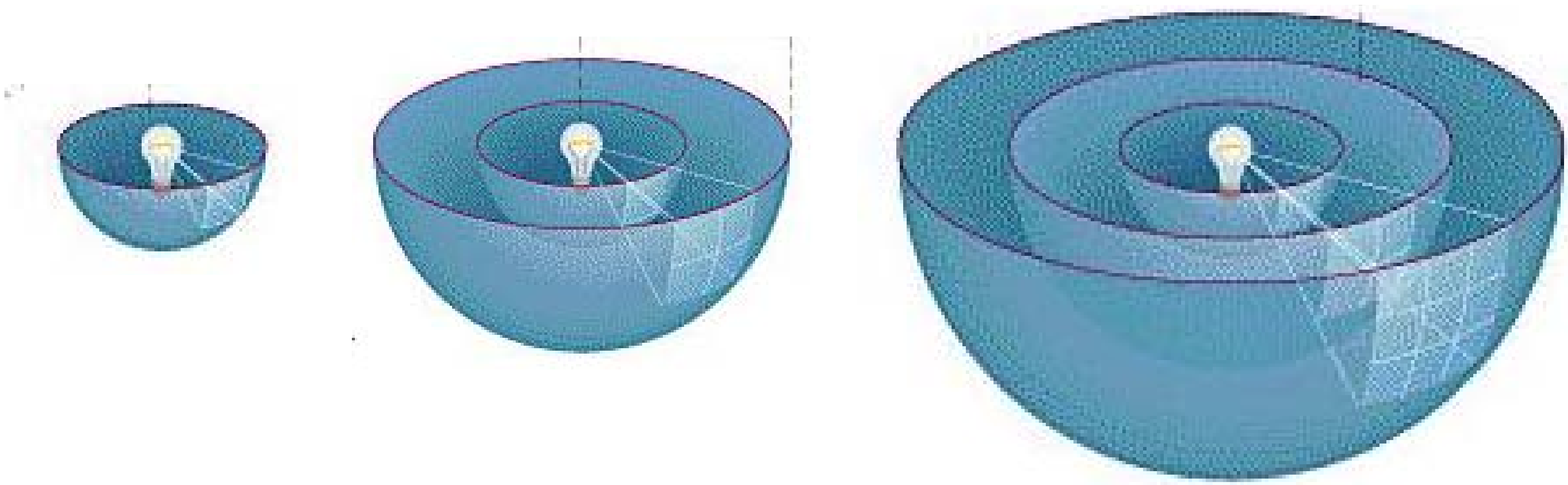
$\Rightarrow$ Bolometric luminosity

e.g. for the Sun

$$\boxed{L_{\text{bol}} = 4\times10^{26}\ \text{W}}$$

Stars radiate **isotropically**
(equally in all directions)

$\Rightarrow$ at distance r, luminosity spread over a sphere of surface area $4\pi r^2$



(this gives rise to the Inverse-Square Law)

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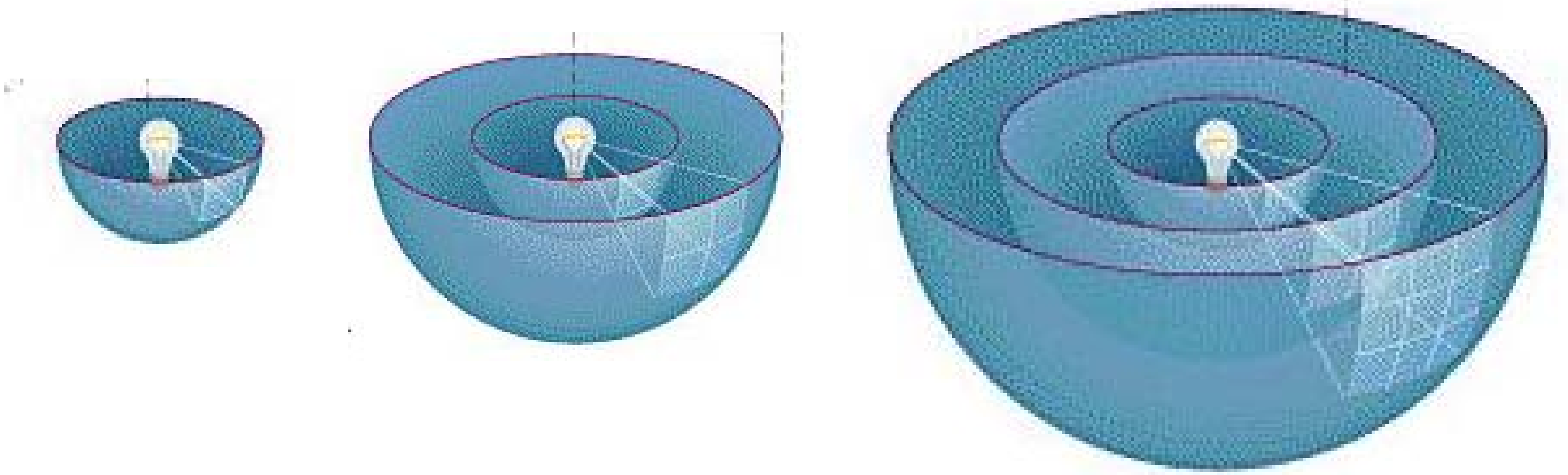

(this gives rise to the Inverse-Square Law)

Planet reflects a tiny fraction of the star's light

Examples

Sun - Earth:

Earth intercepts about half a billionth of the Sun's radiation

Examples

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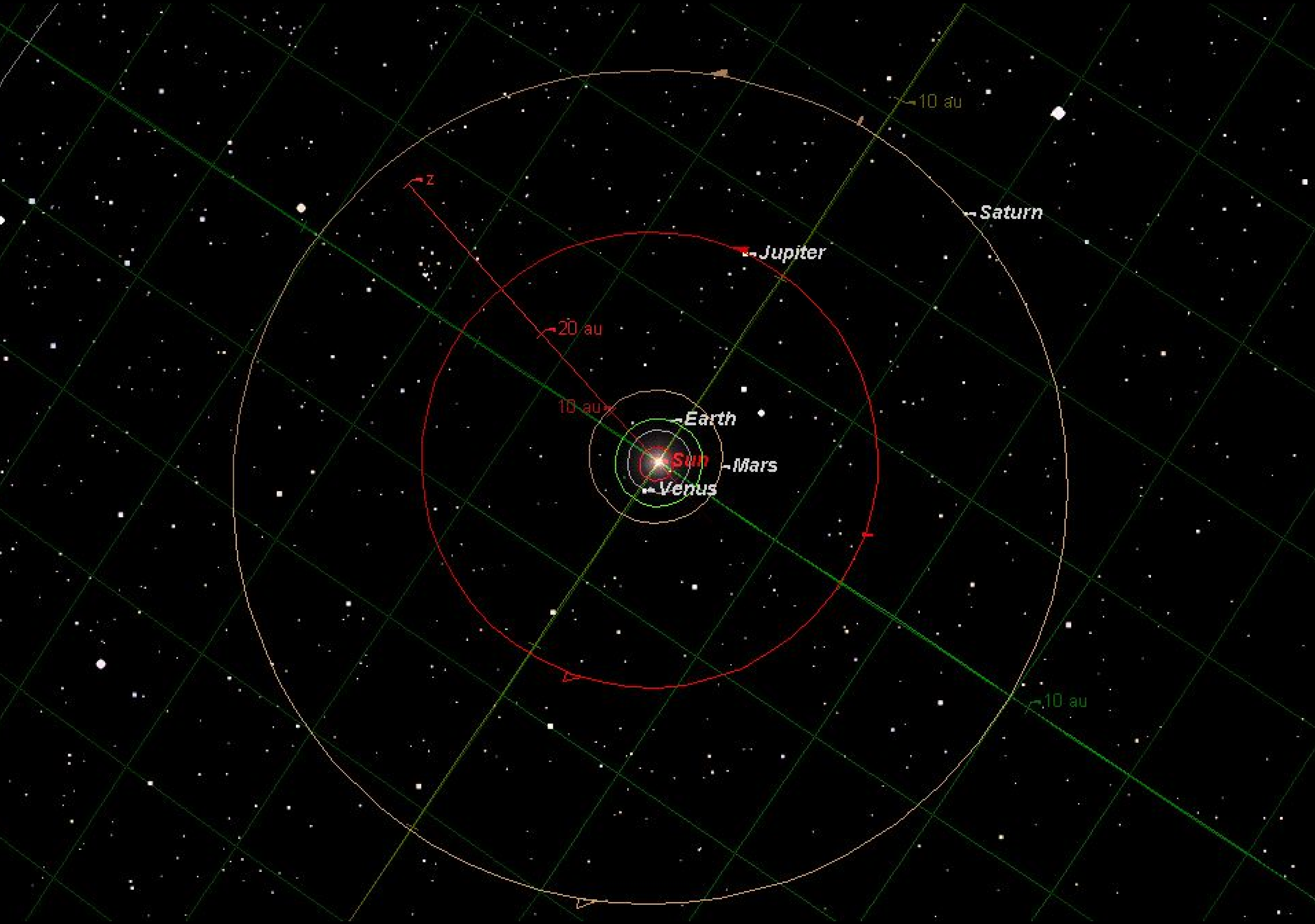
Earth intercepts about half a billionth of the Sun's radiation

Sun - Jupiter:

Jupiter intercepts about two billionths of the Sun's radiation



10 au
z
Saturn
Jupiter
20 au
10 au
Earth
Sun
Mars
Venus
10 au

2nd problem:

Angular separation of star and exoplanet is **tiny**

Distance units

Astronomical Unit = mean Earth-Sun distance

$$\boxed{1\,\text{A.U.} = 150\ \text{million km}}$$

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Distance units

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$$\boxed{1\,\mathrm{A.U.} = 150\text{ million km}}$$

For interstellar distances: **Light year**

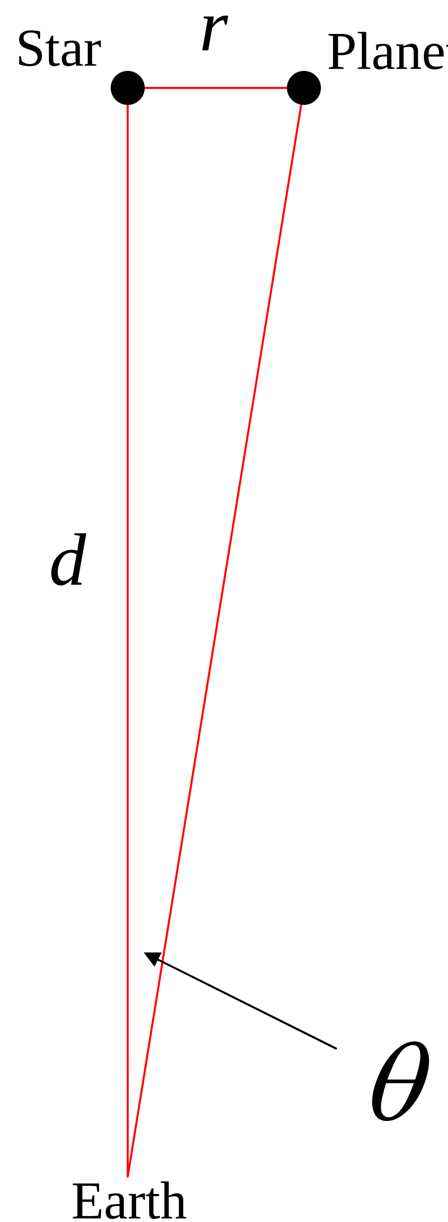
$$\boxed{1\text{ light year} = 63000\text{ A.U.}}$$

e.g. 'Jupiter' at 30 l.y.

$$d = 30\,\text{l.y.} = 2.8\times10^{17}\ \text{m}$$

$$r = 5\,\text{A.U.} = 7.5\times10^{11}\ \text{m}$$

$$\theta = 1.5\times10^{-4}\ \text{deg}$$



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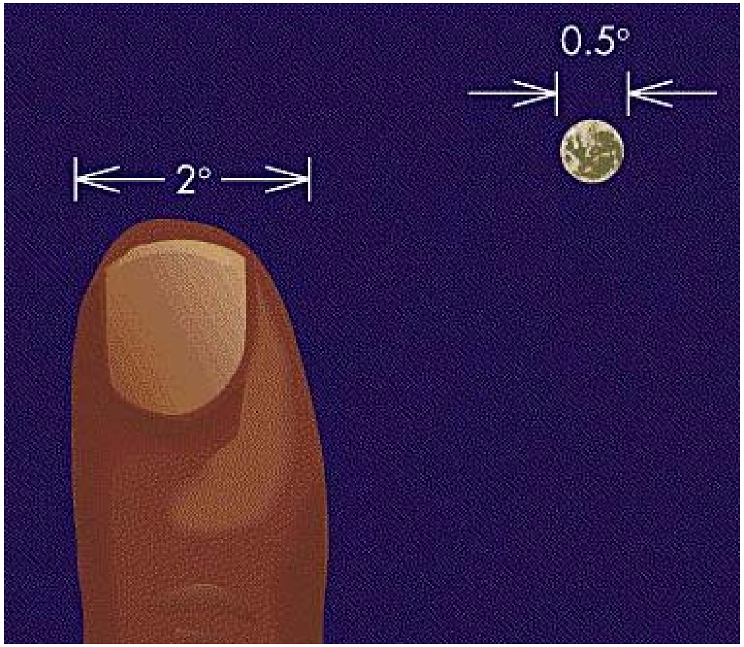

Angular separation = 1 / 3000th of the angular size of the Full Moon

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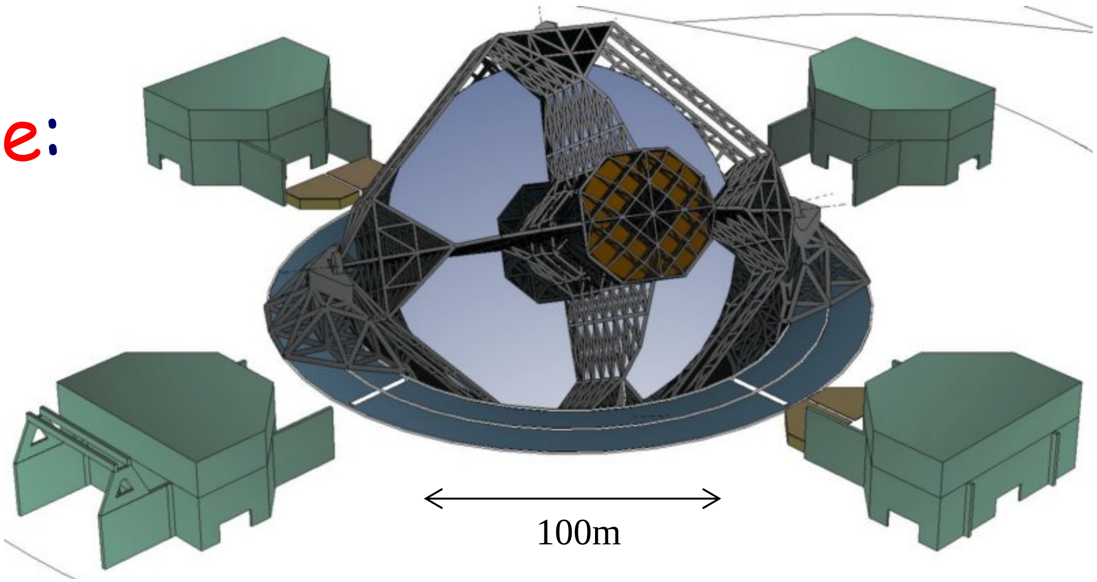
Need OWL telescope:

100m mirror
Completed ~2020



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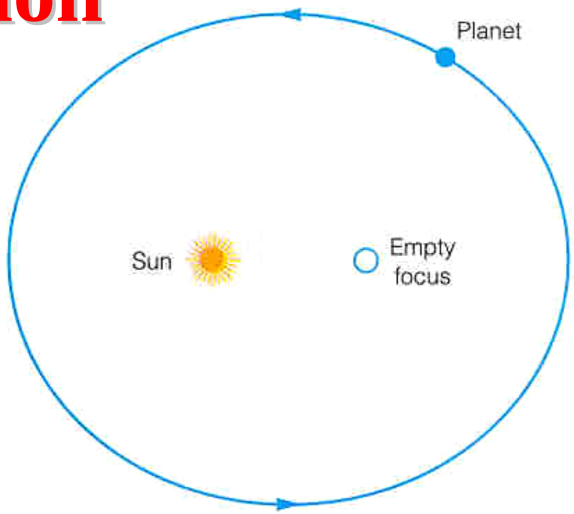
Johannes Kepler

Isaac Newton

Kepler's Laws of Planetary Motion

1) Planets orbit the Sun in an ellipse with the Sun at one focus



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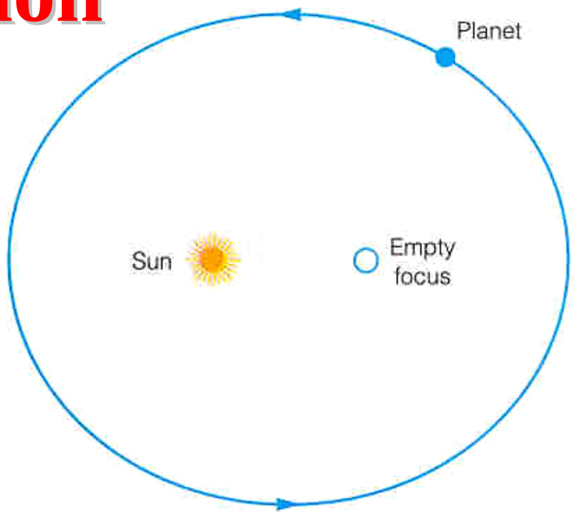
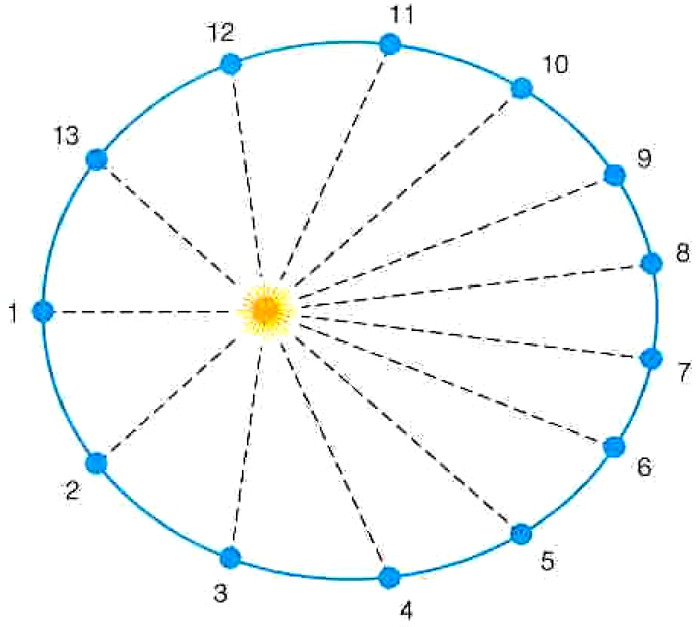


2) During a planet's orbit around the Sun, equal areas are swept out in equal times



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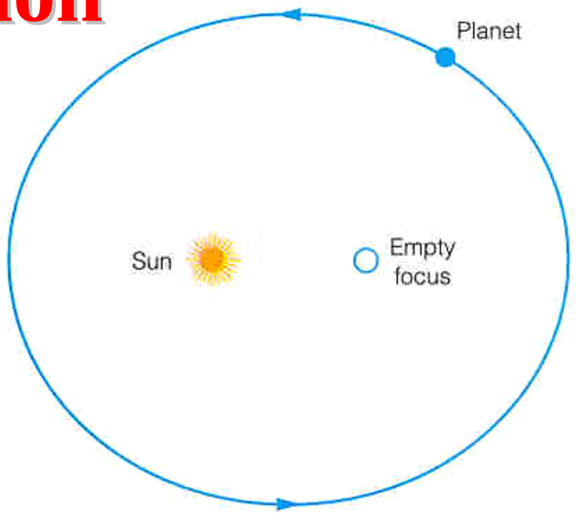

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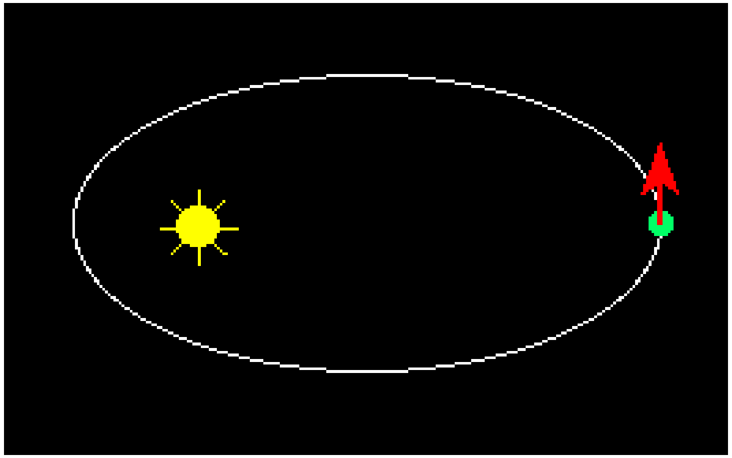

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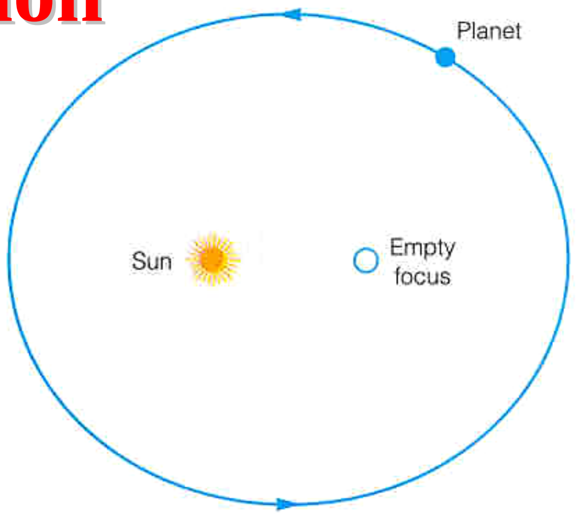

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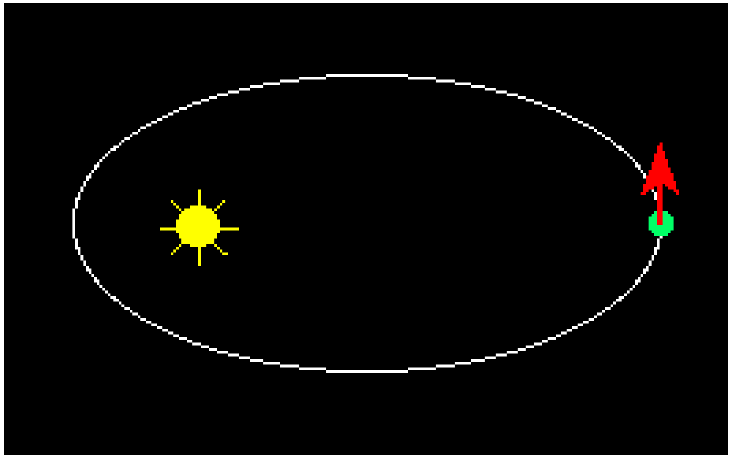

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Kepler's Laws, published 1609, 1619

Kepler's Laws of Planetary Motion

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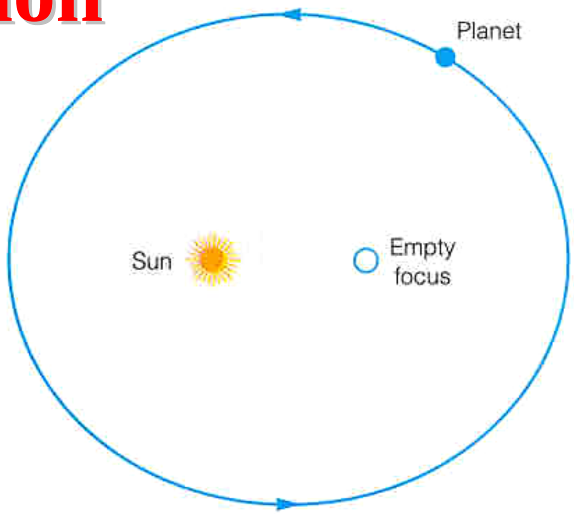

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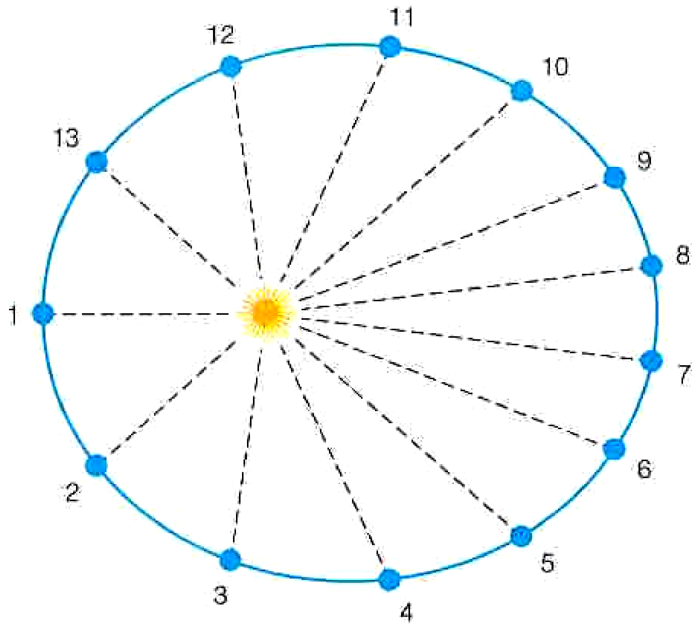

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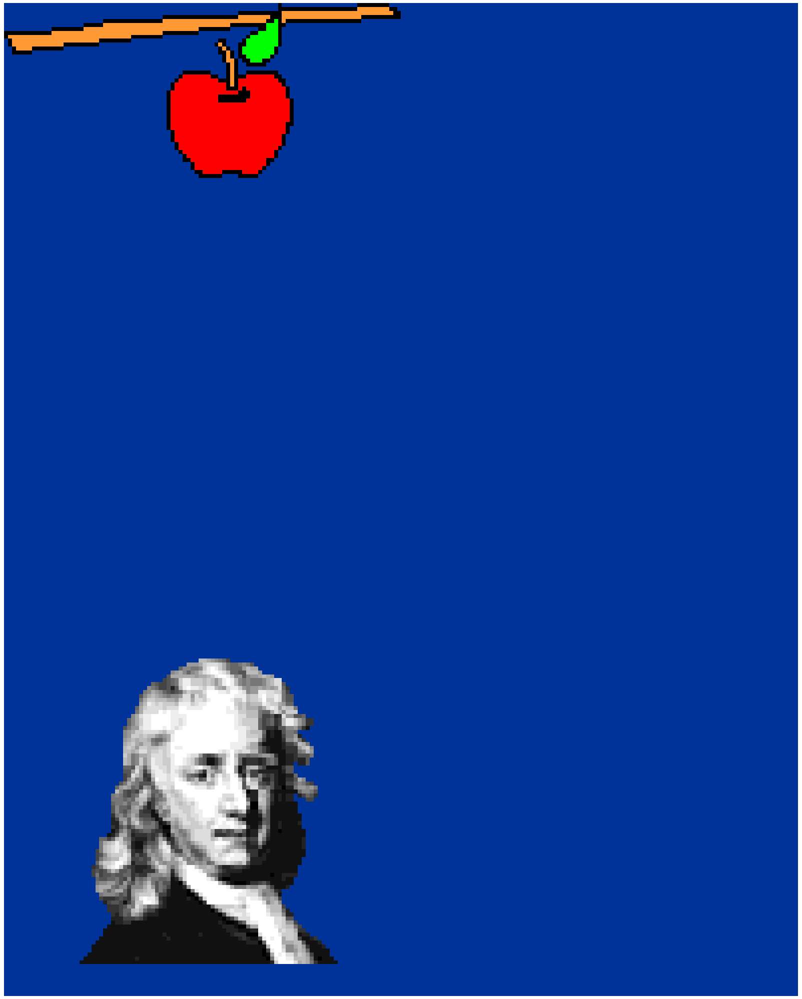
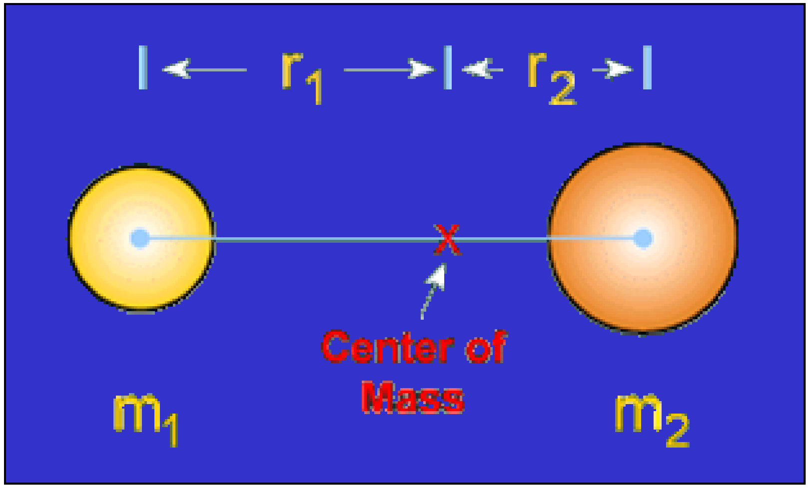
Newton's gravitational force provided a physical explanation for Kepler's laws

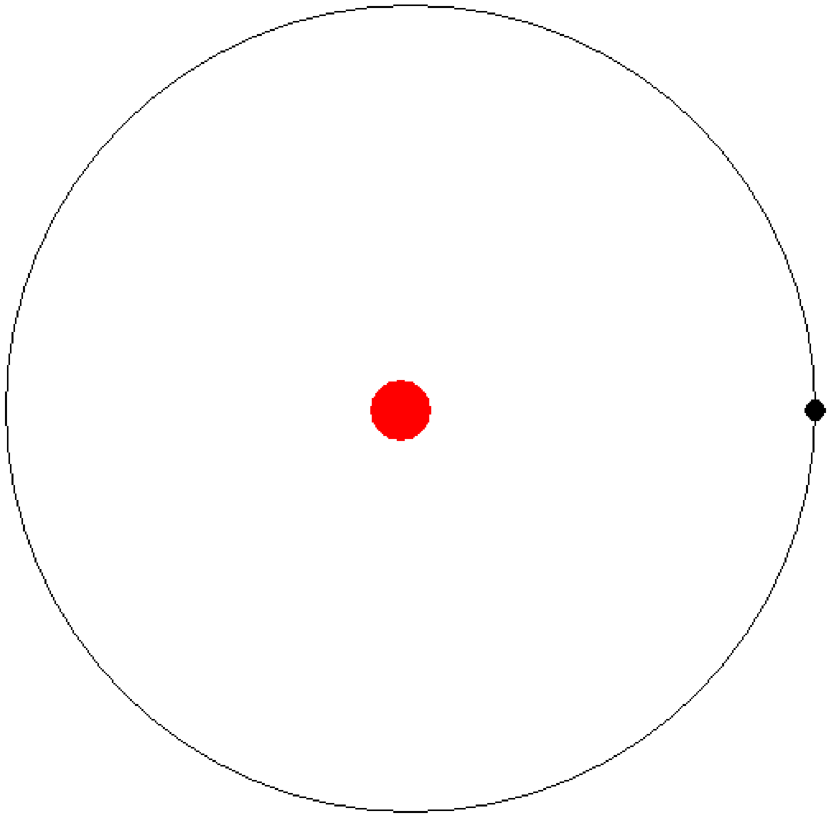


Newton's law of Universal Gravitation, Published in the Principia: 1684 - 1686

Every object in the Universe attracts every other object with a force directed along the line of centers for the two objects that is proportional to the product of their masses and inversely proportional to the square of the separation between the two objects.



Star + planet in circular orbit about centre of mass



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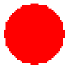
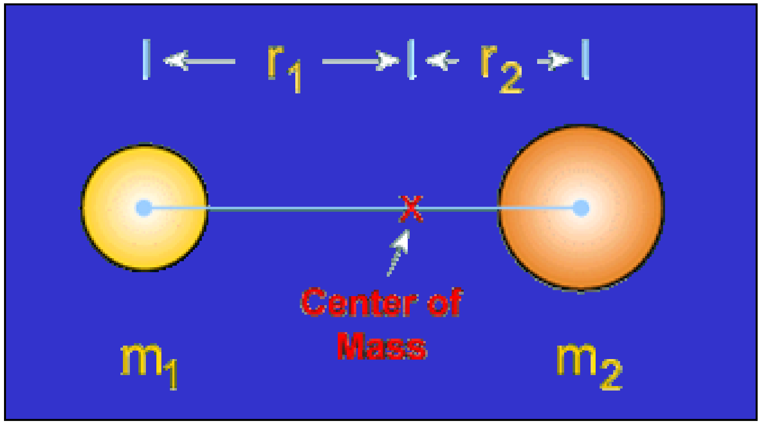
Star + planet in circular orbit about centre of mass

Can see star 'wobble', even when planet is unseen.



But how large is the wobble?...

Star + planet in circular orbit about centre of mass



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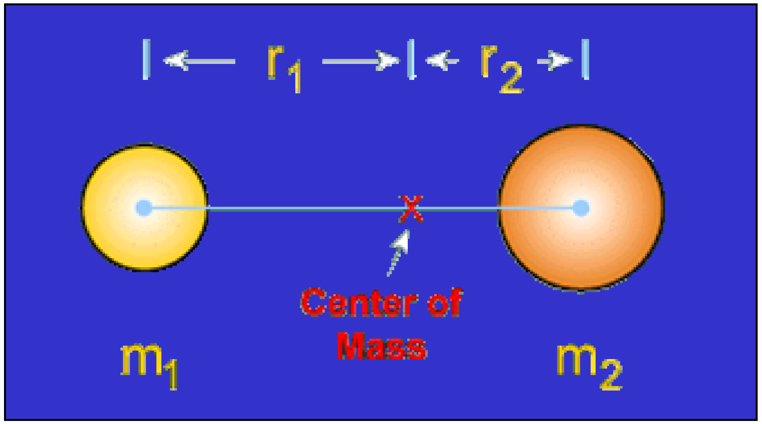
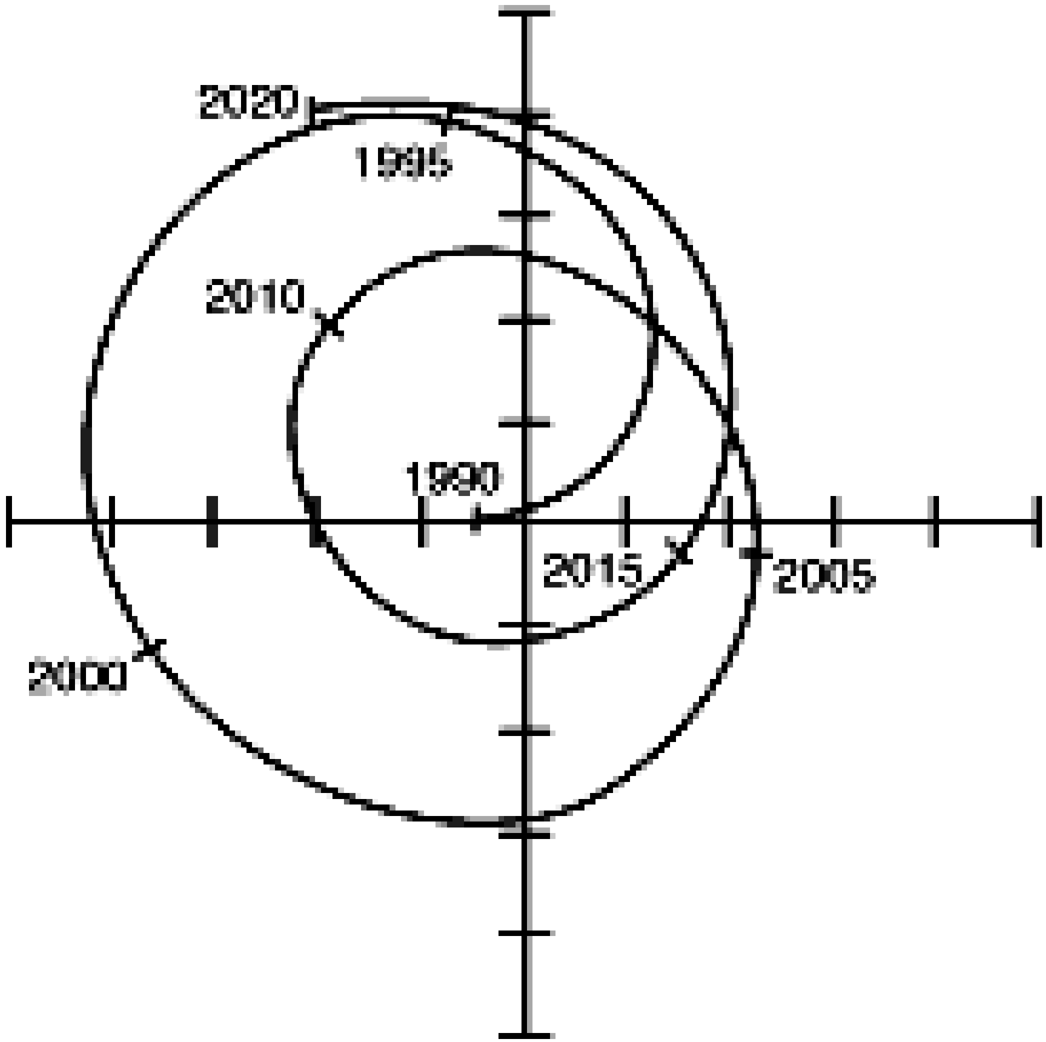


Can see star 'wobble', even when planet is unseen.

But how large is the wobble?...

e.g. 'Jupiter' at 30 l.y.

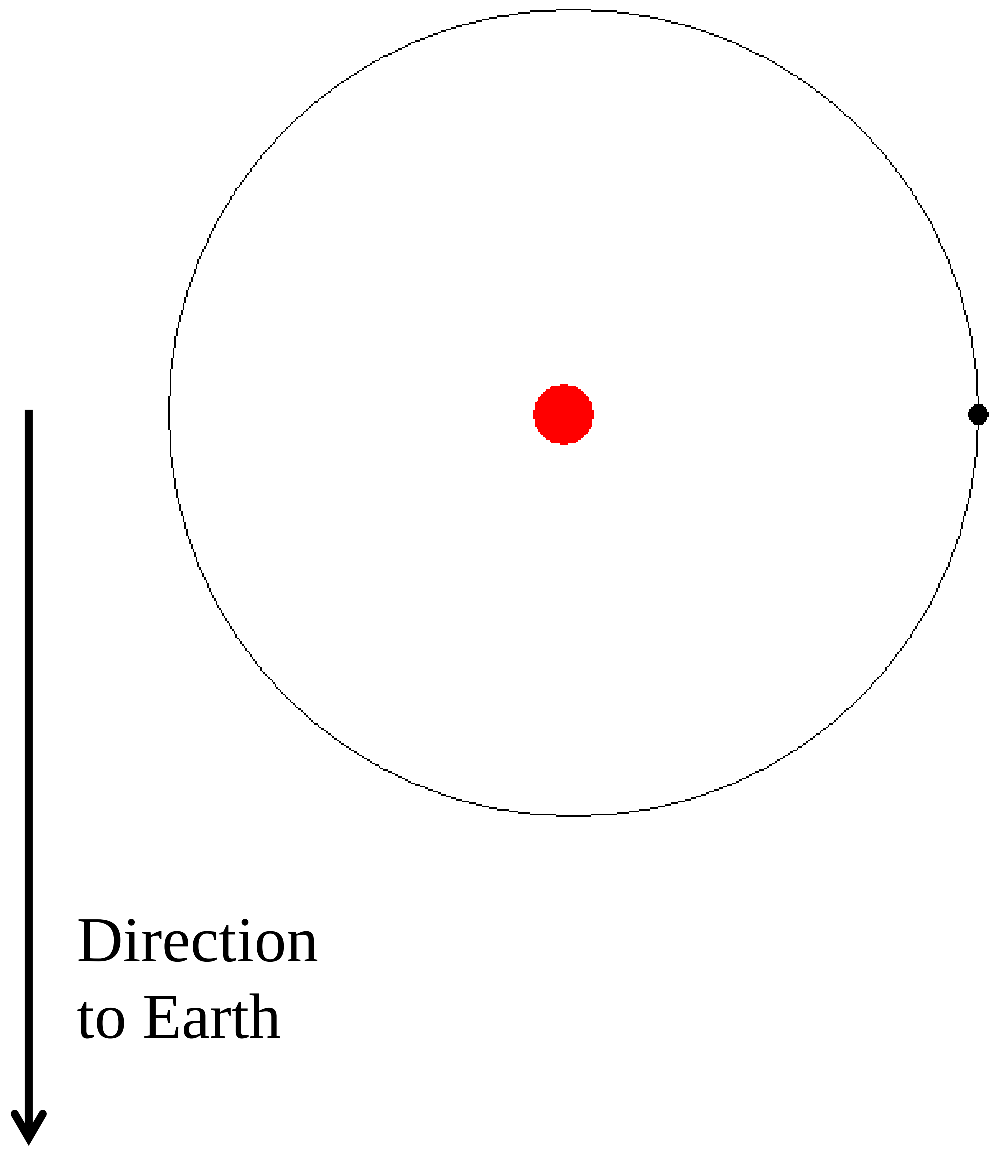
= one three *millionth* of the width of the Full Moon !!!



Detectable routinely with SIM (launch date 2009) but ***not*** currently

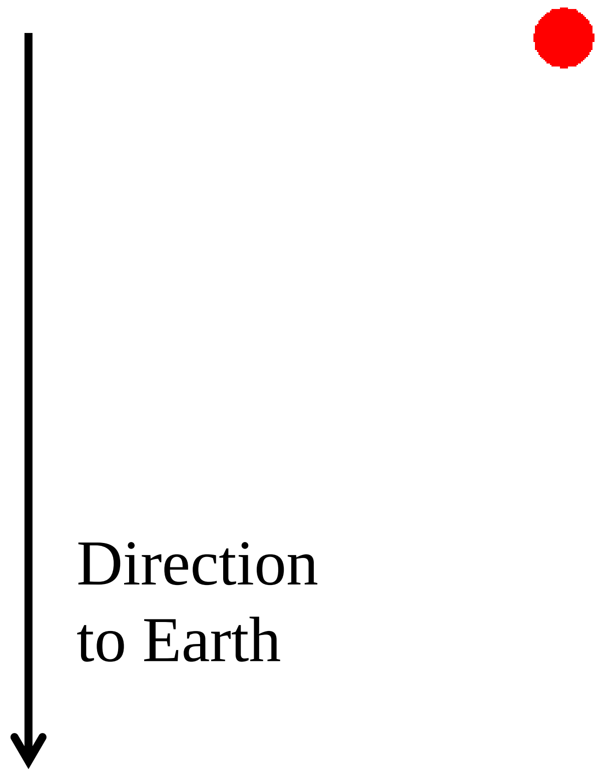
The Sun's "wobble", mainly due to Jupiter, seen from 30 light years away = width of a 5p piece in Baghdad!

Suppose line of sight is in orbital plane



Suppose line of sight is in orbital plane

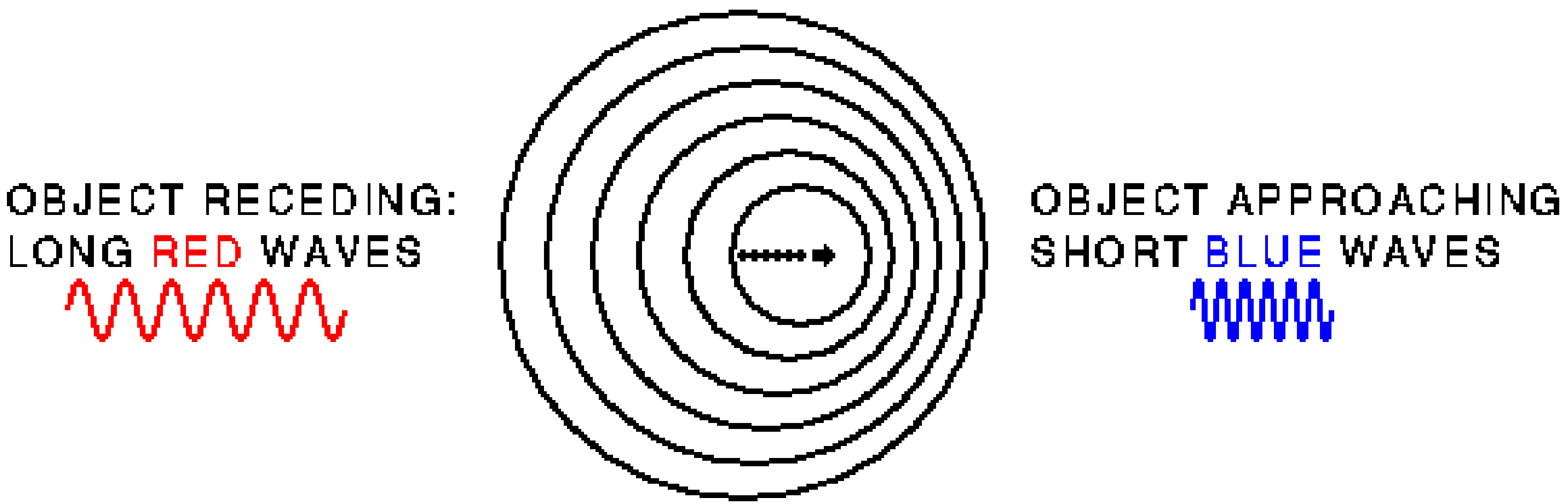
Star has a periodic motion towards and away from Earth



Suppose line of sight is in orbital plane

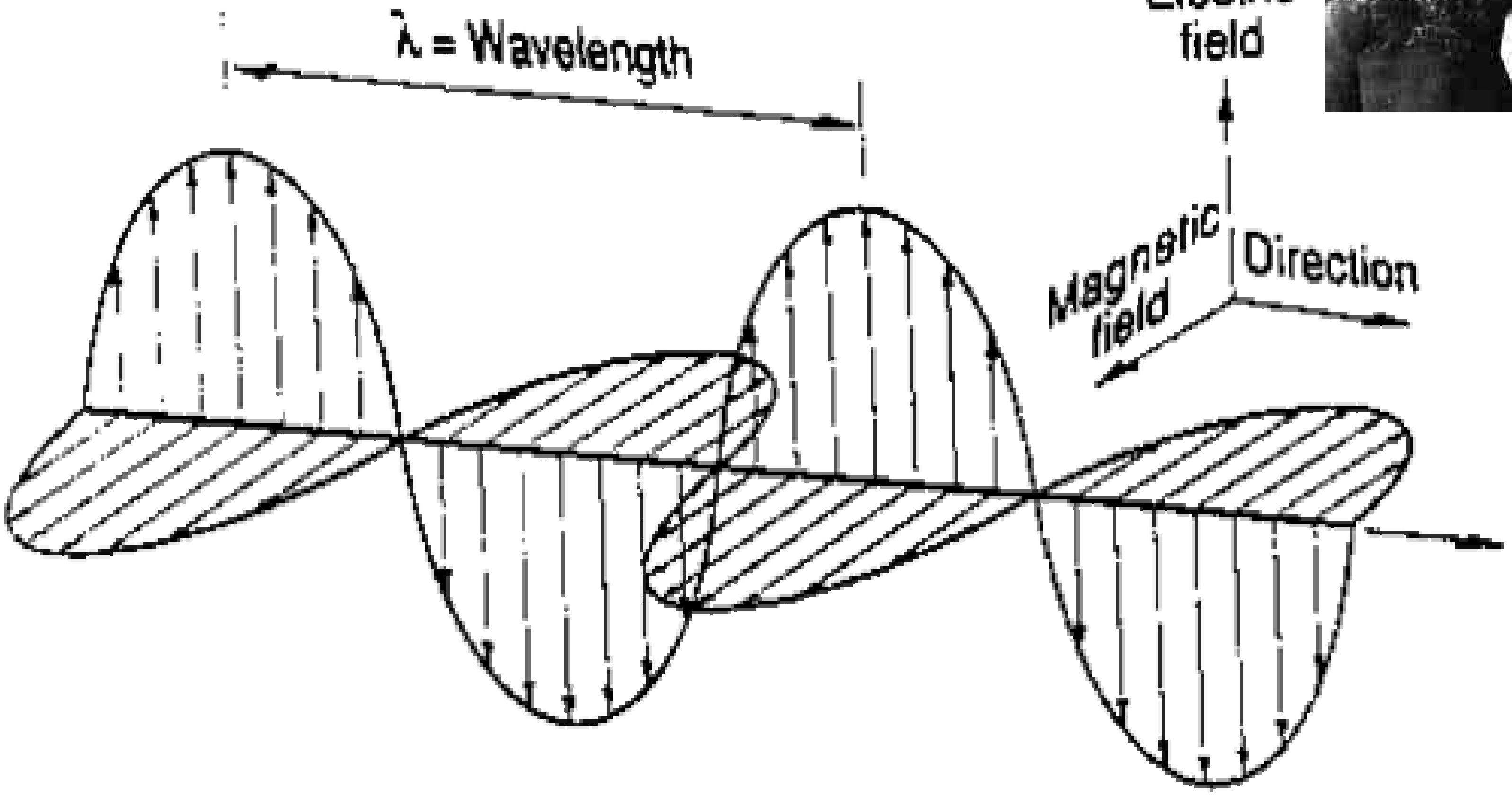
Detectable via the **Doppler Effect**

Star has a periodic motion towards and away from Earth



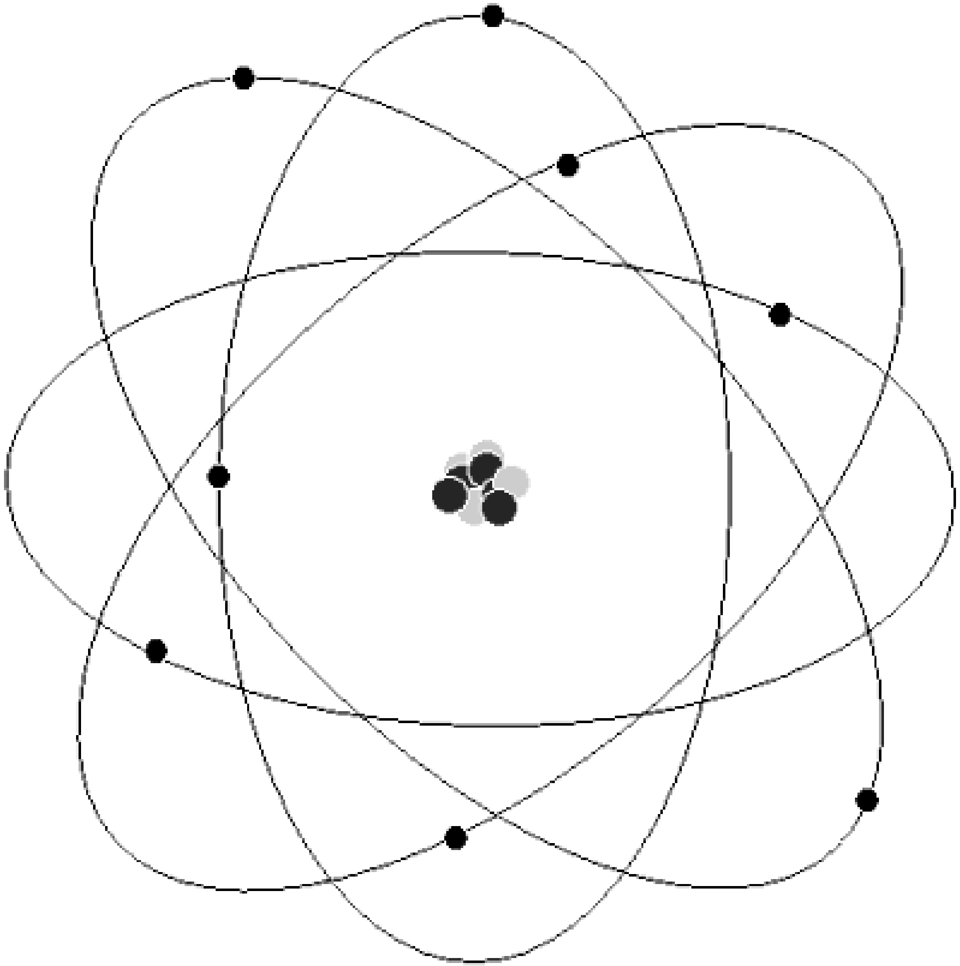
Can detect motion from shifts in ***spectral lines***

Maxwell's theory of light



Early 1900s: accelerated electron radiates

How do atoms persist?

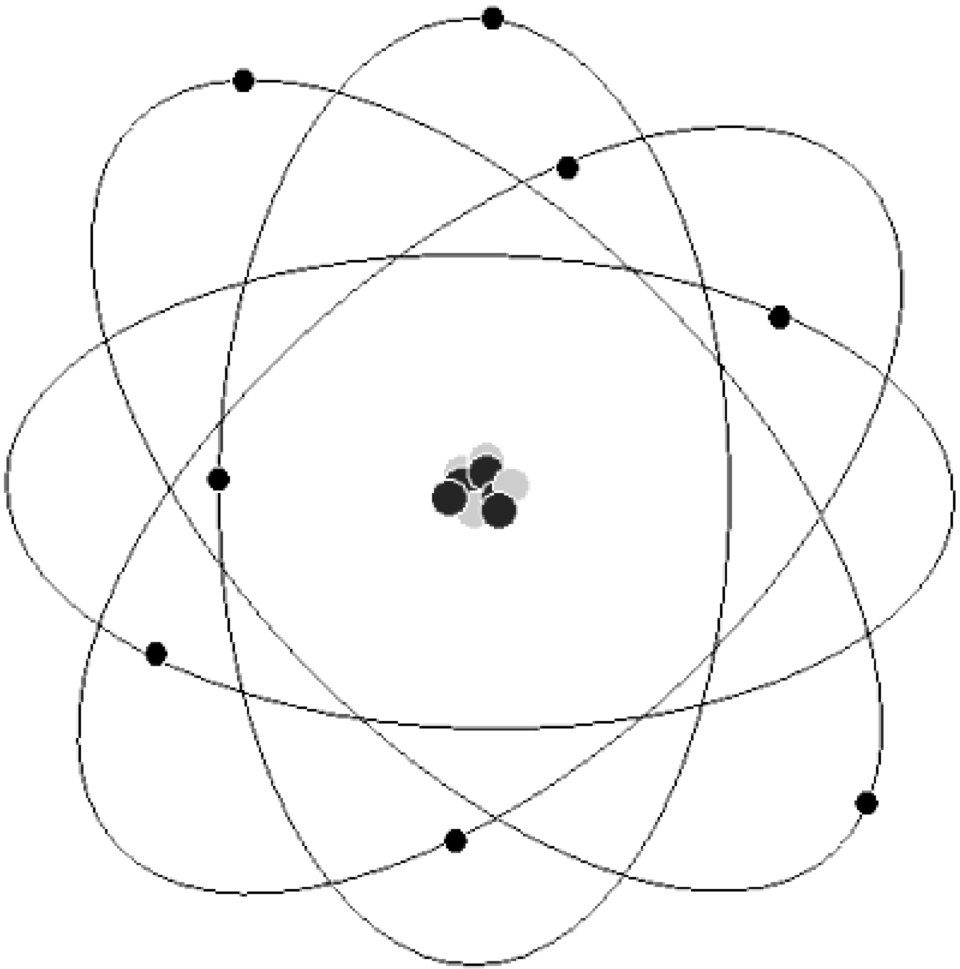


Requires *quantised* orbits

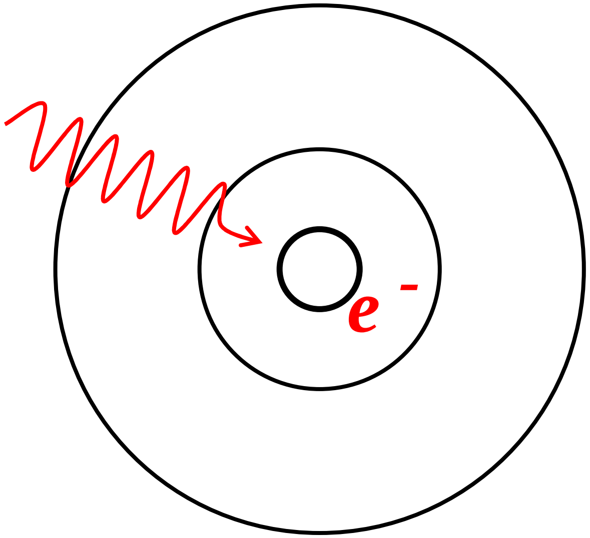
Spectral lines arise when electrons change energy level inside atoms.

This occurs when atoms absorb or emit light energy.

Since electron energies are ***quantised***, spectral lines occur at precisely defined colours, or *wavelengths*

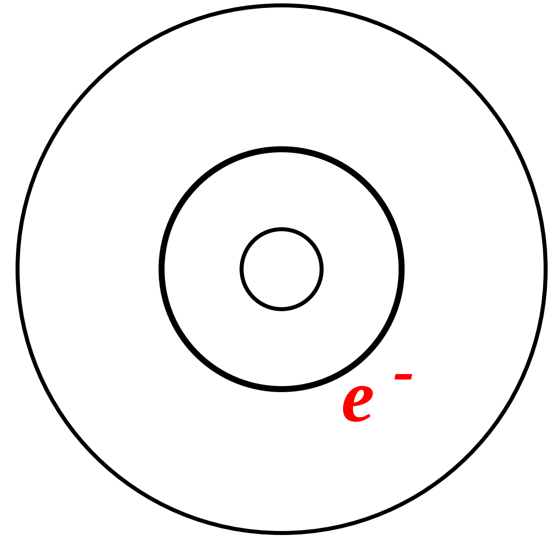


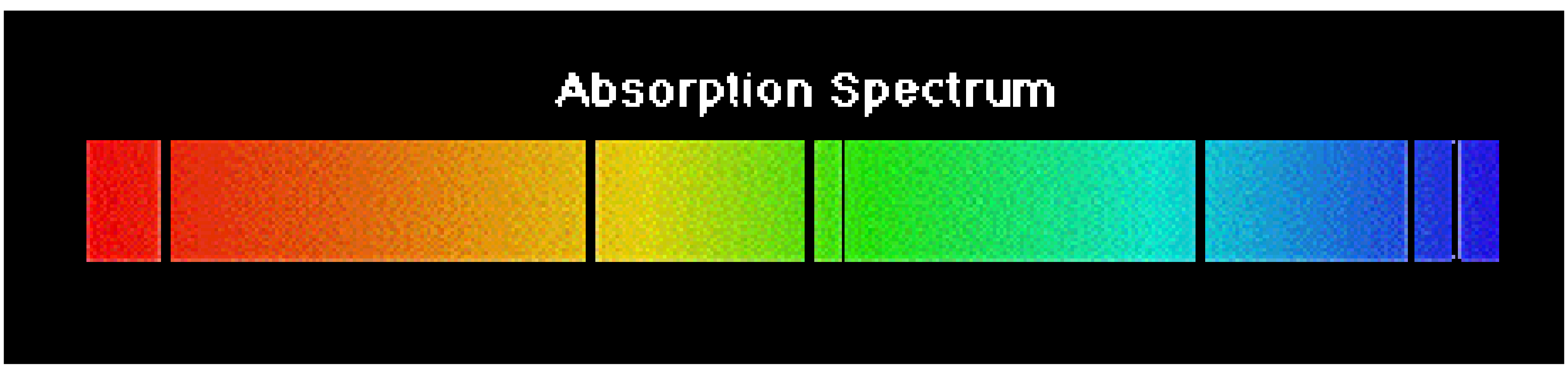
Absorption



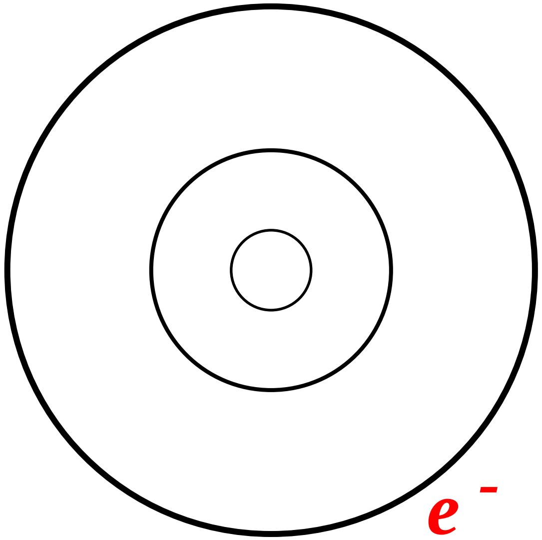
Electron absorbs photon of the precise energy required to jump to higher level.

Light of this energy (wavelength) is missing from the continuous spectrum from a cool gas



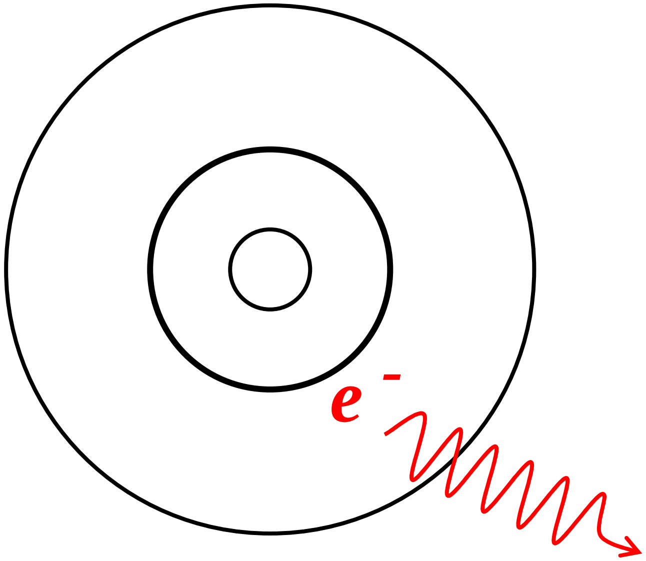


Emission

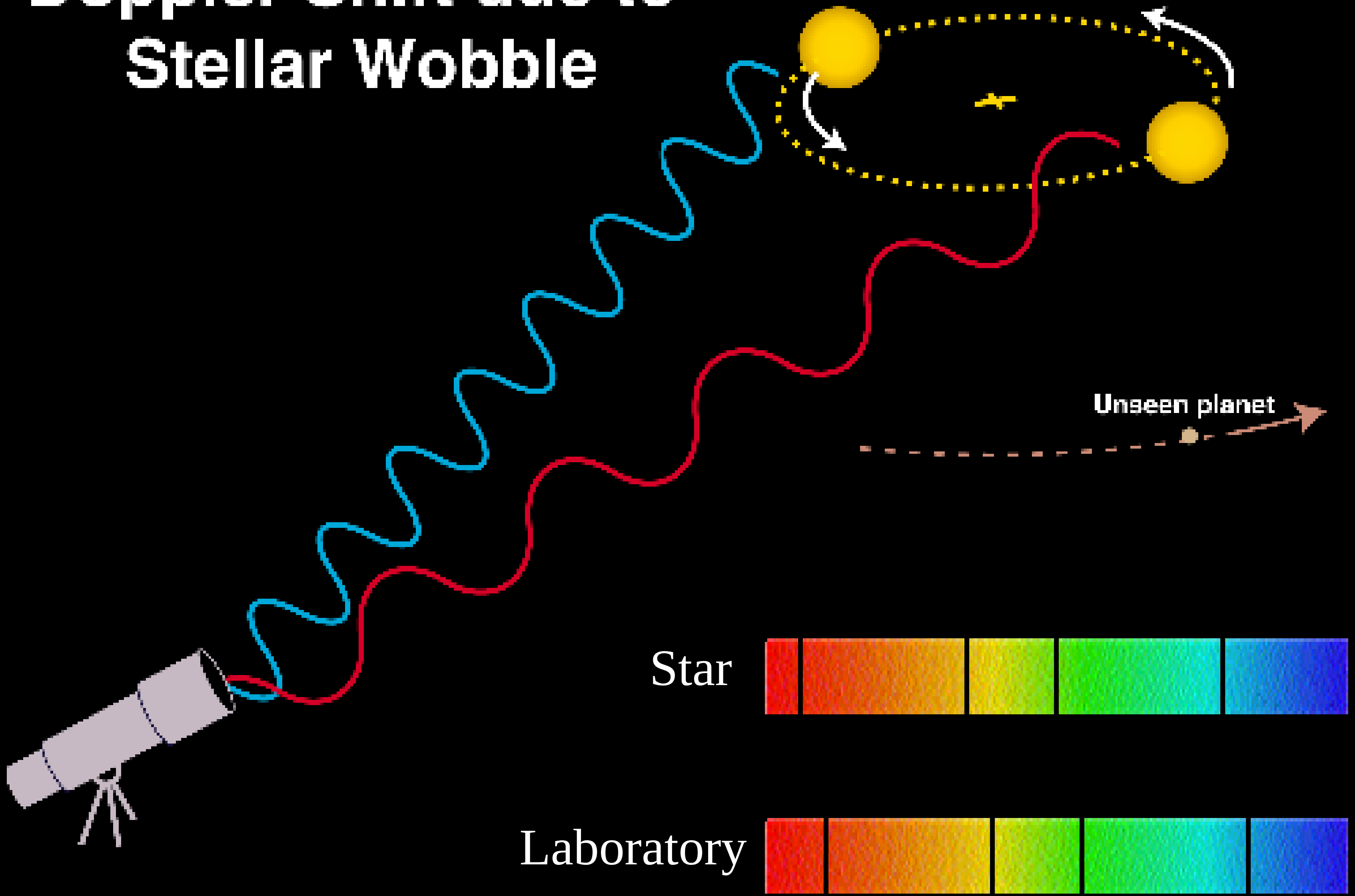


Electron jumps down to lower energy level, and emits photon of energy equal to the difference between the energy levels.

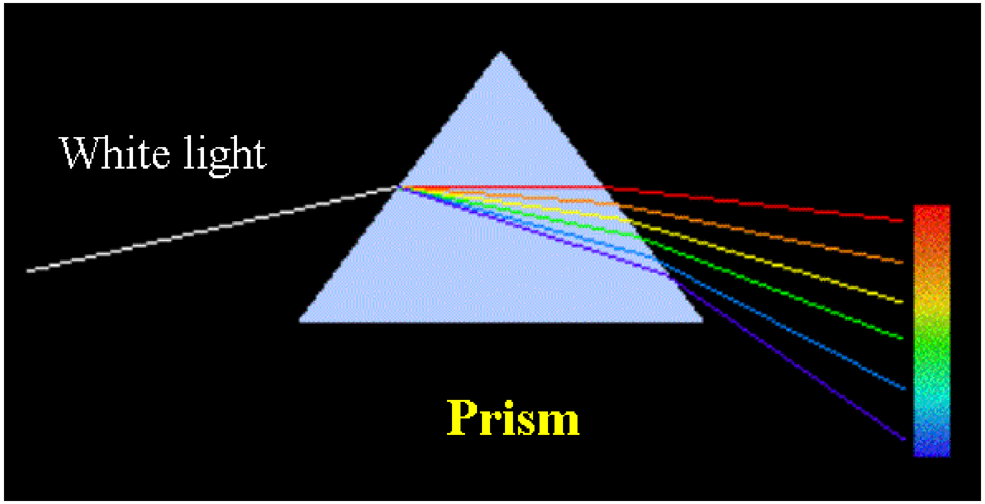
Light of this energy (wavelength) appears in the spectrum from a hot gas



Doppler Shift due to Stellar Wobble



Stellar spectra are observed using prisms or diffraction gratings, which disperse starlight into its constituent colours



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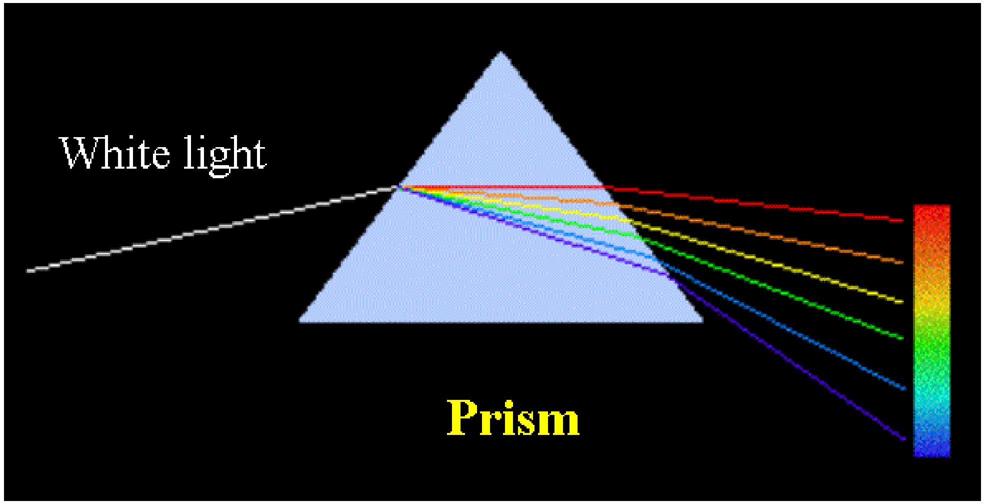

Doppler formula

Change in wavelength

Radial velocity

$$\boxed{\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}}$$

Wavelength of light as measured in the laboratory

Speed of light

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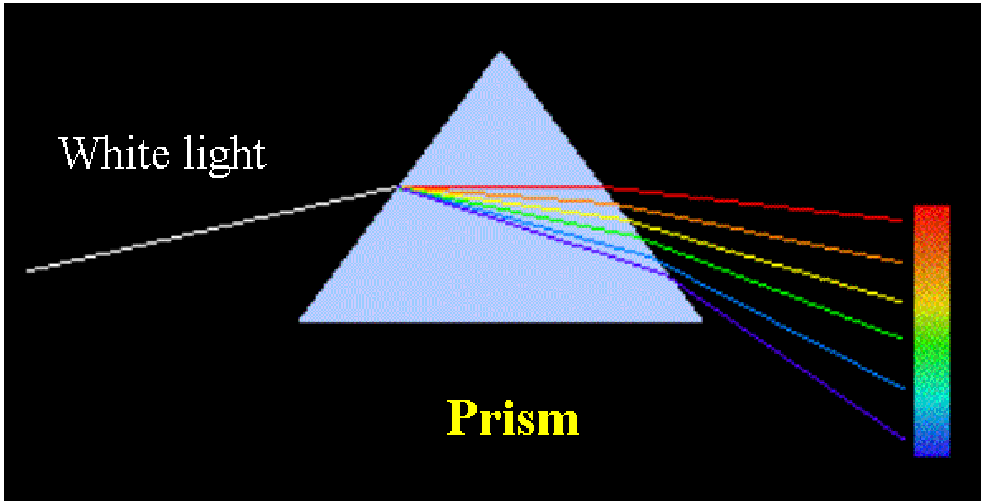


Doppler formula

Change in wavelength

Radial velocity

$$\boxed{\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}}$$

Wavelength of light as measured in the laboratory

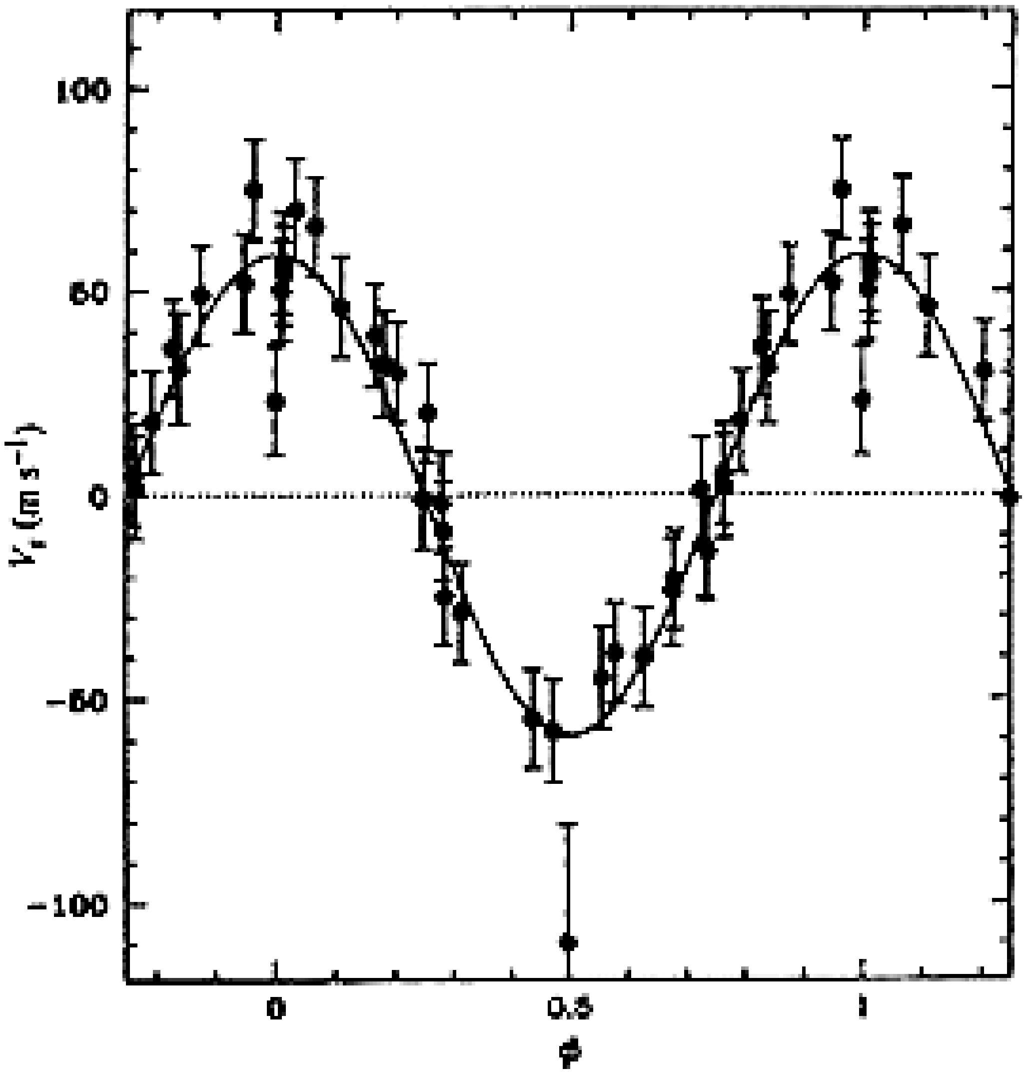
Speed of light

Limits of current technology:

$$\frac{\Delta\lambda}{\lambda_0} \approx 100 \text{ millionth}$$

$$\Rightarrow \boxed{v \approx 3\,\mathrm{ms}^{-1}}$$

51 Peg – the first new planet

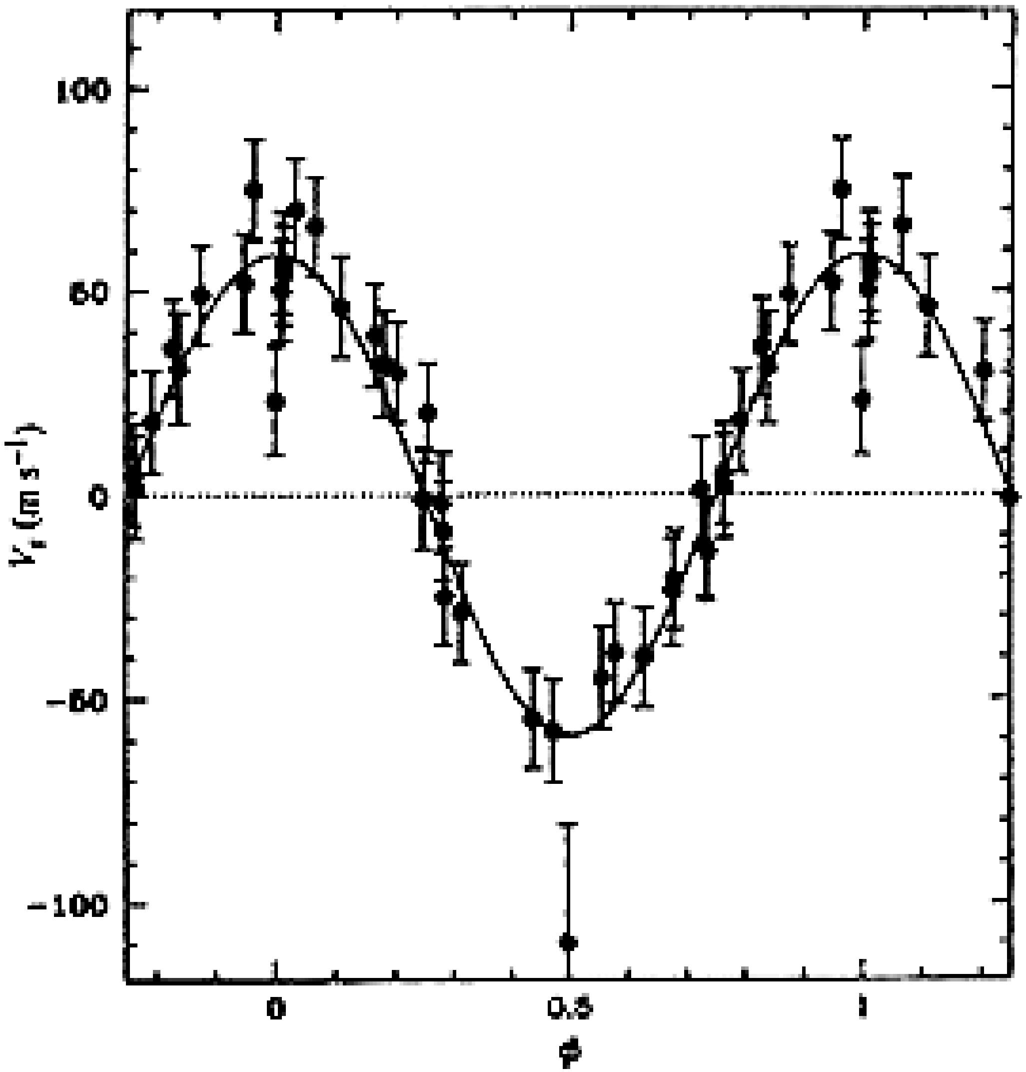


Discovered in 1995

Doppler wobble

$$\boxed{v = 55\,\mathrm{ms}^{-1}}$$

51 Peg – the first new planet



Discovered in 1995

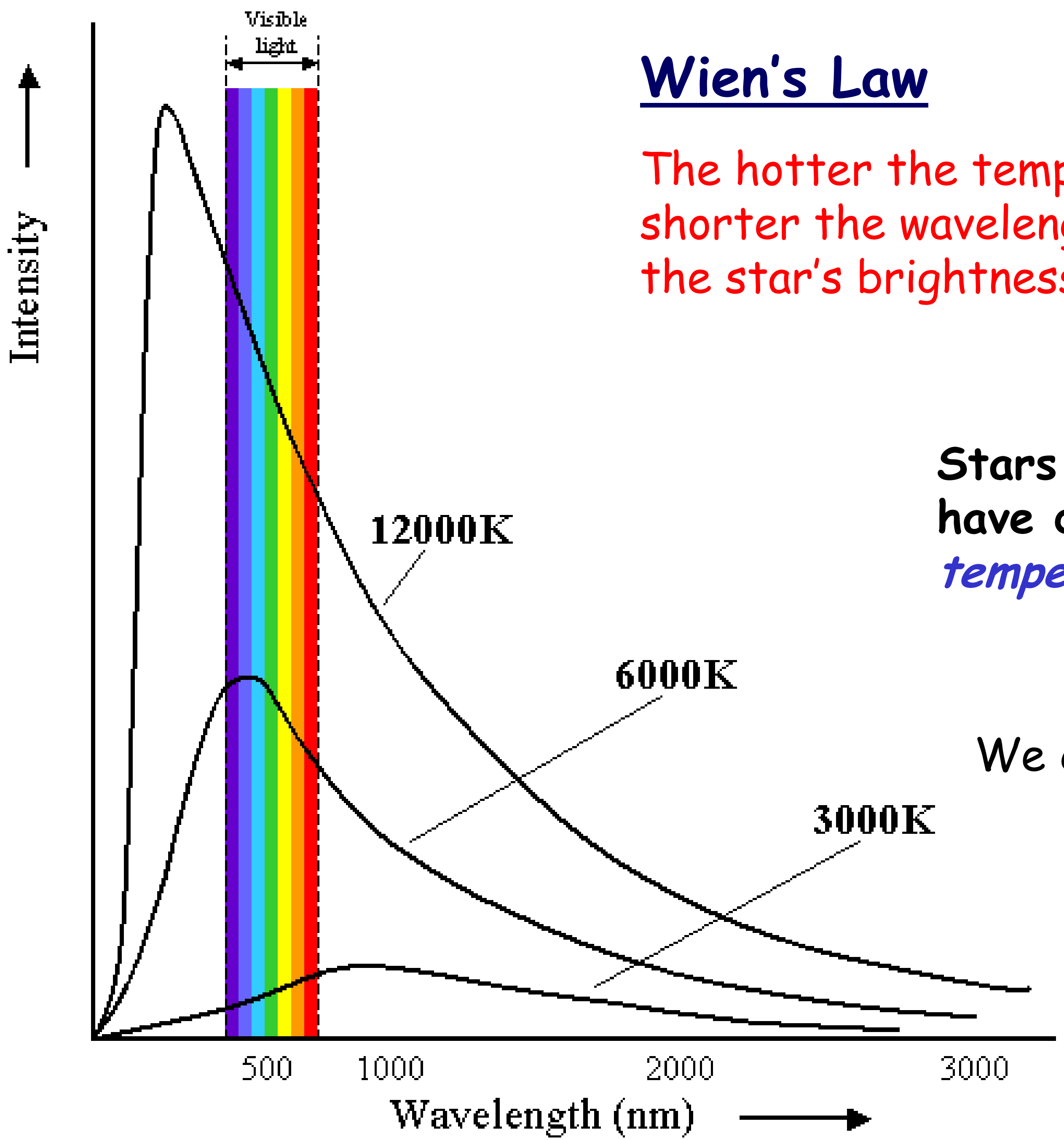
Doppler wobble

$$\boxed{v = 55\,\mathrm{ms}^{-1}}$$

How do we deduce planet's data from this curve?

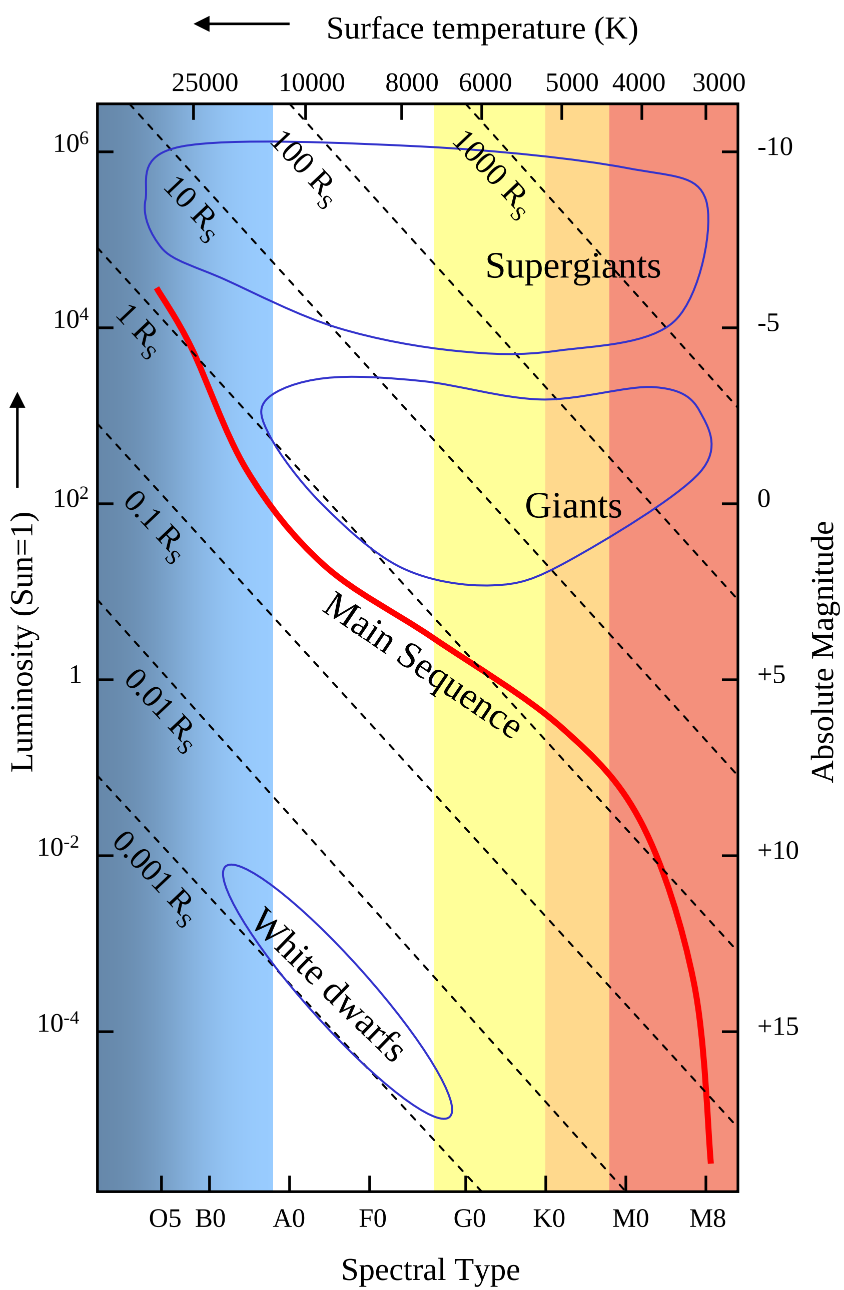
Wien's Law

The hotter the temperature, the shorter the wavelength at which the star's brightness curve peaks

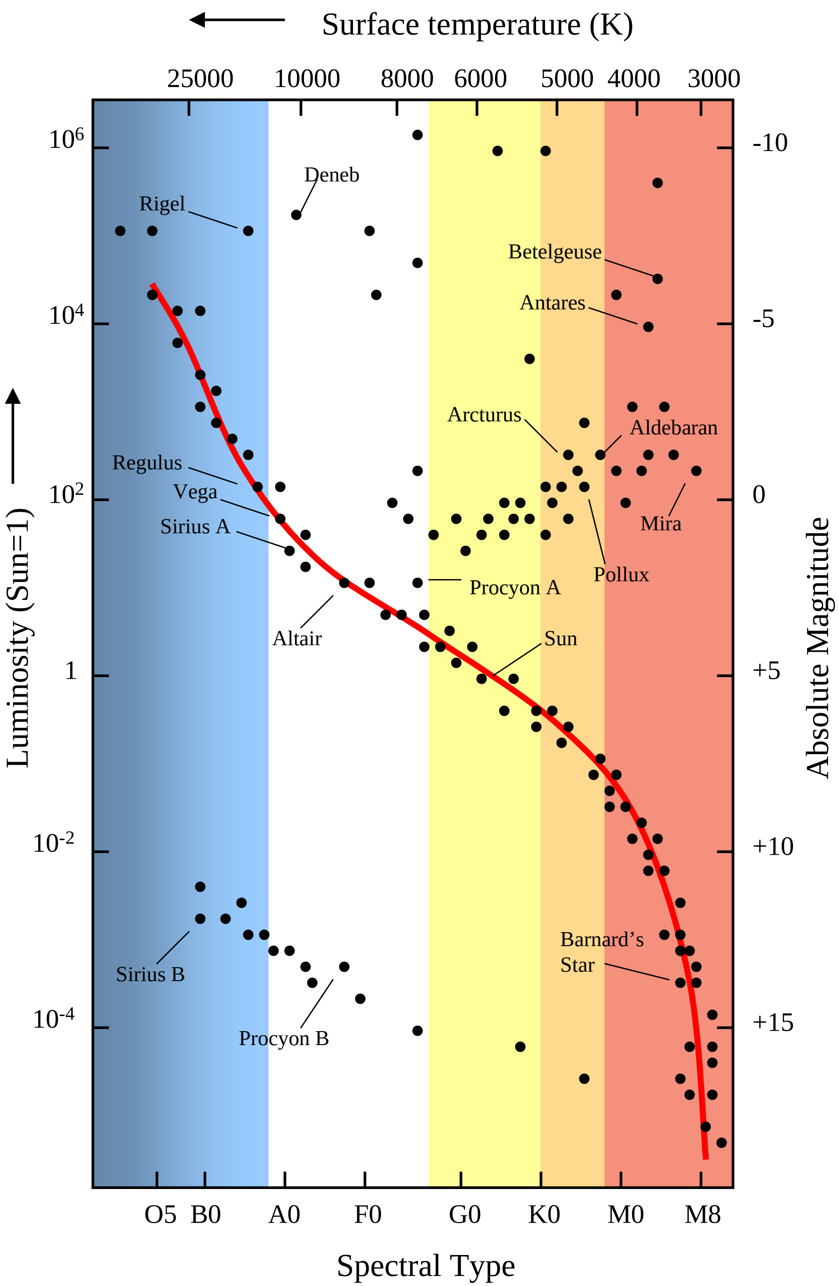


Stars of different colours have different surface *temperatures*

We can determine a star's temperature from its **spectrum**



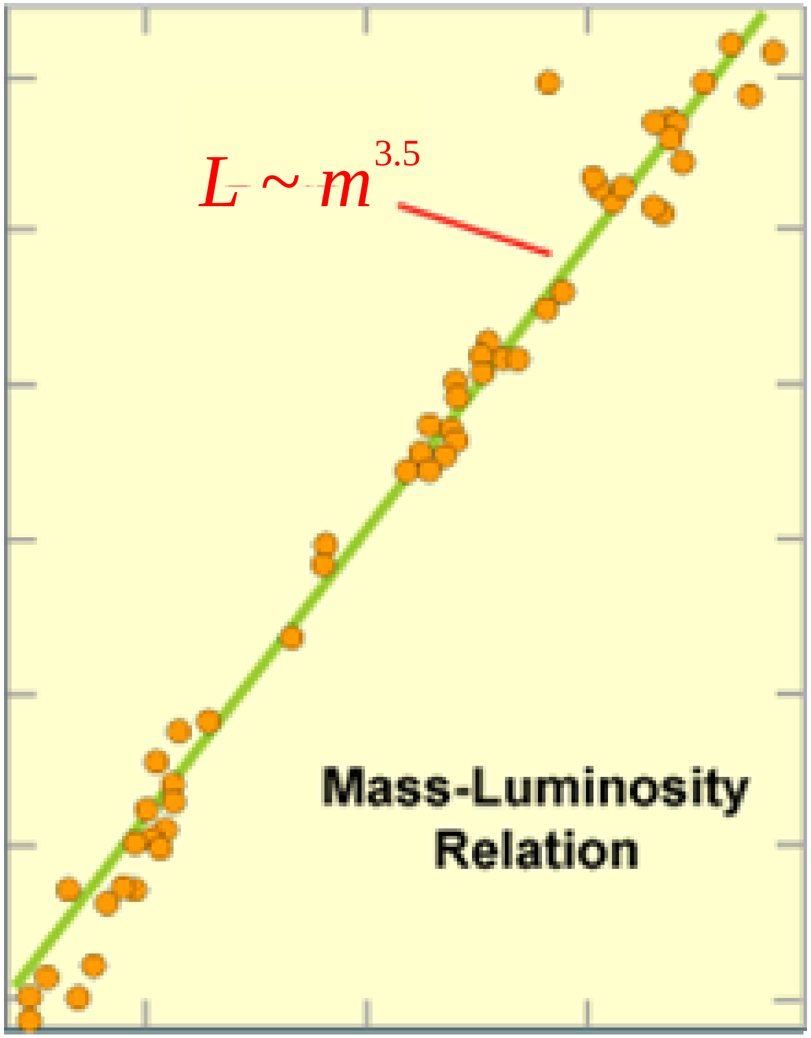
When we plot the temperature and luminosity of stars on a diagram most are found on the **Main Sequence**



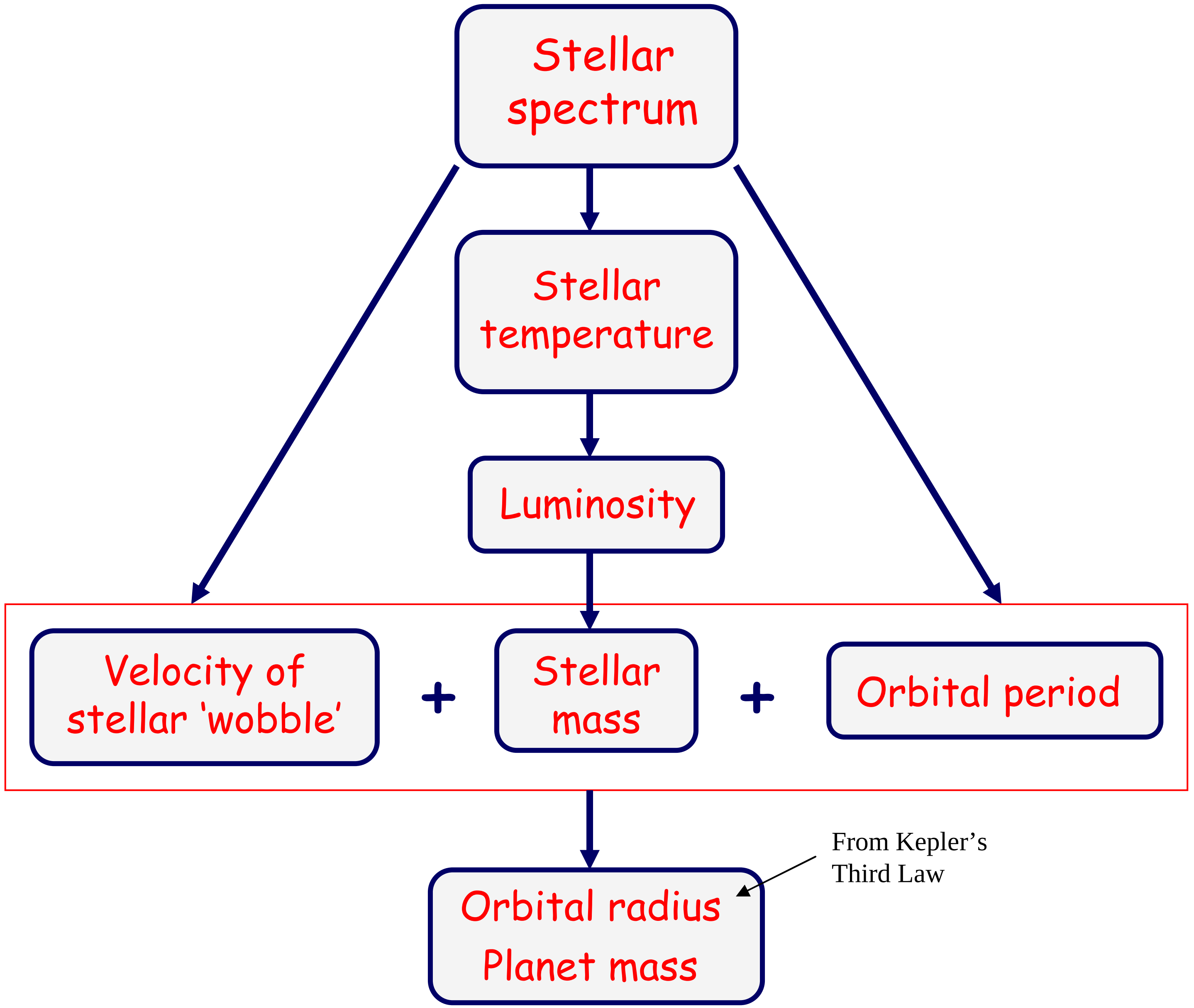
When we plot the **temperature** and **luminosity** of stars on a diagram most are found on the **Main Sequence**

Stars on the **Main Sequence** turn hydrogen into helium.

Stars like the Sun can do this for about ten billion years

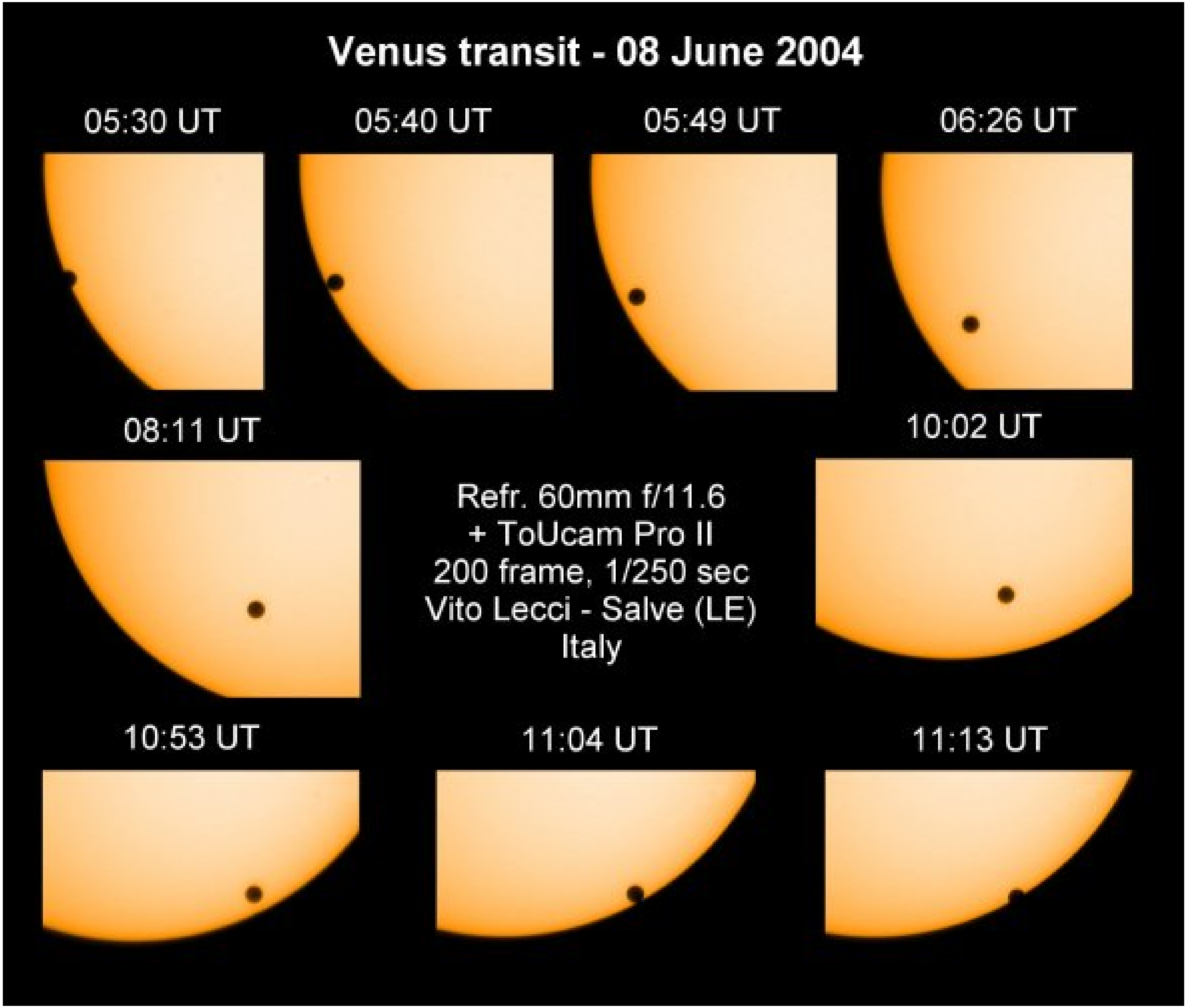

$L \sim m^{3.5}$
Mass-Luminosity
Relation

Summary: Doppler 'Wobble' method

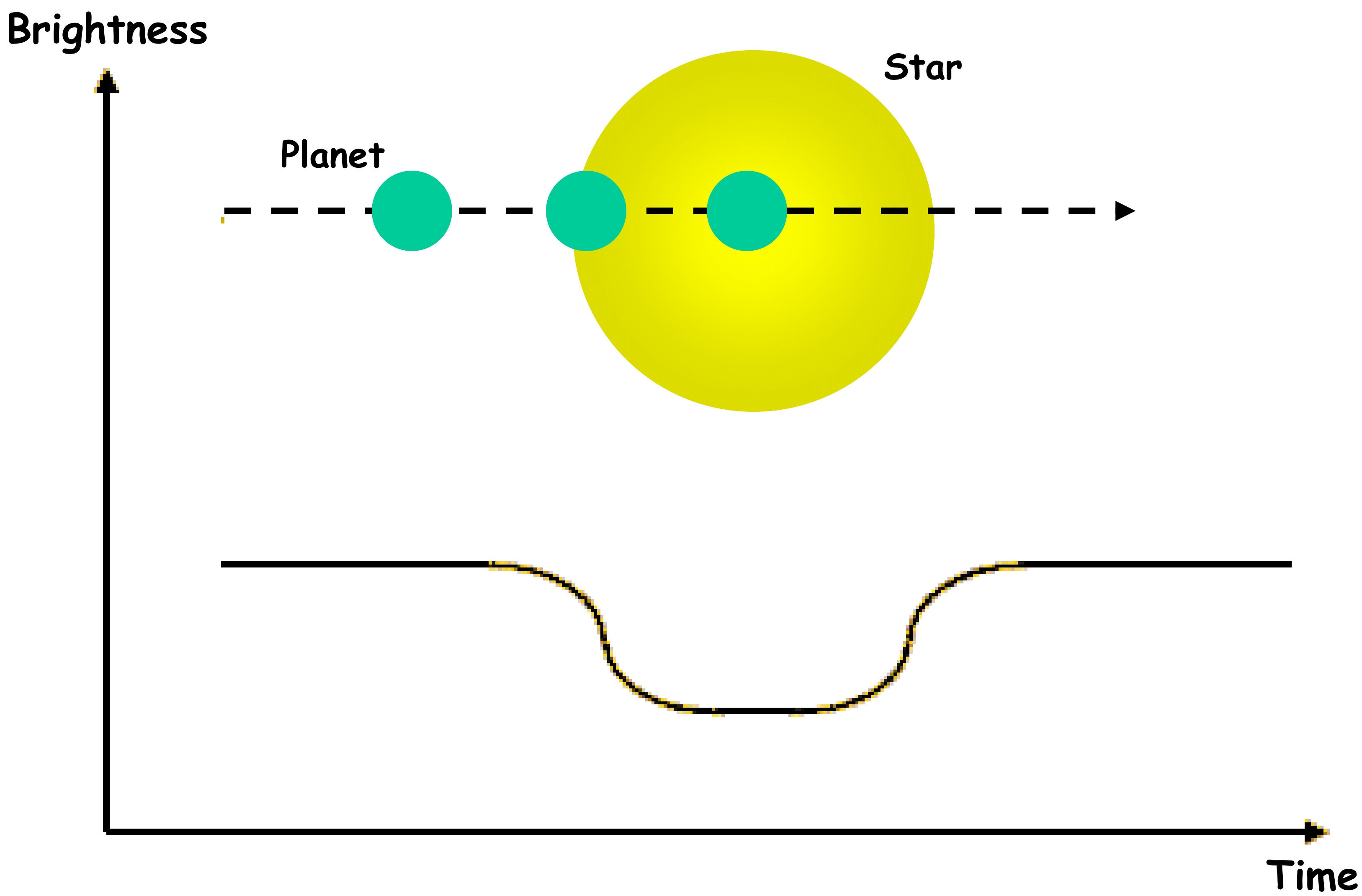


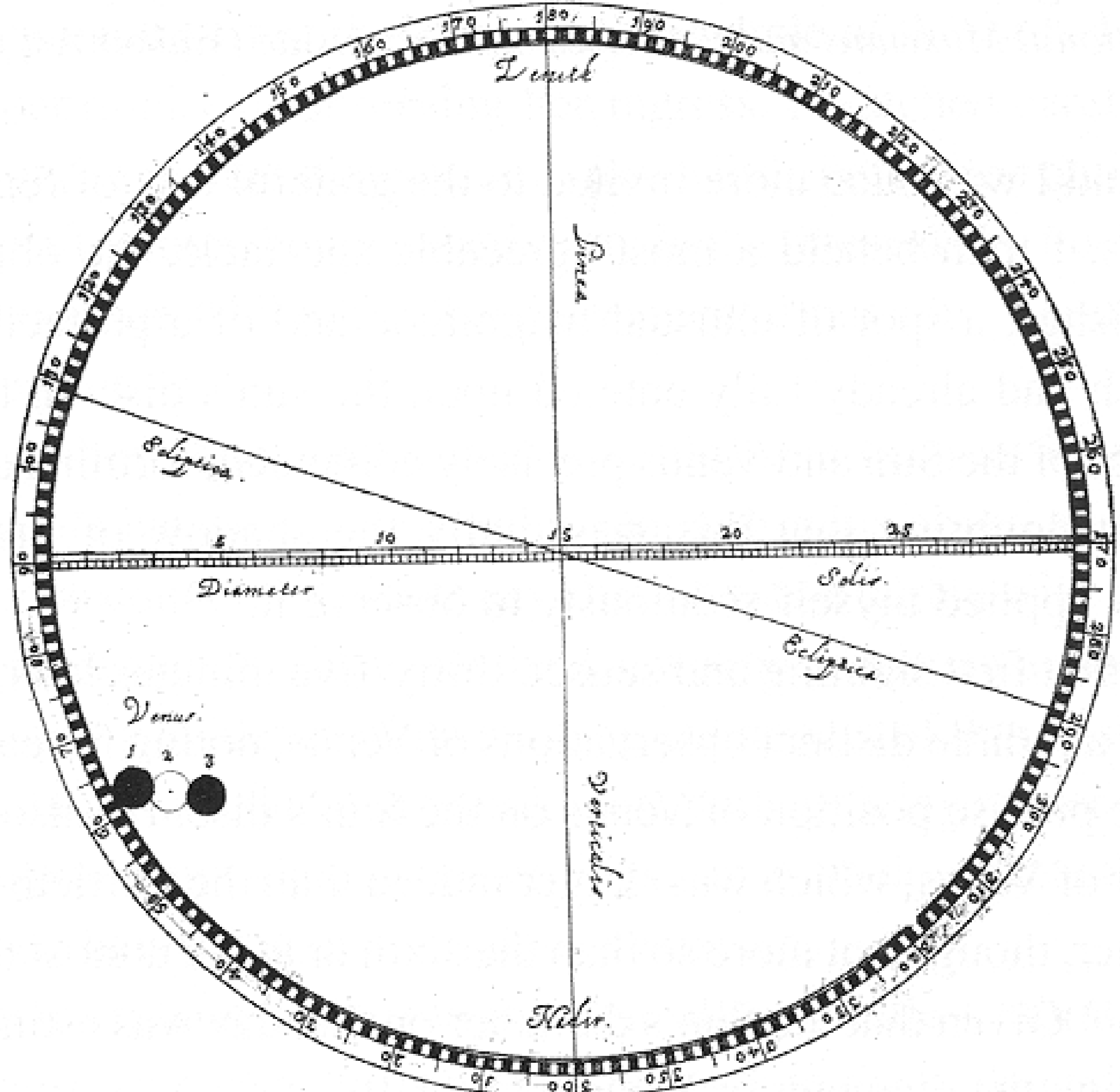
In recent years a growing number of exoplanets have been detected via **transits** = temporary drop in brightness of parent star as the planet crosses the star's disk along our line of sight.

Transit of Mercury: May 7th 2003

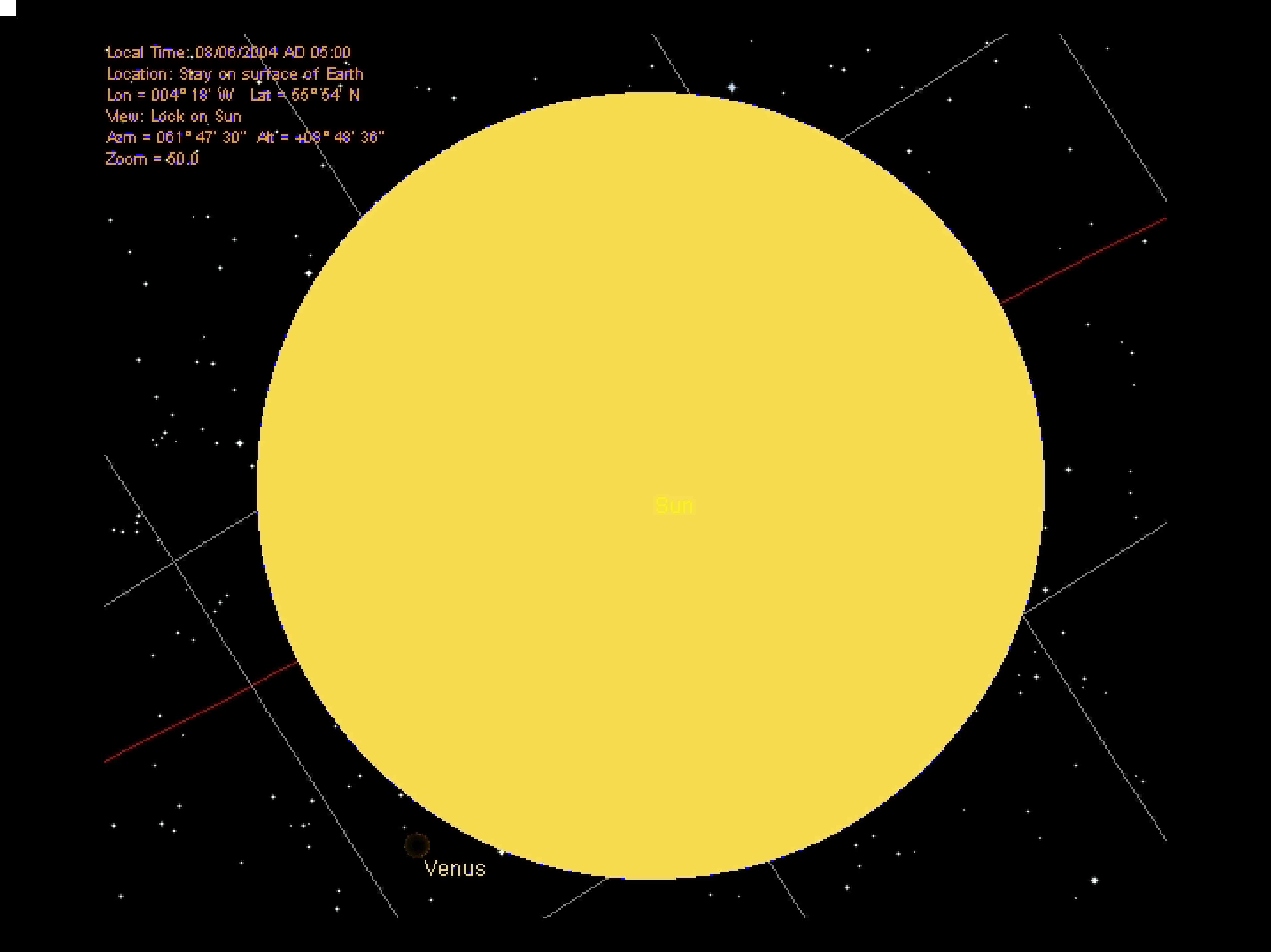

Venus transit - 08 June 2004
05:30 UT
05:40 UT
05:49 UT
06:26 UT
08:11 UT
Refr. 60mm f/11.6
+ ToUcam Pro II
200 frame, 1/250 sec
Vito Lecci - Salve (LE)
Italy
10:02 UT
10:53 UT
11:04 UT
11:13 UT

Change in brightness from a planetary transit



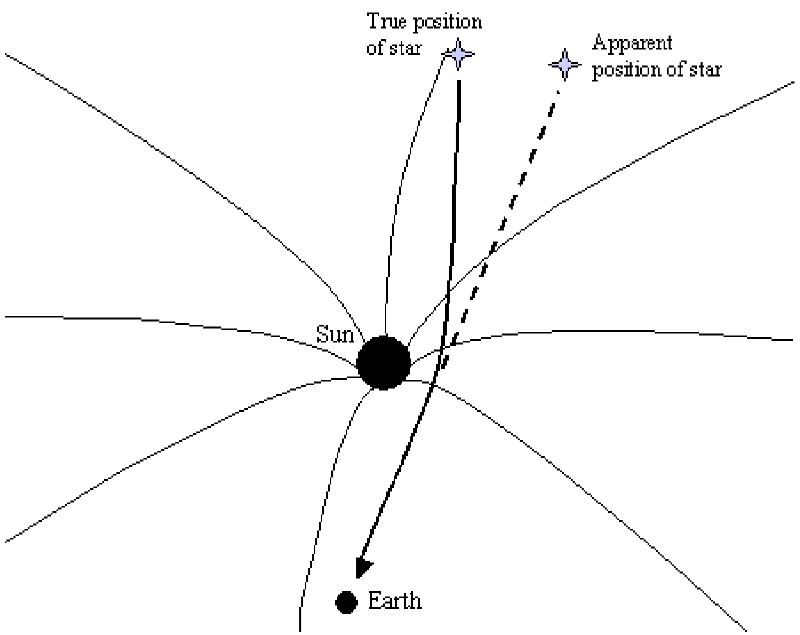


Zenith
Linea
Verticalis
Nadir
Ecliptica
Ecliptica
Diameter
Solis
Venus
1
2
3

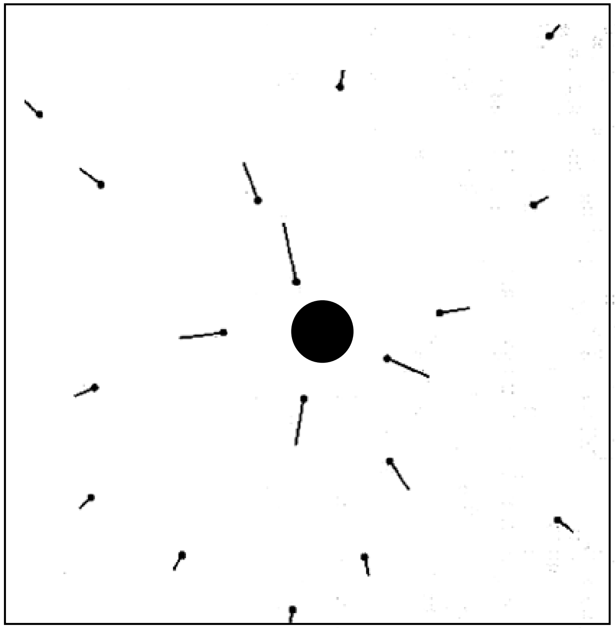

Local Time: 08/06/2004 AD 05:00
Location: Stay on surface of Earth
Lon = 004° 18' W   Lat = 55° 54' N
View: Lock on Sun
Azm = 061° 47' 30"   Alt = +08° 48' 36"
Zoom = 60.0
Sun
Venus

Another method for finding planets is gravitational lensing

The physics behind this method is based on Einstein's General Theory of Relativity, which predicts that gravity *bends* light, because gravity causes spacetime to be curved.



This was one of the first experiments to test GR: Arthur Eddington's 1919 observations of a total solar eclipse.



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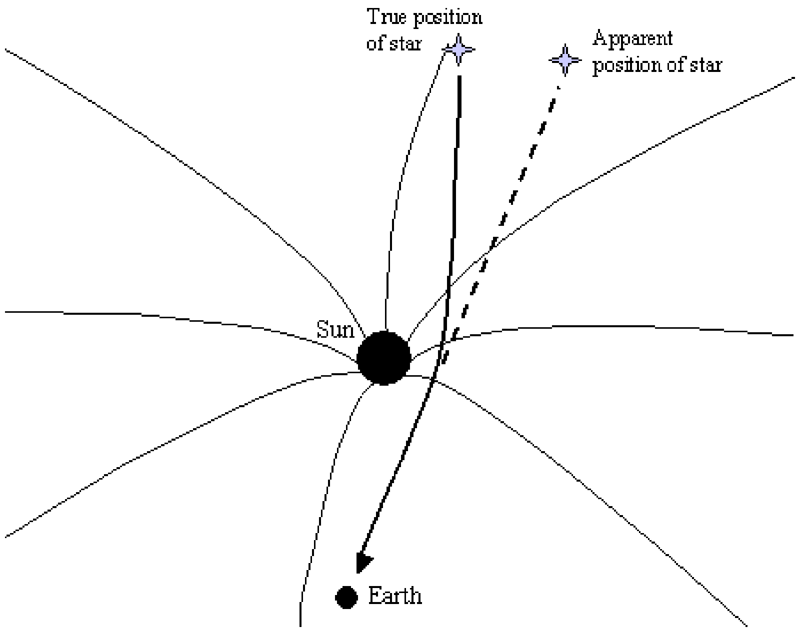

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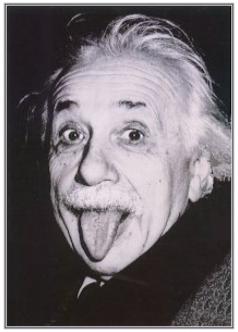
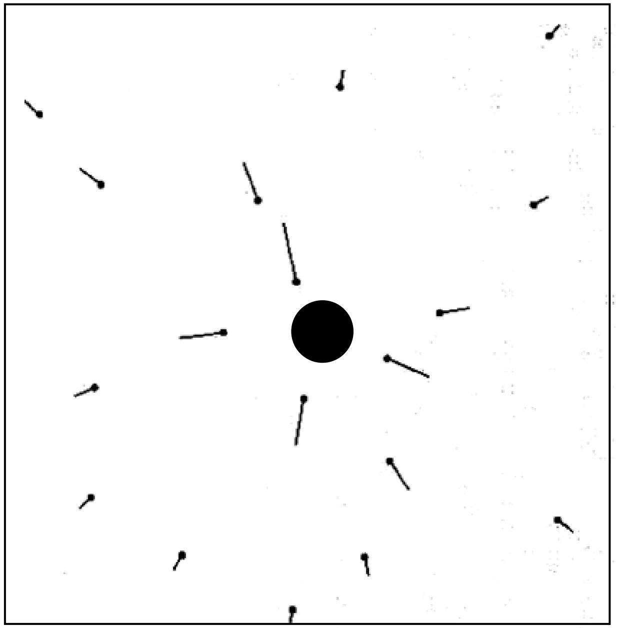
GR passed the test!



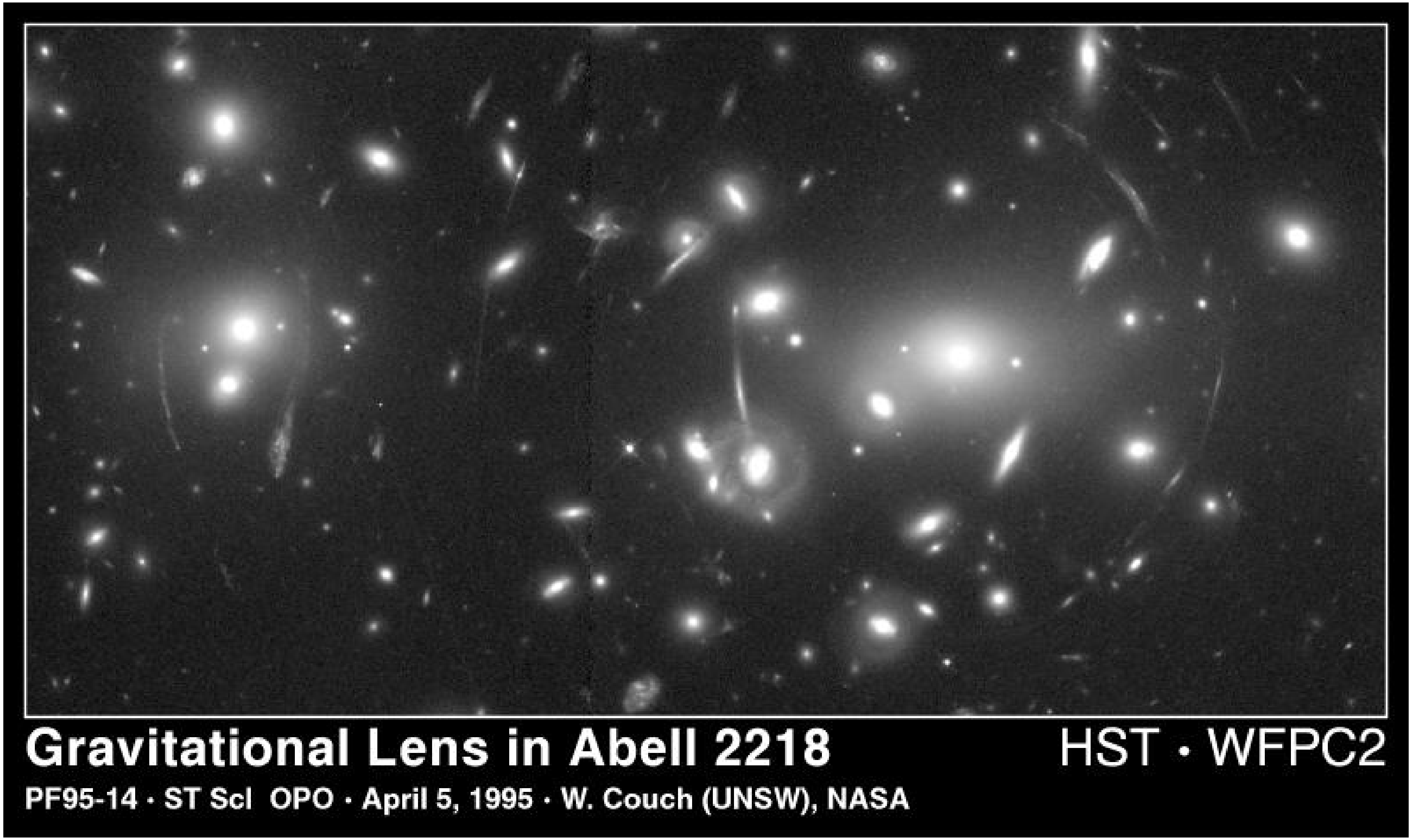


"He was one of the finest people I have ever known…but he didn't really understand physics because, during the eclipse of 1919 he stayed up all night to see if it would confirm the bending of light by the gravitational field. If he had really understood general relativity he would have gone to bed the way I did"

Einstein, on Max Planck

Another method for finding planets is gravitational lensing

If some massive object passes between us and a background light source, it can bend and focus the light from the source, producing multiple, distorted images.



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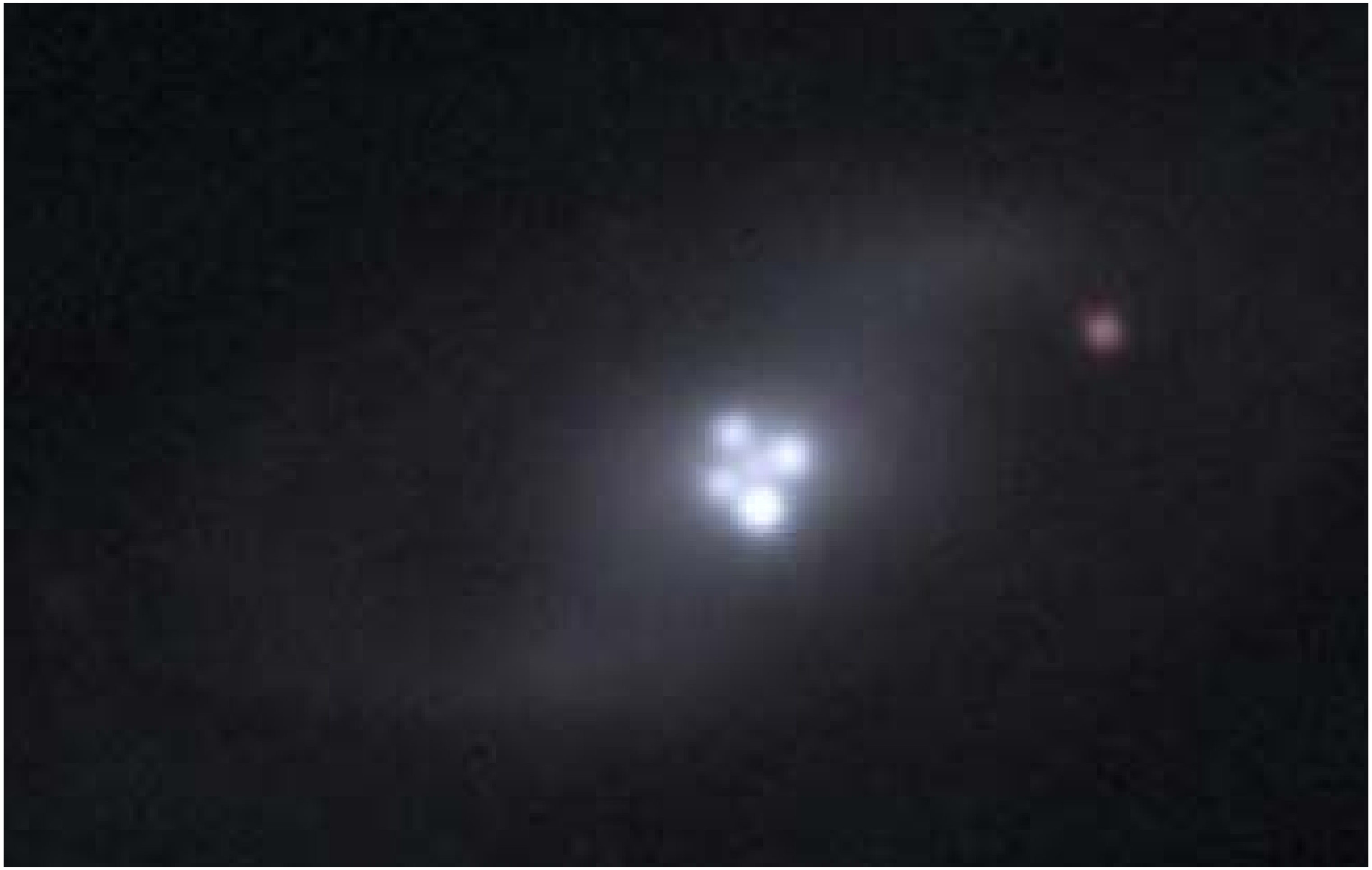

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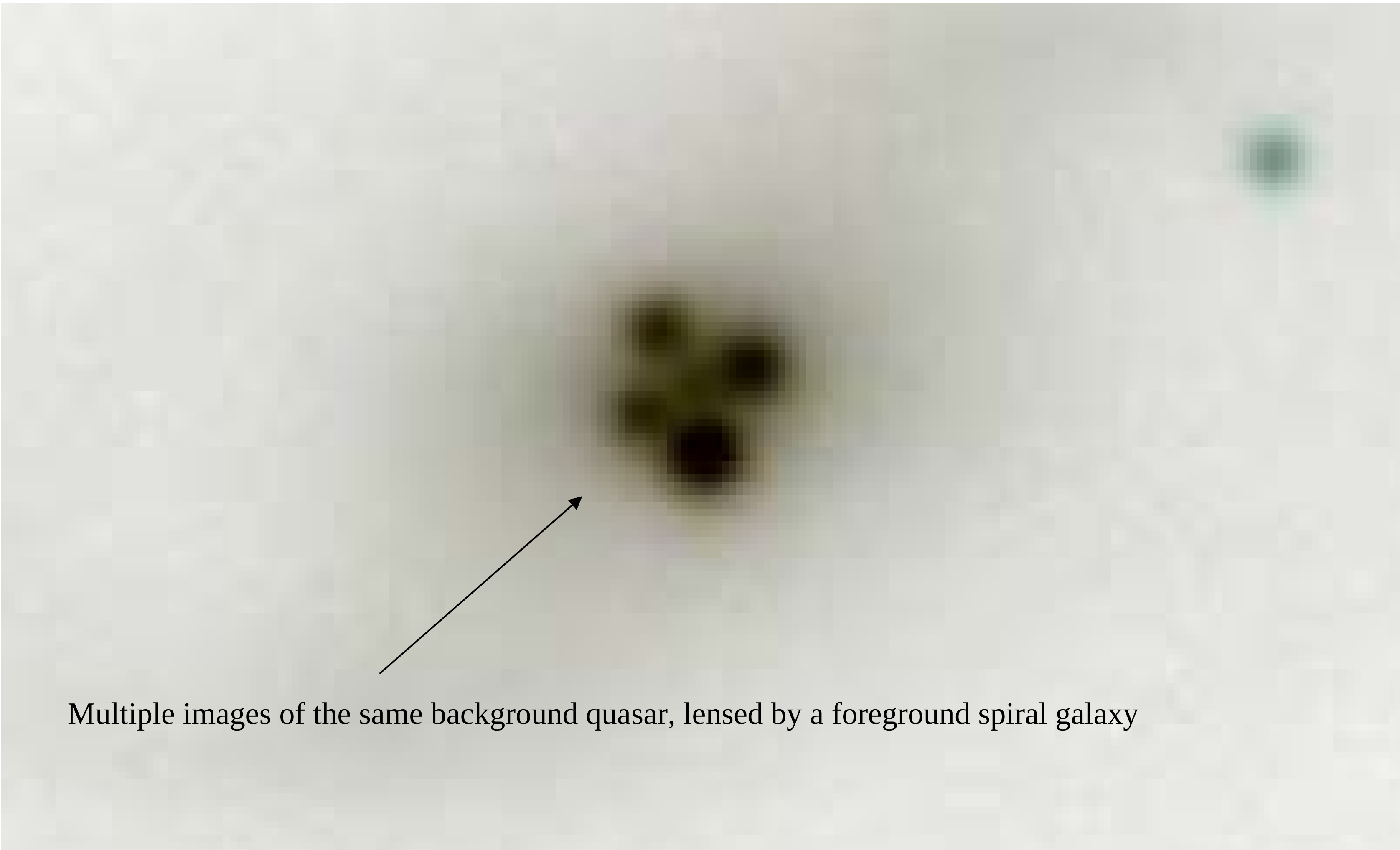
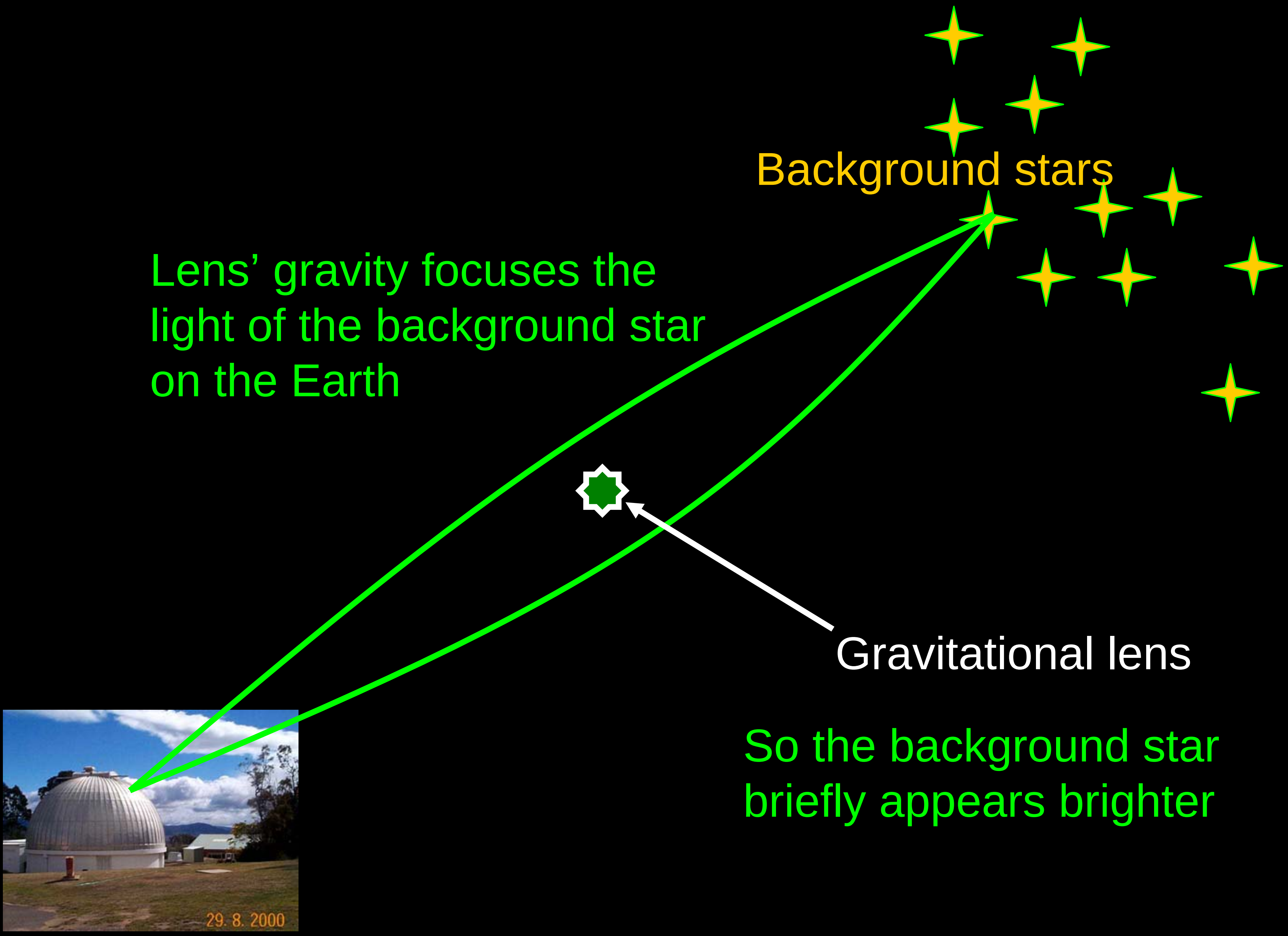


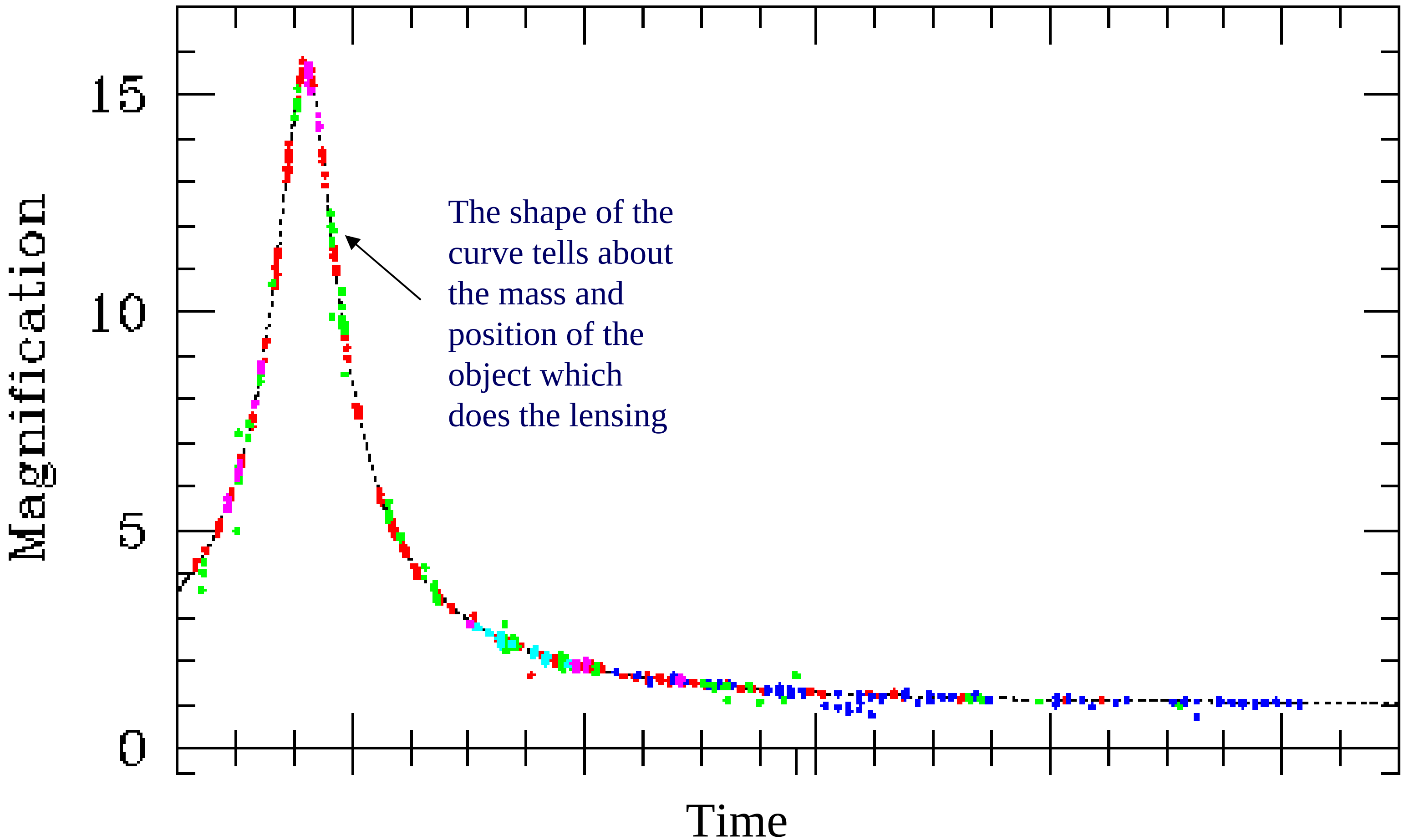
Multiple images of the same background quasar, lensed by a foreground spiral galaxy

Even if the multiple images are too close together to be resolved separately, they will still make the background source appear (temporarily) brighter.


Background stars
Lens’ gravity focuses the light of the background star on the Earth
Gravitational lens
So the background star briefly appears brighter
29. 8. 2000

Even if the multiple images are too close together to be resolved separately, they will still make the background source appear (temporarily) brighter.

We call this case **gravitational microlensing**. We can plot a light curve showing how the brightness of the background source changes with time.



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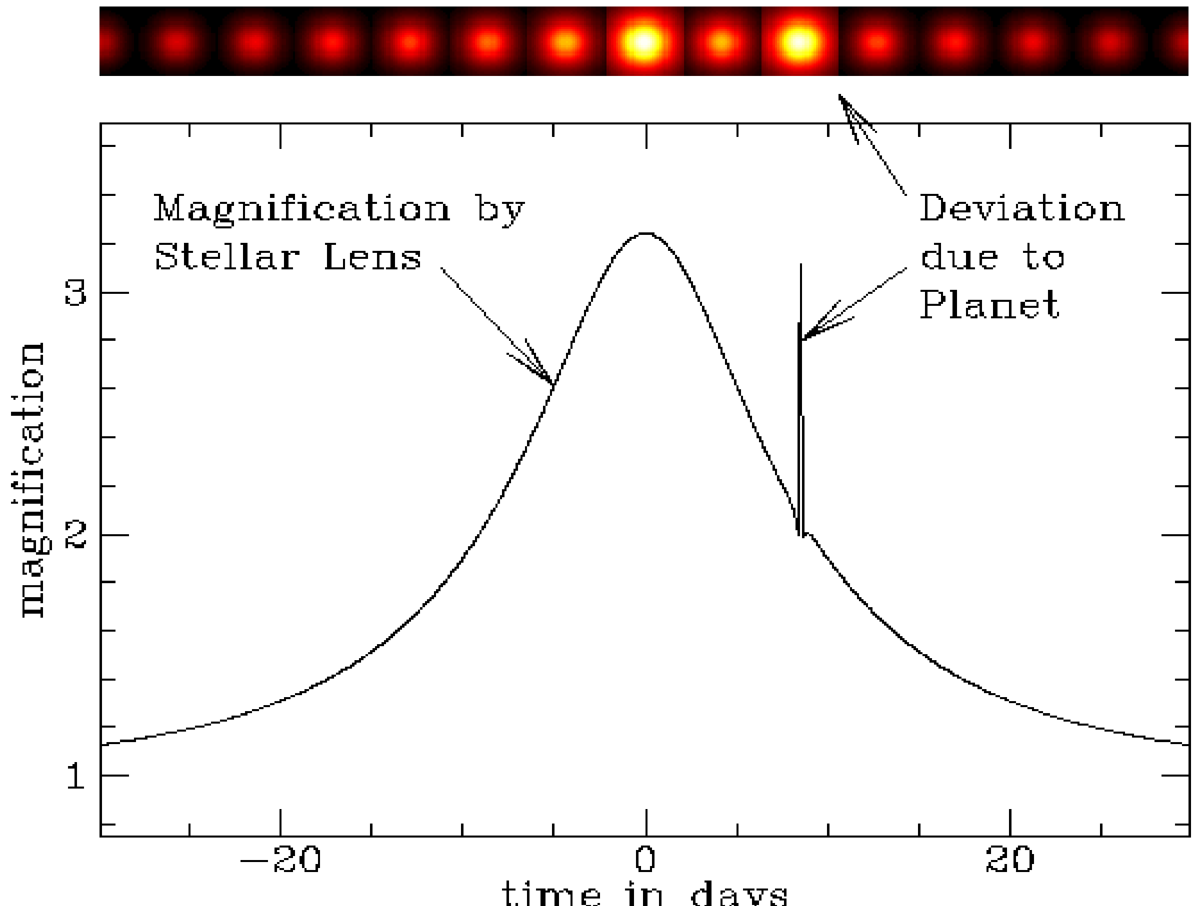
We call this case **gravitational microlensing**. We can plot a light curve showing how the brightness of the background source changes with time.

If the lensing star has a planet which *also* passes exactly between us and the background source, then the light curve will show a second peak.

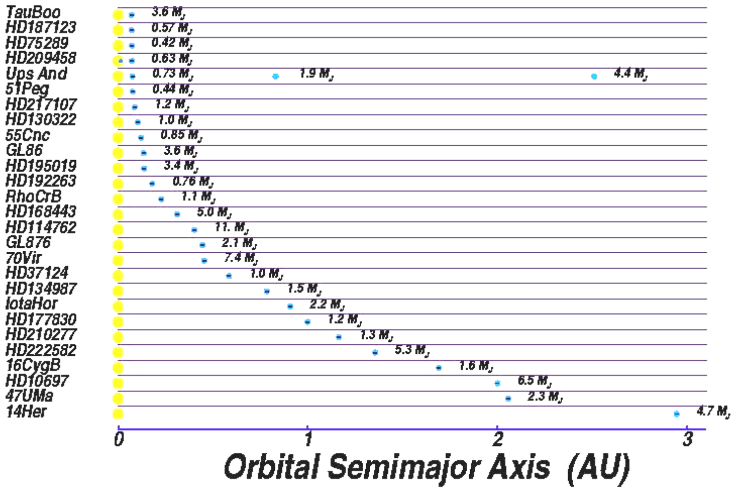
Even low mass planets can produce a high peak (but for a short time, and we only observe it once...)



Could in principle detect Earth mass planets!

What have we learned about exoplanets?

Highly active, and rapidly changing, field



Aug 2000: 29 exoplanets

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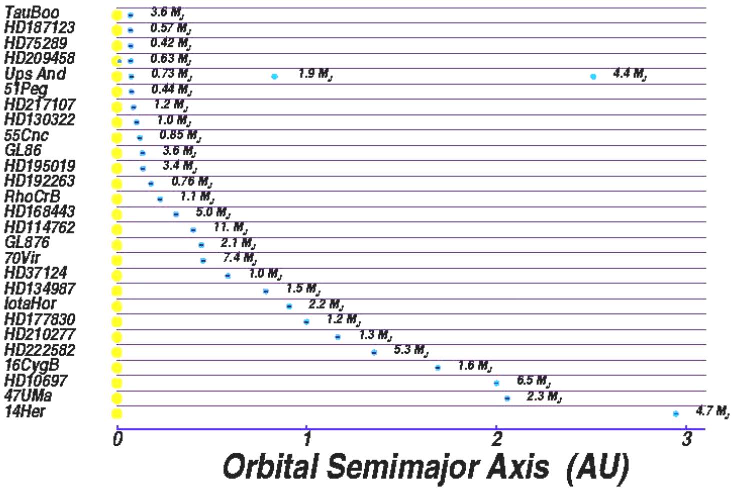

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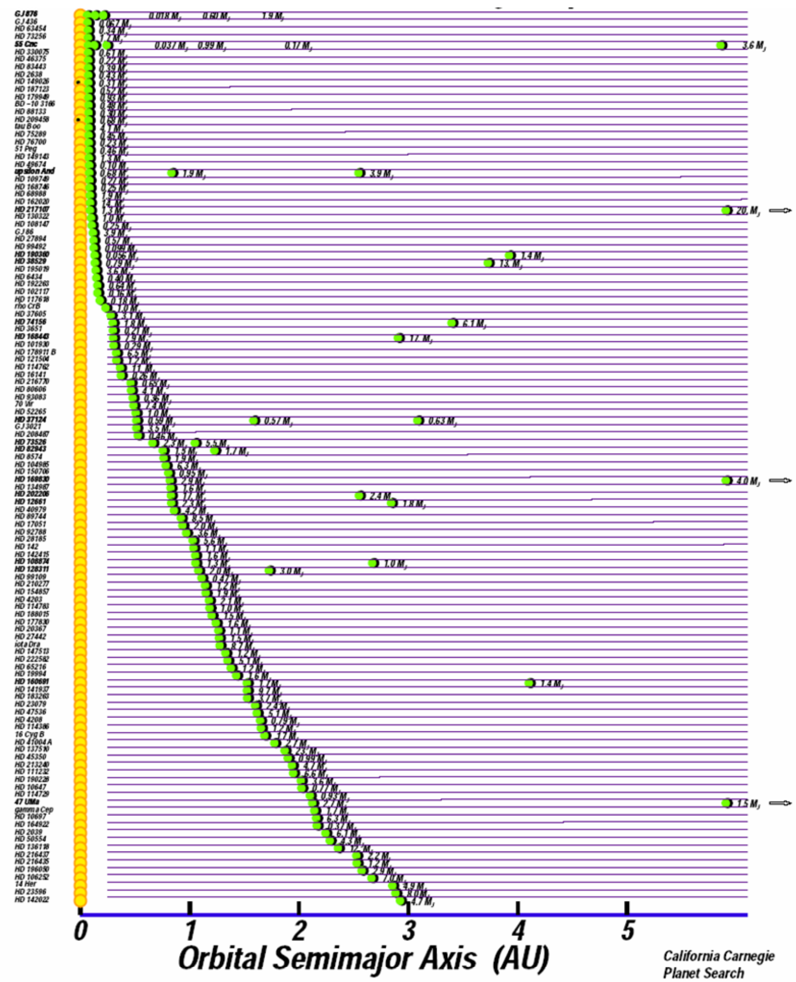

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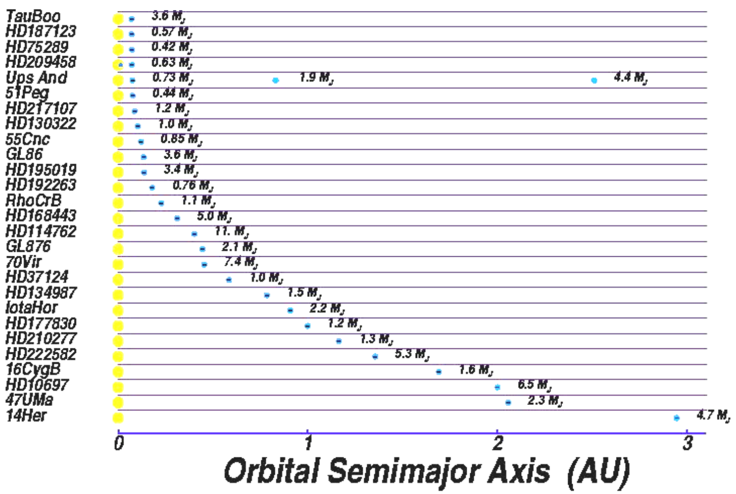

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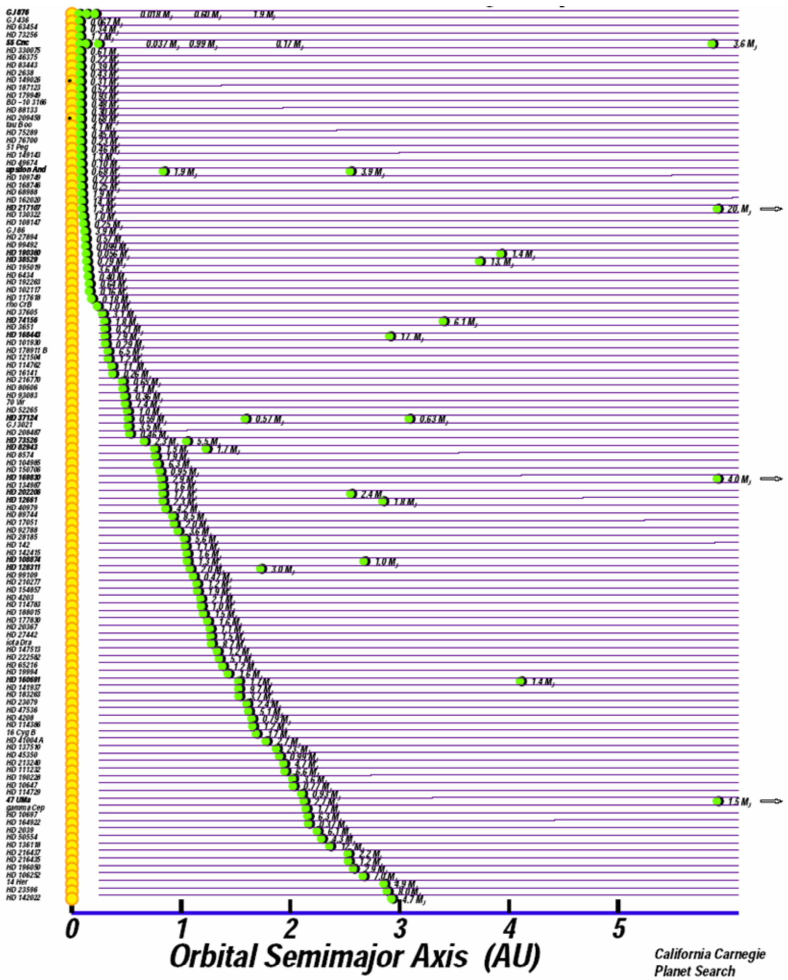
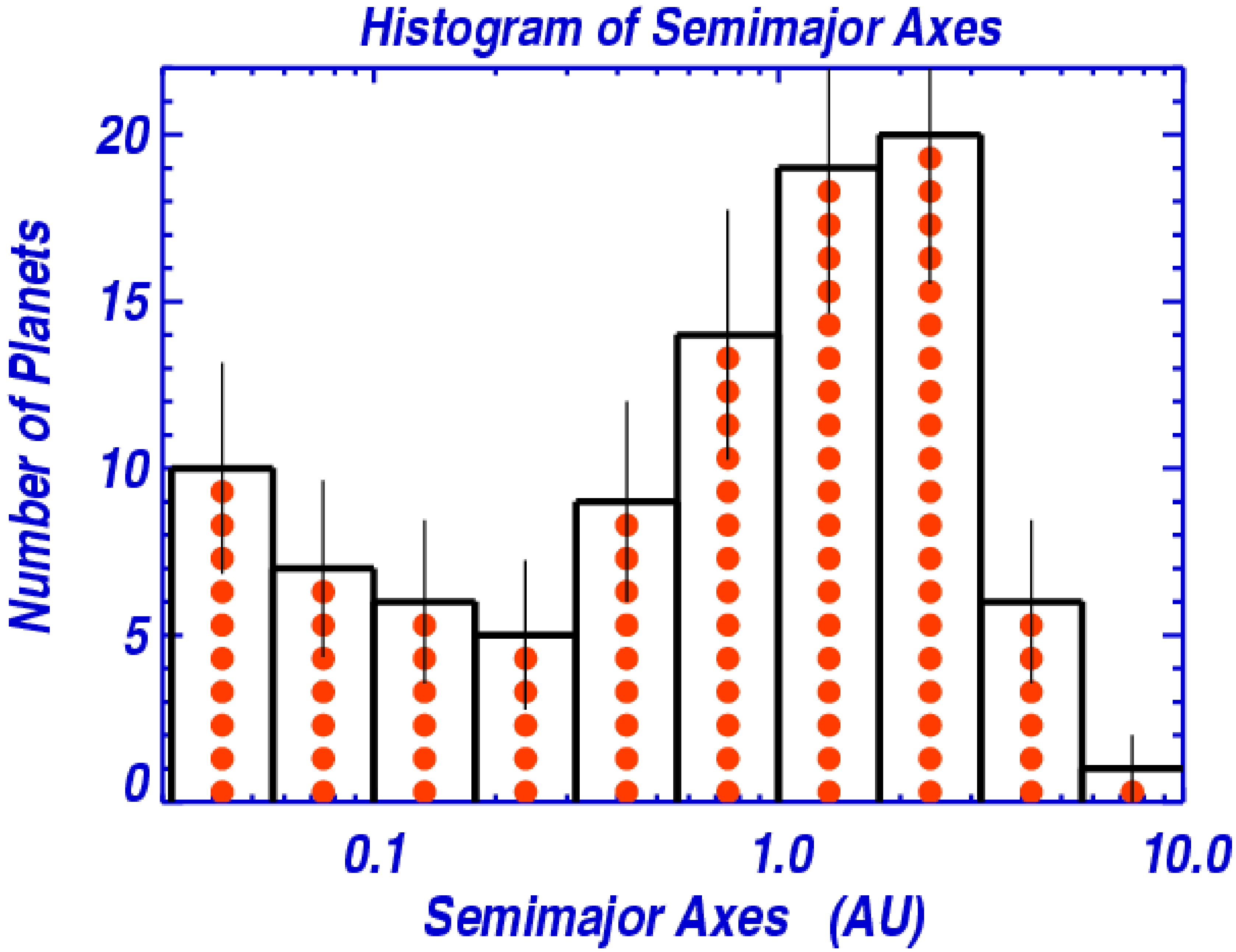


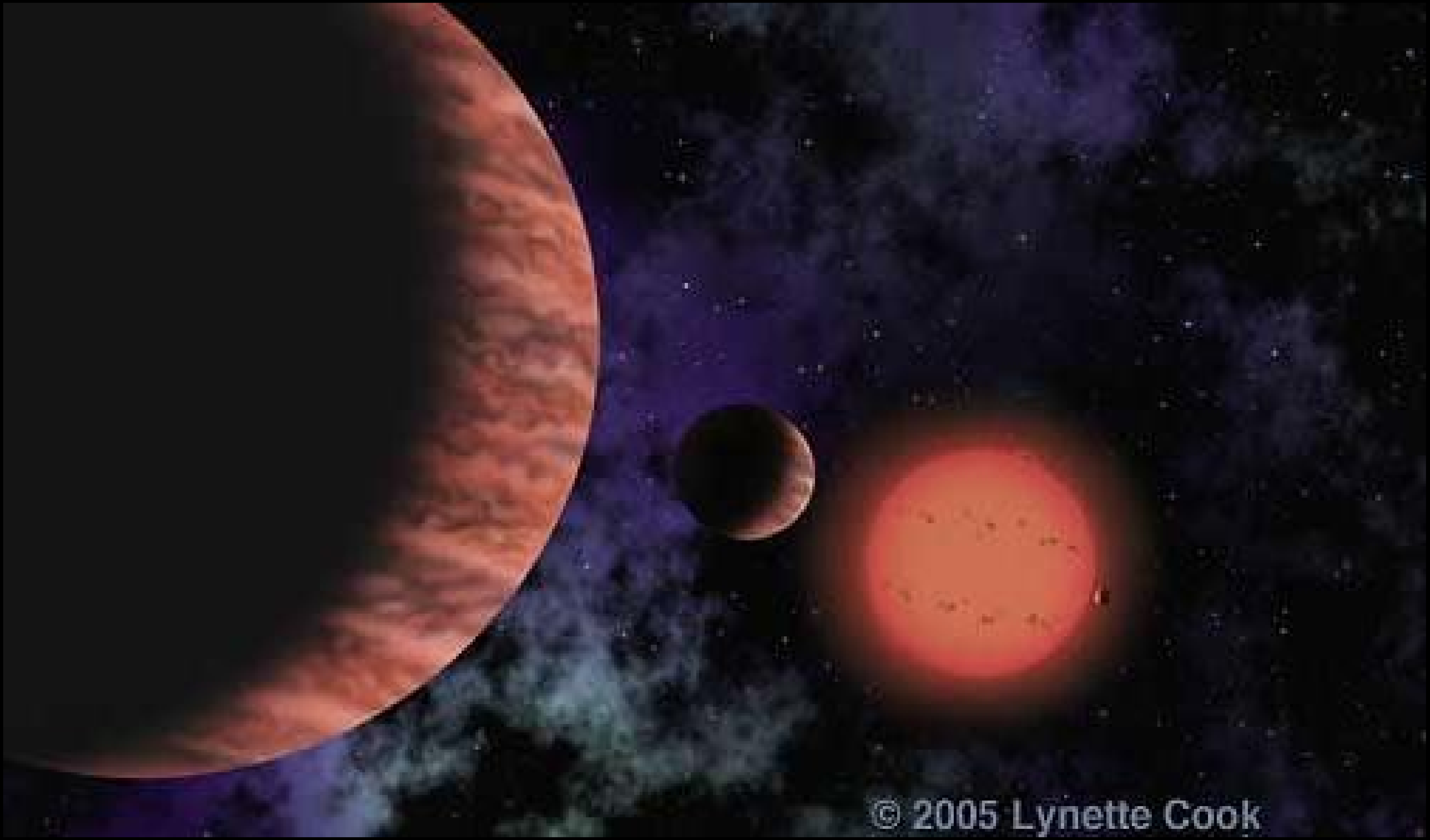
Sep 2005: 156 exoplanets

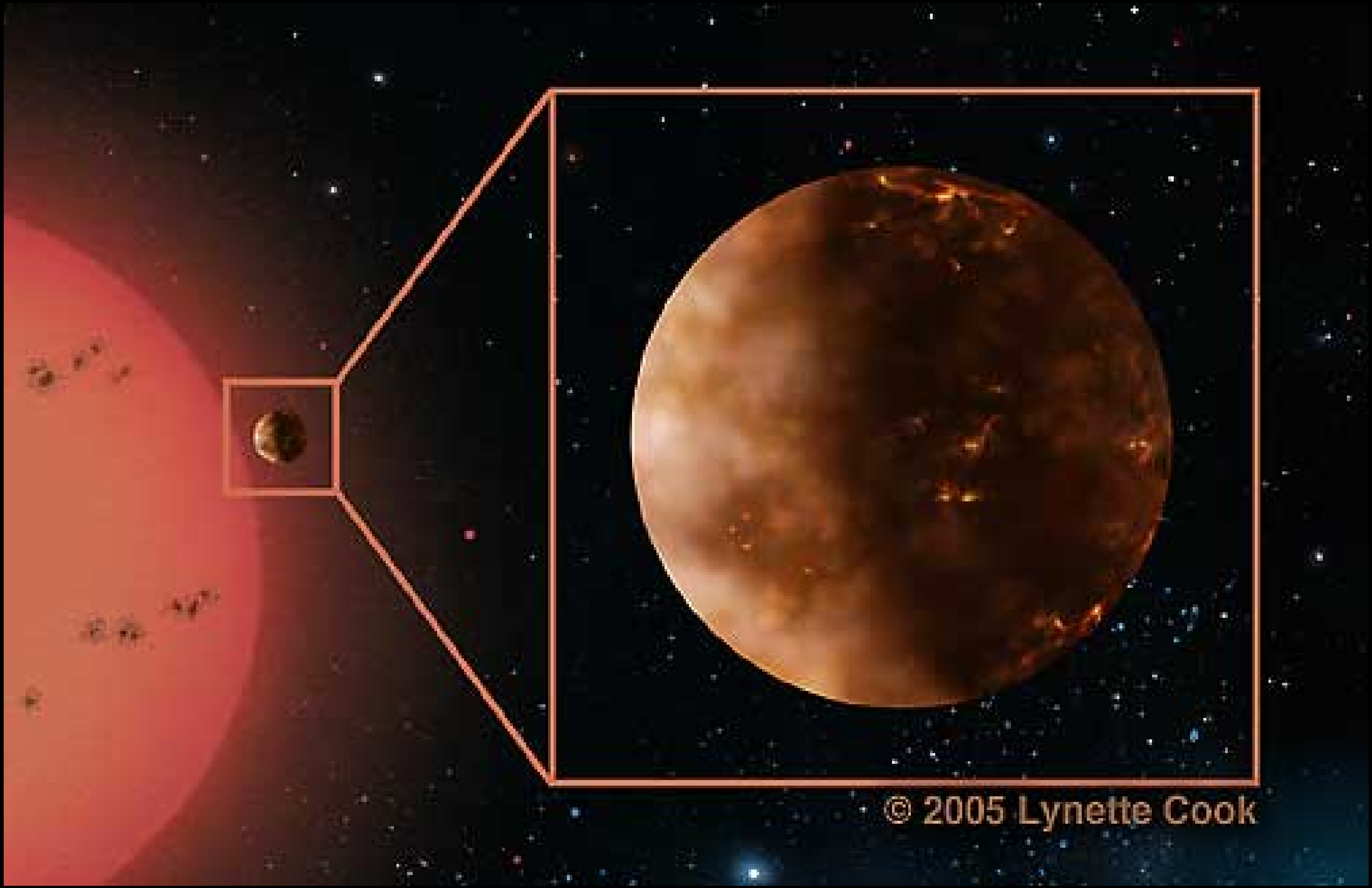
Up-to-date summary at

http://www.exoplanets.org

Now finding planets at larger orbital semimajor axis


Histogram of Semimajor Axes
Number of Planets
0
5
10
15
20
0.1
1.0
10.0
Semimajor Axes (AU)


© 2005 Lynette Cook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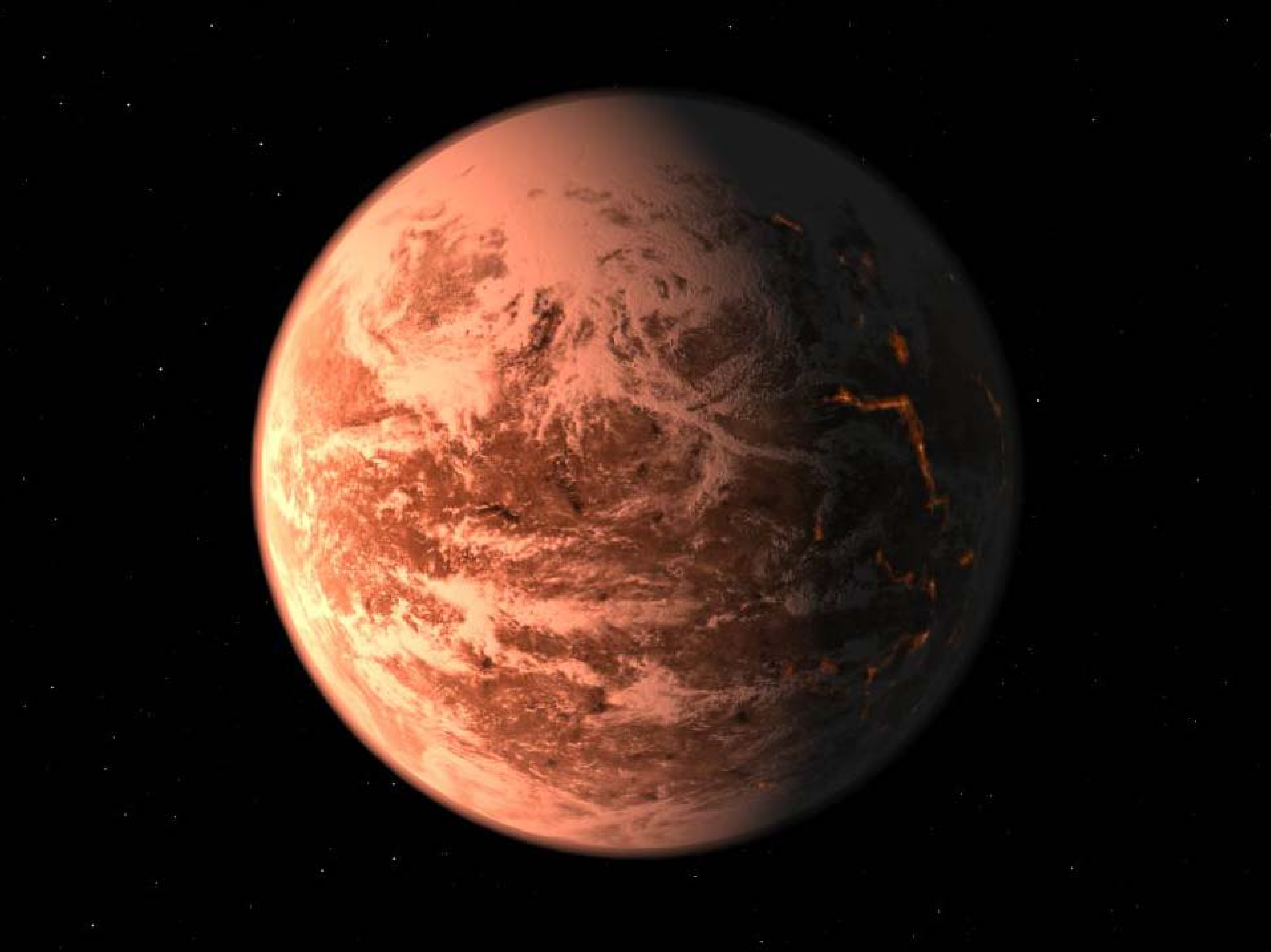
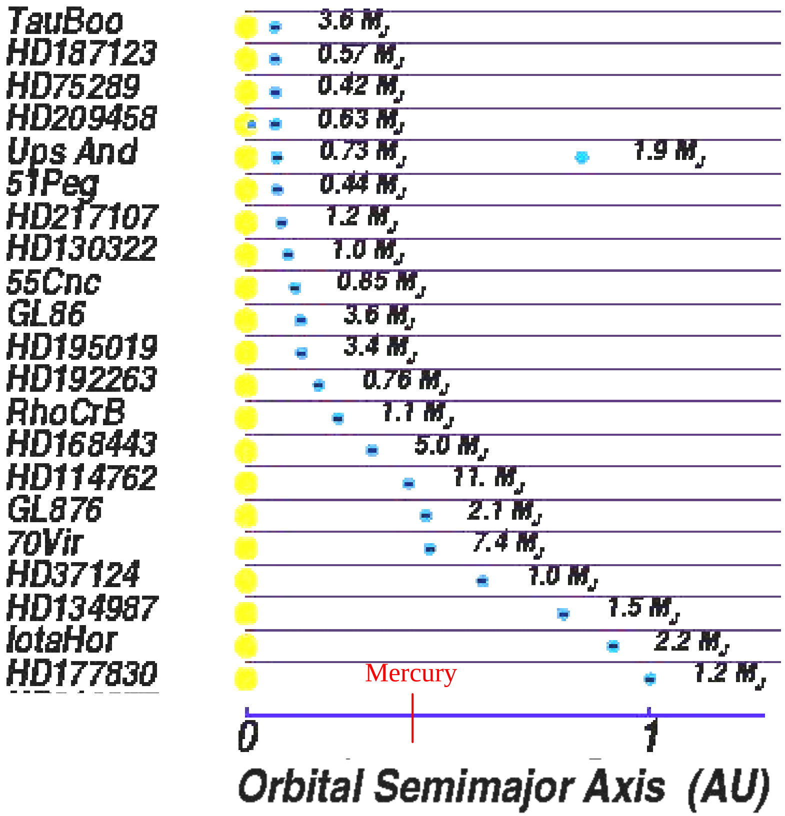


What have we learned about exoplanets?

Discovery of many 'Hot Jupiters':

Massive planets with orbits closer to their star than Mercury is to the Sun

Very likely to be gas giants, but with surface temperatures of several thousand degrees.



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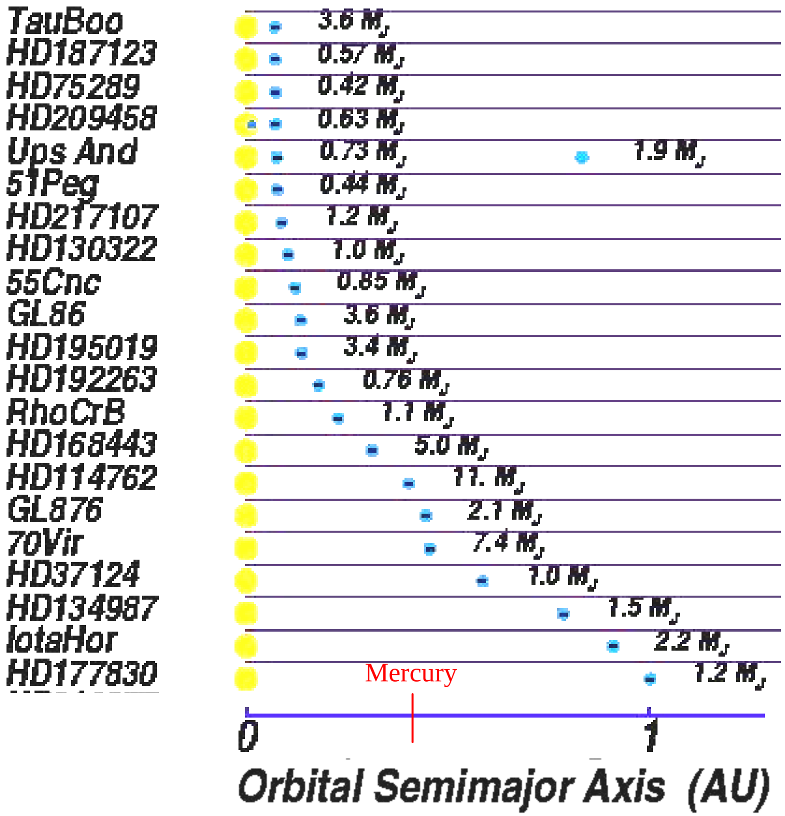
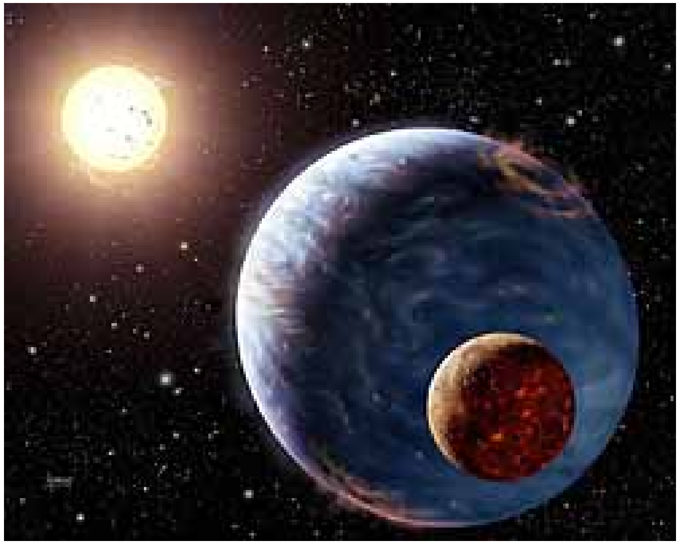




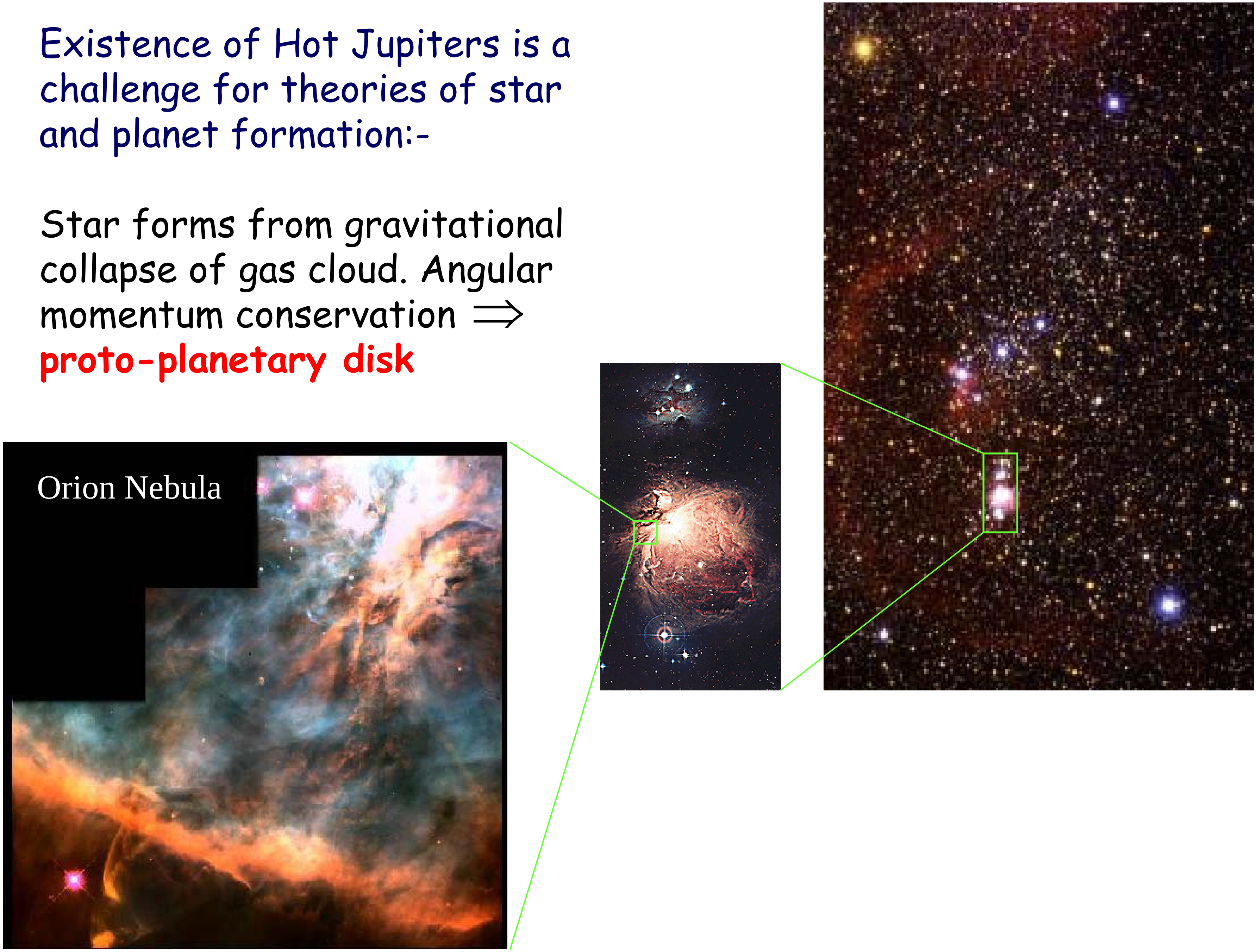
Artist's impression of 'Hot Jupiter' orbiting HD195019

'Hot Jupiters' produce Doppler wobbles of very large amplitude

e.g. Tau Boo: $v_S \sin i = 474\,\mathrm{ms}^{-1}$

Existence of Hot Jupiters is a challenge for theories of star and planet formation:-

Star forms from gravitational collapse of gas cloud. Angular momentum conservation $\Rightarrow$ **proto-planetary disk**



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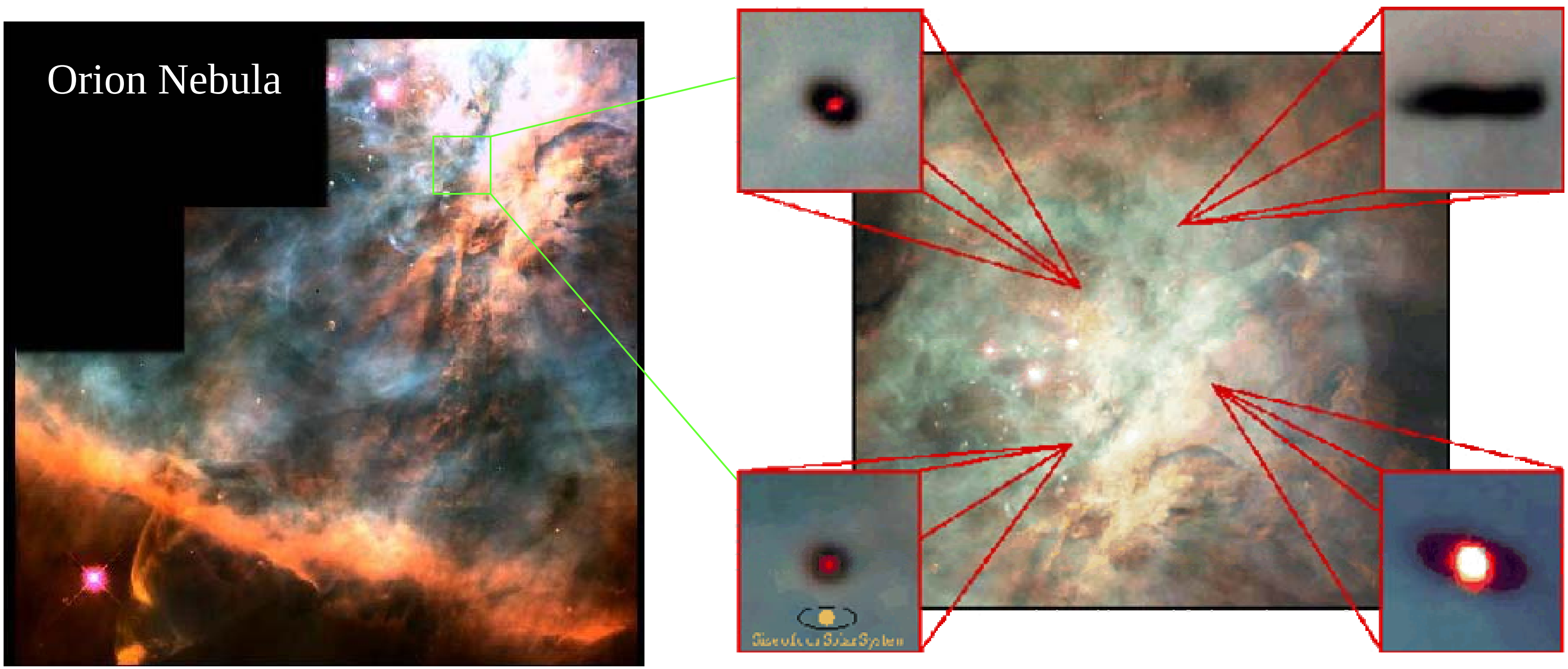

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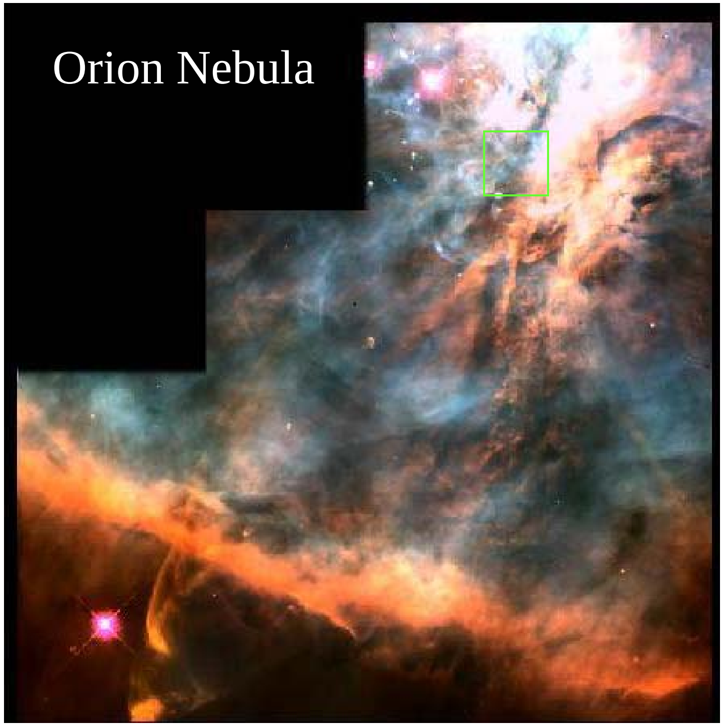
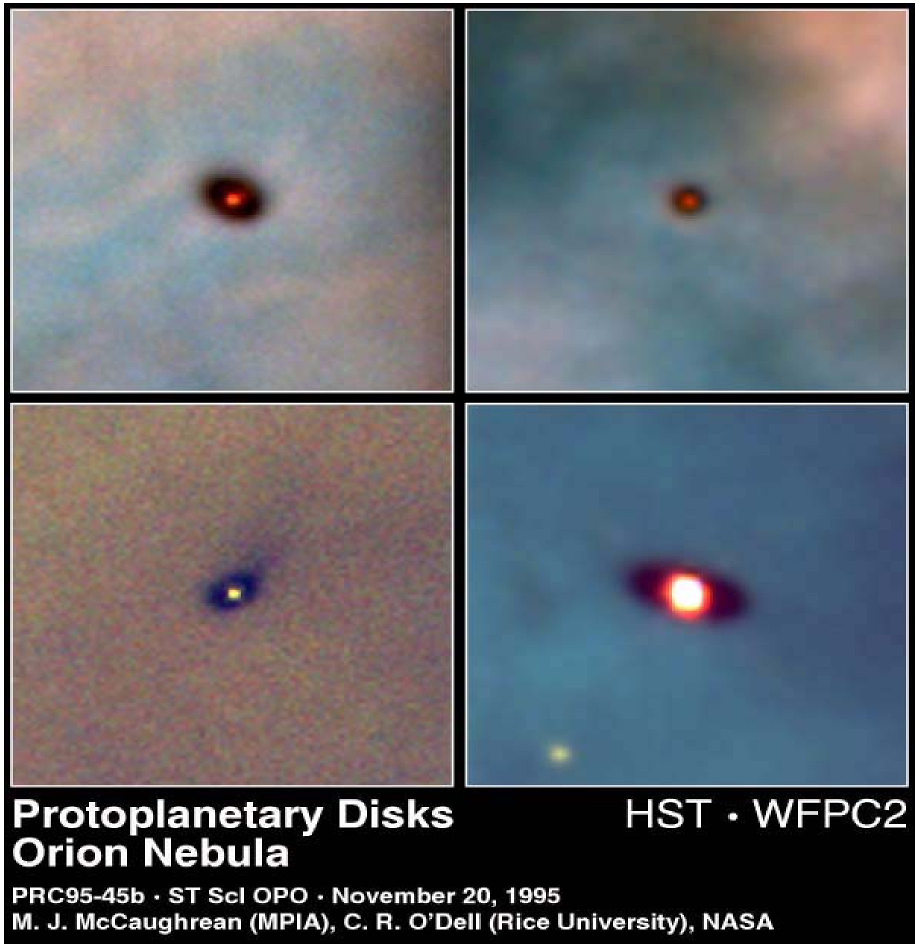
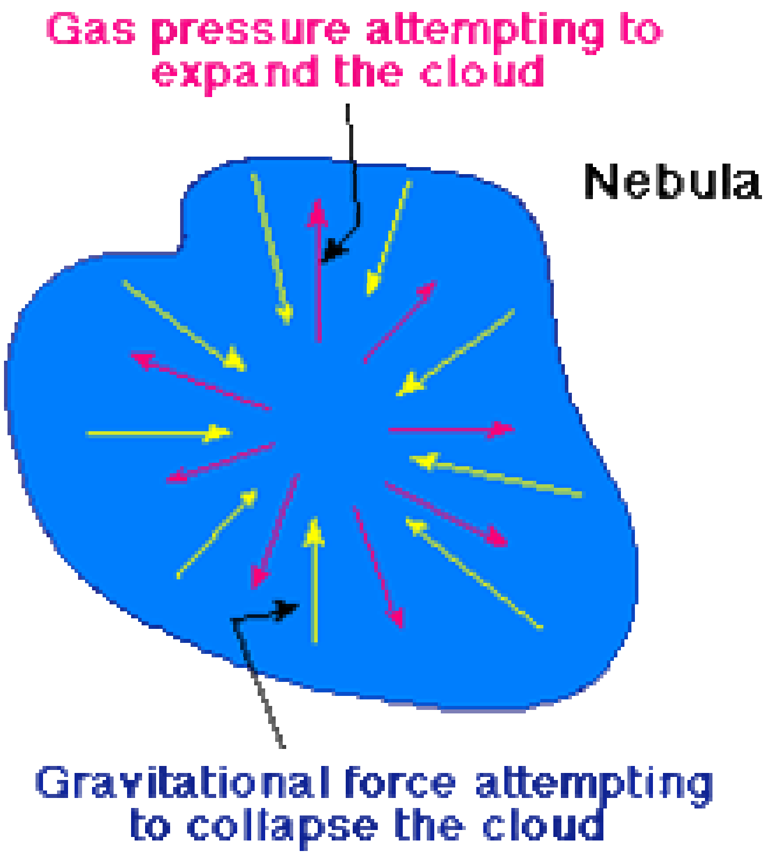




Forming stars and planets….

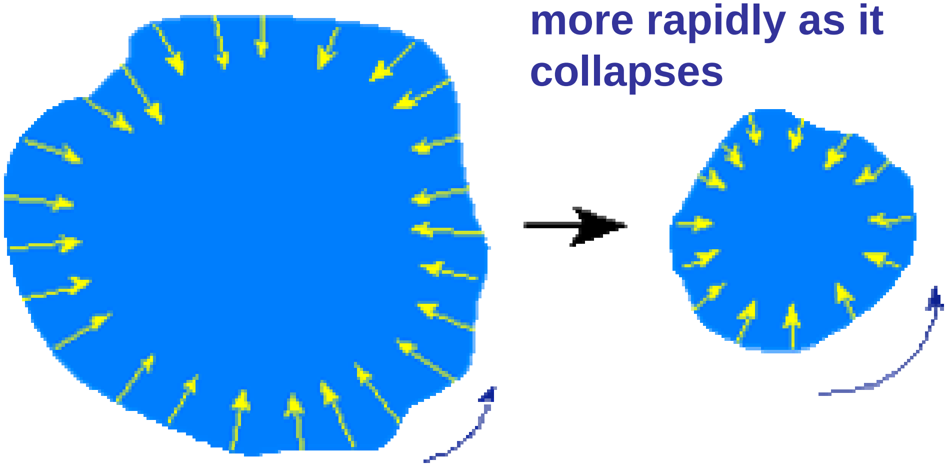


Pressure

versus

Gravity

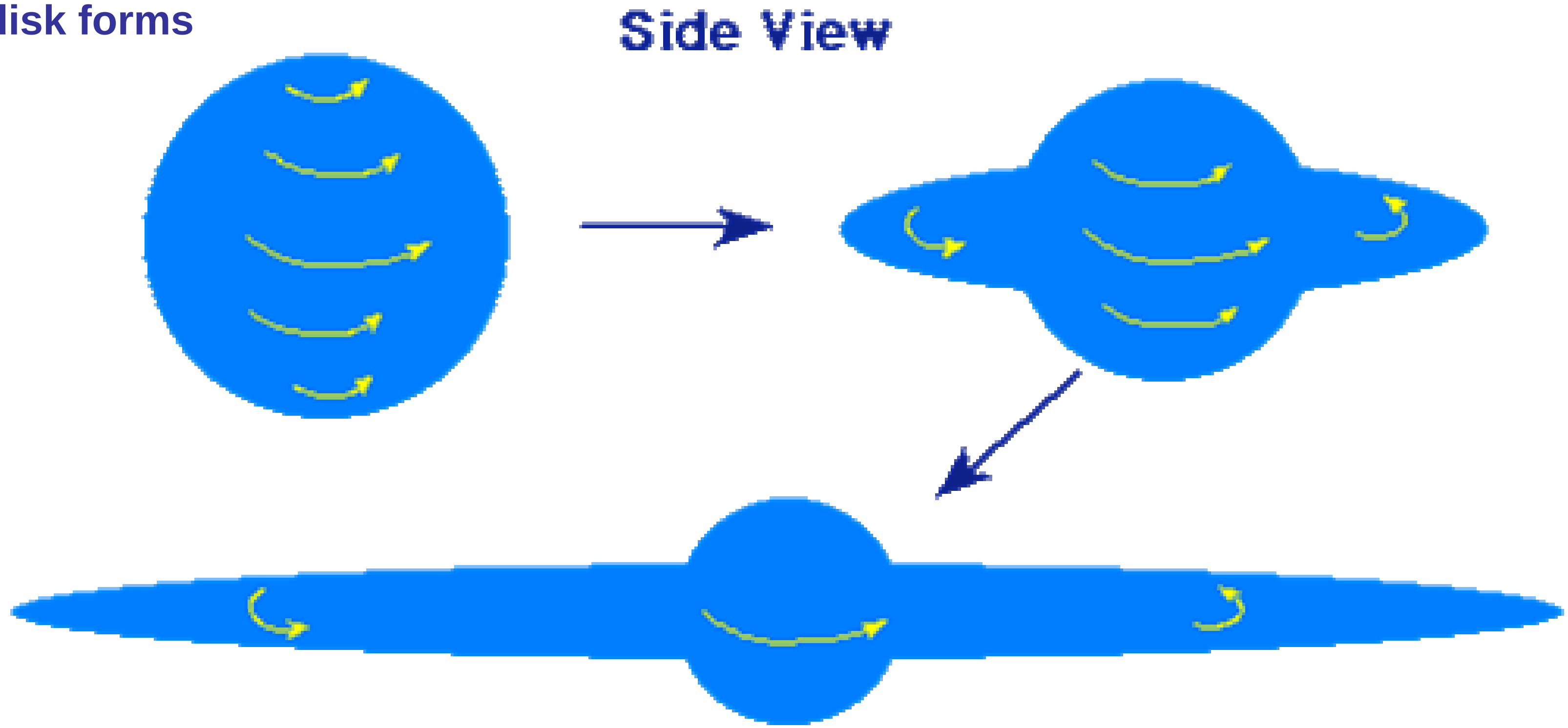
The nebula spins more rapidly as it collapses



Forming stars and planets….

PreSSure versus Gravity

As the nebula collapses
a disk forms



Forming stars and planets….

Pressure

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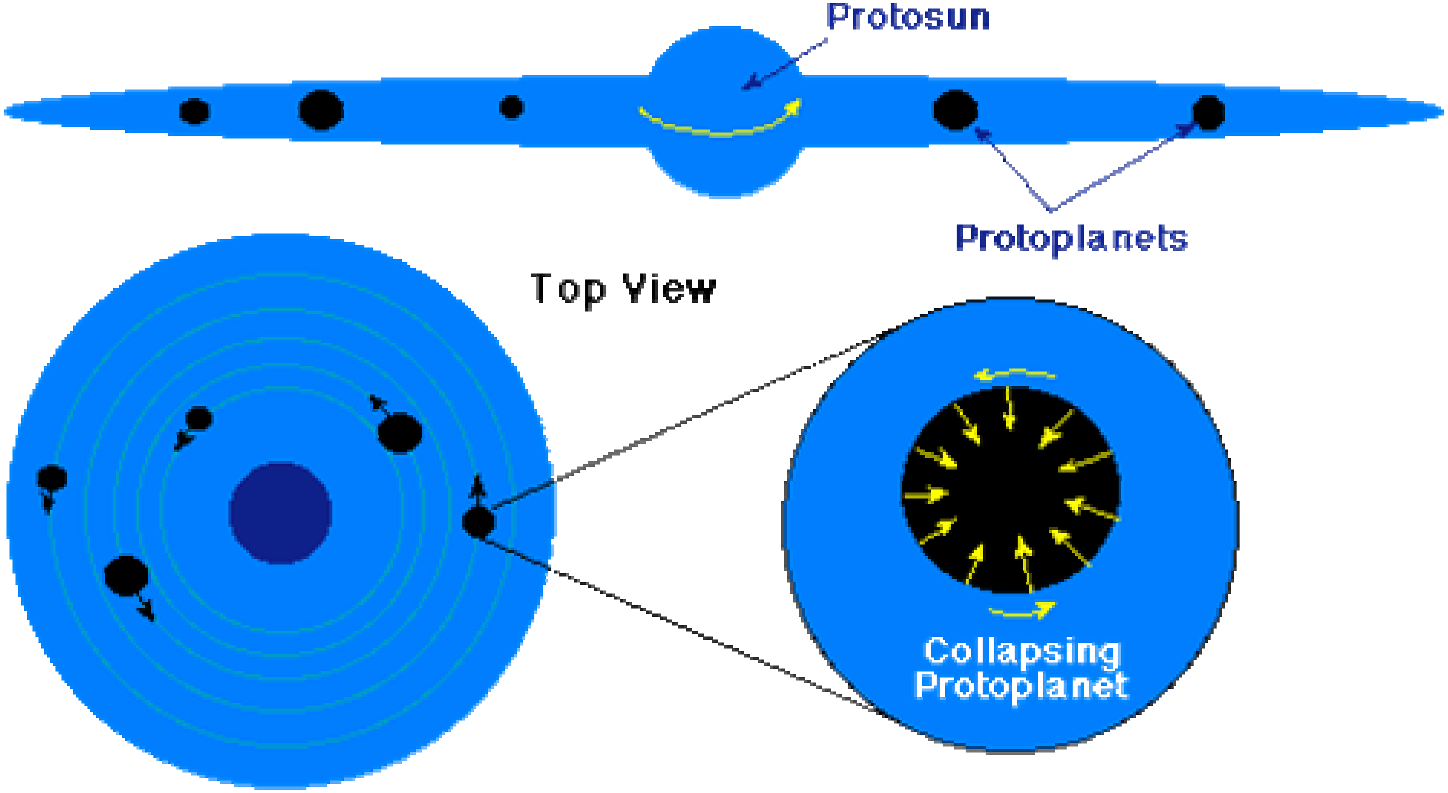
Lumps in the disk form planets



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How common are 'Hot Jupiters'?

- We need to observe more planetary systems before we can answer this. Their common initial detection was partly because they give such a large Doppler wobble.

  As sensitivity increases, and lower mass planets are found, the statistics on planetary systems will improve.

Looking to the Future

1. The Doppler wobble technique will not be sensitive enough to detect Earth-type planets (i.e. Earth mass at 1 A.U.), but will continue to detect more massive planets

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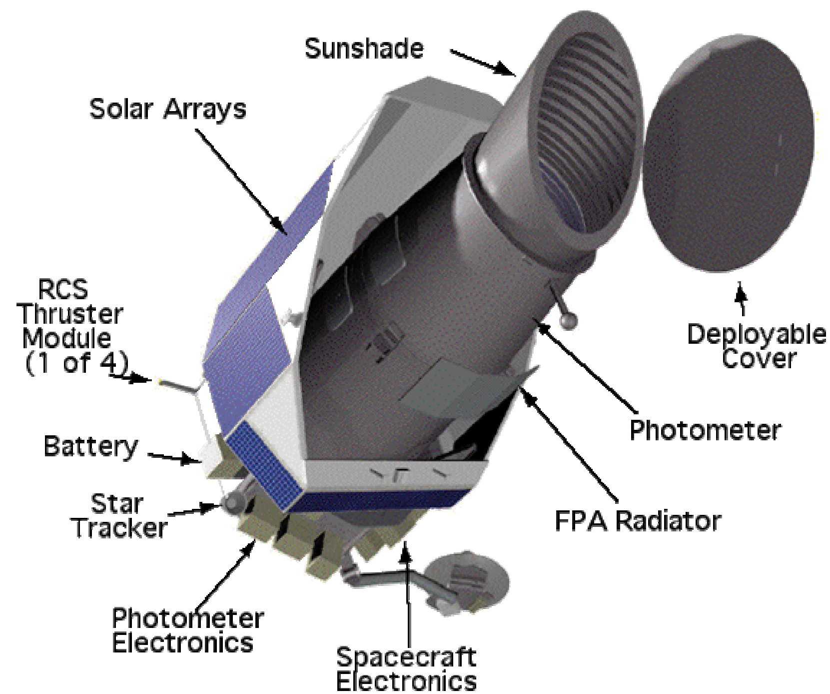

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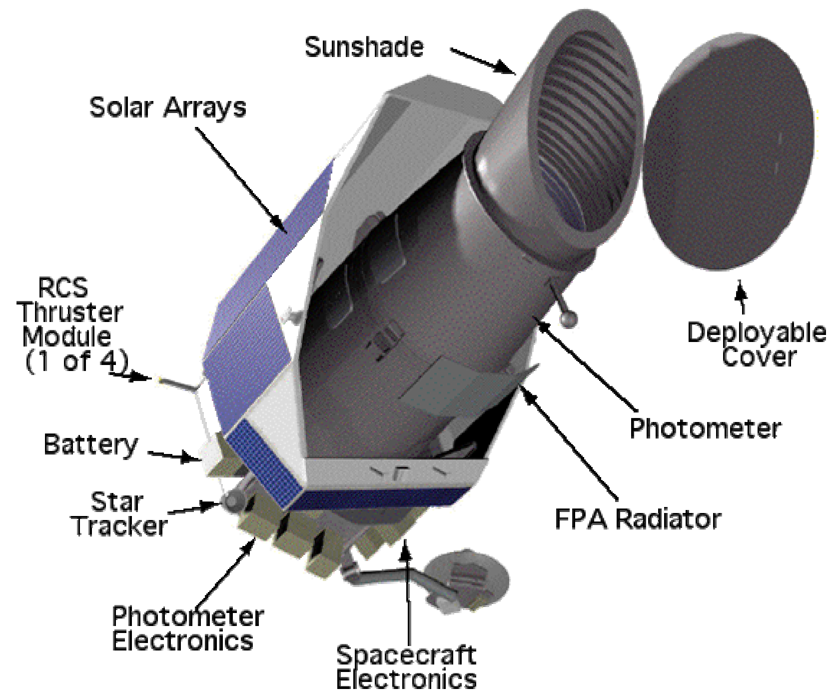
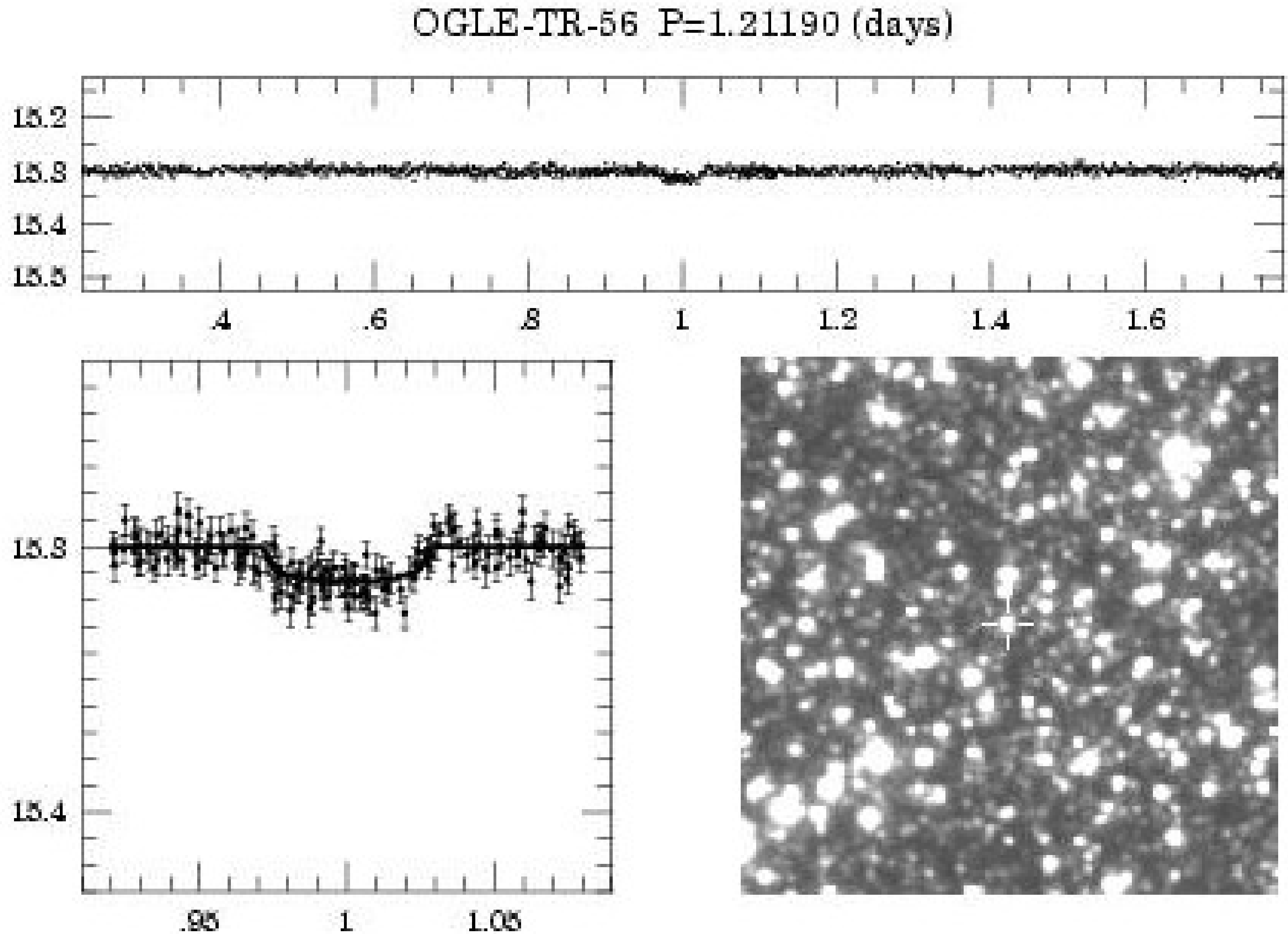


Transit *Detection* by OGLE III program in 2003



SuperWASP

www.superwasp.org

Wide Angle Search for Planets

Search the SuperWASP site:

Search

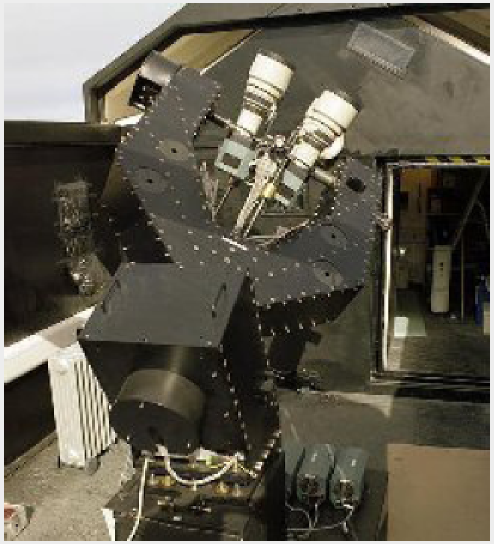
Quicklinks

- wasp@leicester
- wasp@st. andrews
- wasp@keele
- wasp@QUB

Members Only:

- WASP project
- steering group
- pipeline group
- hardware group
- archive group
- resources
- planets group

LATEST: First light images from SuperWASP-South now available click here for more



Welcome to the SuperWASP website

SuperWASP is the UK's leading extra-solar planet detection program comprising of a consortium of eight academic institutions which include Cambridge University, the Instituto de Astrofisica de Canarias, the Isaac Newton Group of telescopes, Keele University, Leicester University, the Open University, Queen's University Belfast and St. Andrew's University. It is expected that SuperWASP will revolutionise our understanding of planet formation paving the way for future space missions searching for 'earth' like worlds that might hold life.

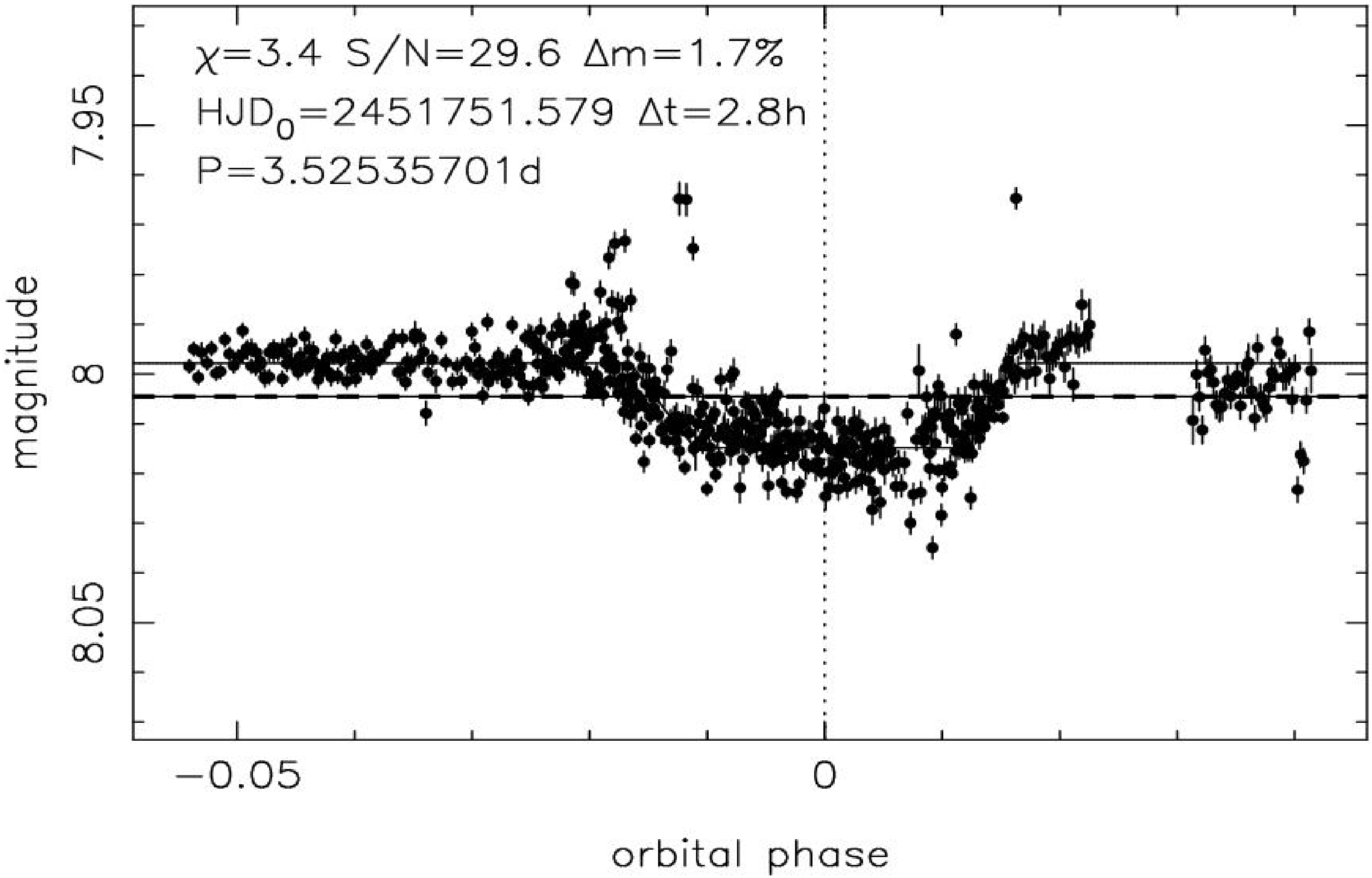
SuperWASP-North is an observatory on the island of La Palma and is located amongst the Isaac Newton Group of telescopes (ING). It consists of 8 wide-angle cameras that simultaneously monitor the sky for planetary transit events. A transit occurs when a planet passes in front of its parent star temporarily blocking some of the light from it (see the How it works section). By continuously imaging the sky, SuperWASP can detect these changes in brightness and infer the presence of a planet.

Where is SuperWASP? Click picture

Data from the 2004 observing season from SuperWASP-N is in the process of being analysed and we hope to announce our first transit candidates soon. A second identical observatory, SuperWASP-South, is currently being constructed at the site of the South African Astronomical Observatory (SAAO), just outside Sutherland, South Africa. Robotic operations at this observatory are expected to begin by the winter of 2005. With both observatories scanning the sky we hope to complete the largest exoplanet survey ever.

Please take the time to explore our site and check back regularly for news. If you have any questions please feel free to contact us at the address below.

Possible transit detection by SuperWASP from 2004?



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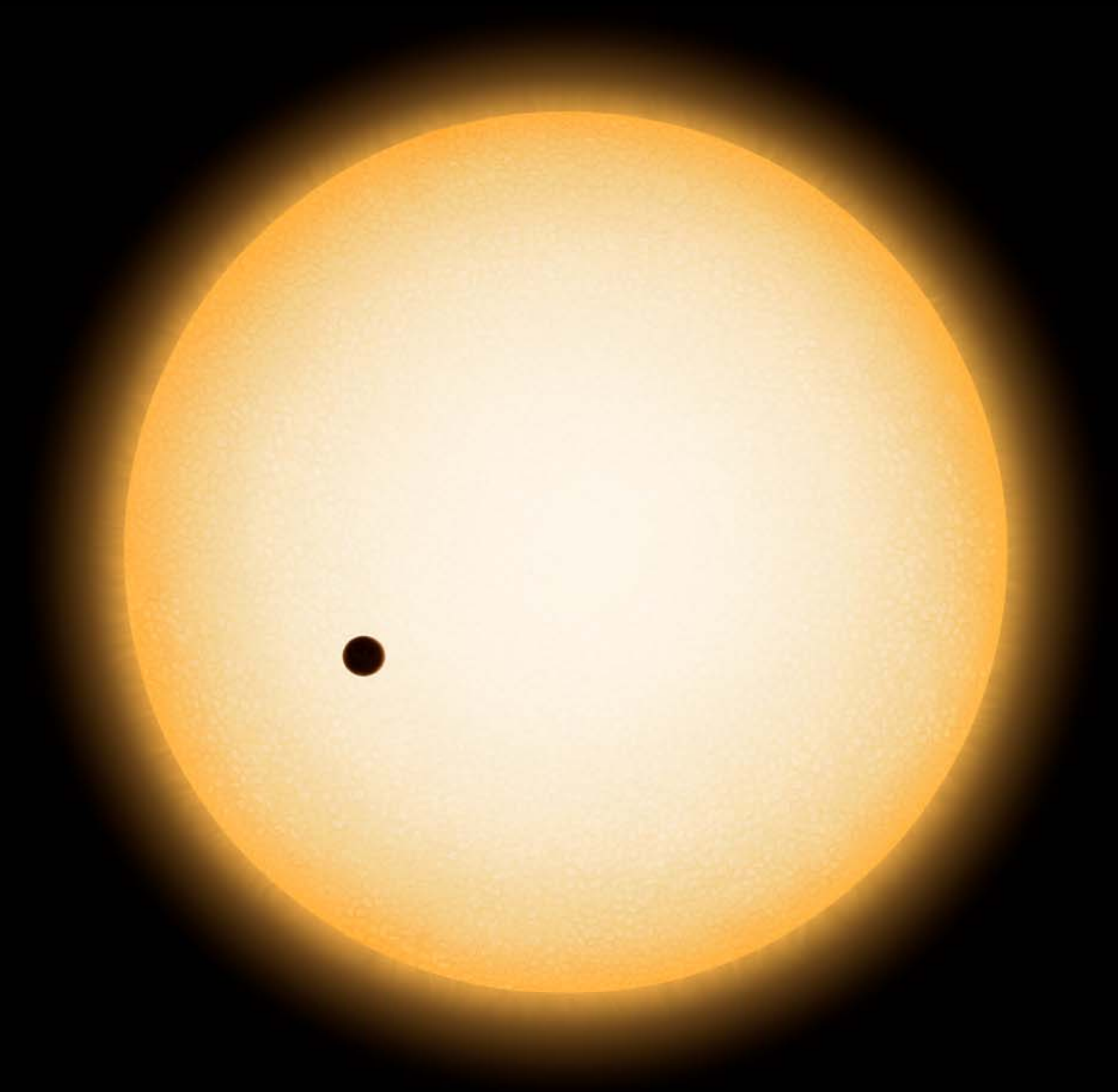
Note that (2) and (3) permit measurement of the orbital inclination

$\Rightarrow$ Can determine m_P and not just $m_P \sin i$



Saturn mass planet in transit across HD149026

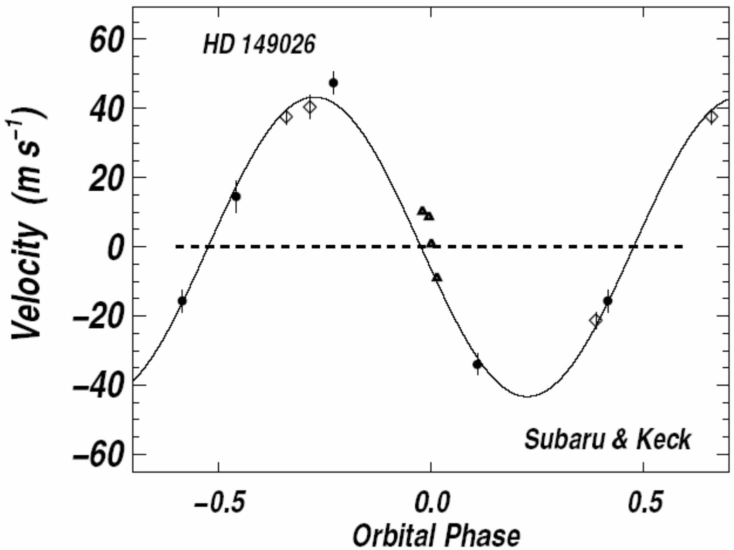


Table 3. Spectroscopic Orbital Solution for HD 149026b

Parameter	Value
P (days)	2.8766 (0.001)
T_c (JD)	2453317.838 (0.003)
Eccentricity	0 (fixed)
K_1 (m s^{-1})	43.3 (1.2)
a (AU)	0.042
$a_1 \sin i$ (AU)	1.037e-05
f_1(m) ($M_\odot$)	1.839e-11
$M \sin i$ ($M_{\rm Jup}$)	0.36 (0.03)
Nobs	7 (out of transit)
RMS (m s^{-1})	3.8
Reduced $\sqrt{\chi^2_\nu}$	1.22

From Doppler wobble method

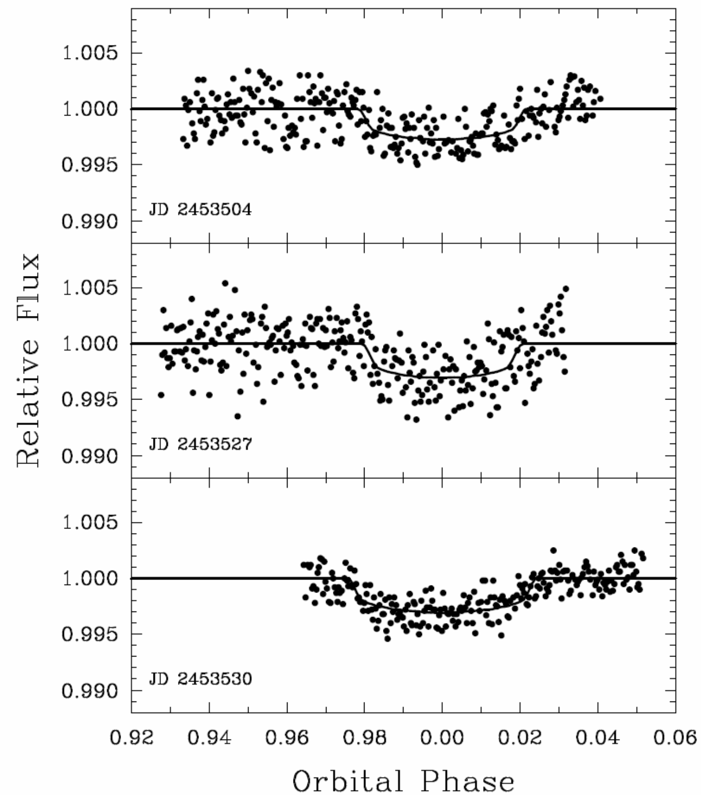
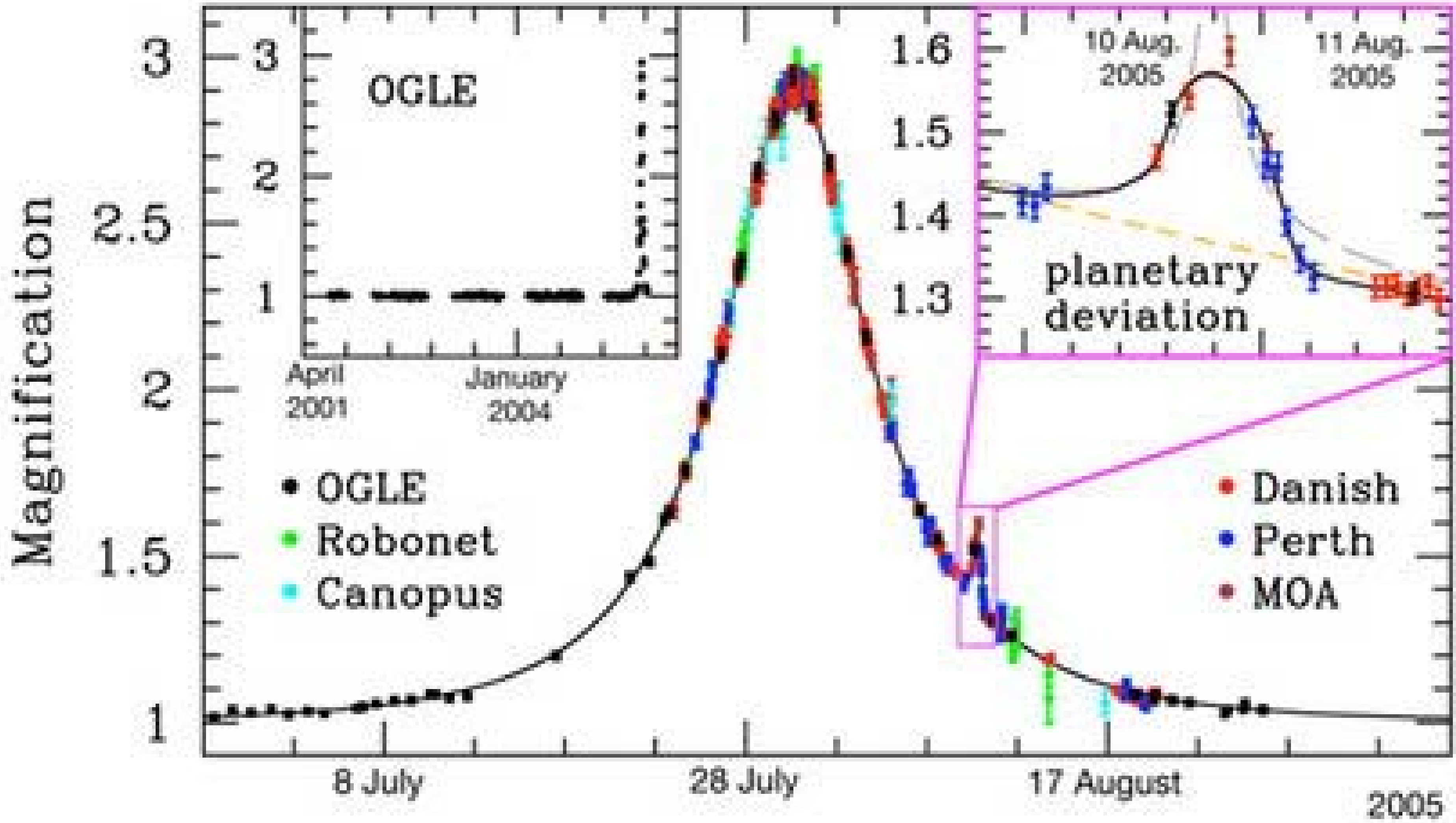


Table 5. PHOTOMETRIC SOLUTIONS FOR HD 149026b

Transit	APT	Date (UT)	T_{mid} (HJD)	Planetary Radius ($R_{\rm Jup}$)	Inclination (degrees)	rms (mag)
1	11	2005 May 14	2,453,504.865	0.705	84.6	0.0017
2	11	2005 June 6	2,453,527.864	0.759	84.1	0.0021
3	8,10,11	2005 June 9	2,453,530.751	0.719	86.2	0.0012
Weighted Mean				0.725	85.3	

From transit method

From Sato et al 2006



Light Curve of OGLE-2005-BLG-390

ESO PR Photo 03b/06 (January 25, 2006)

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   ESA: Darwin

   ~ 2015 launch???

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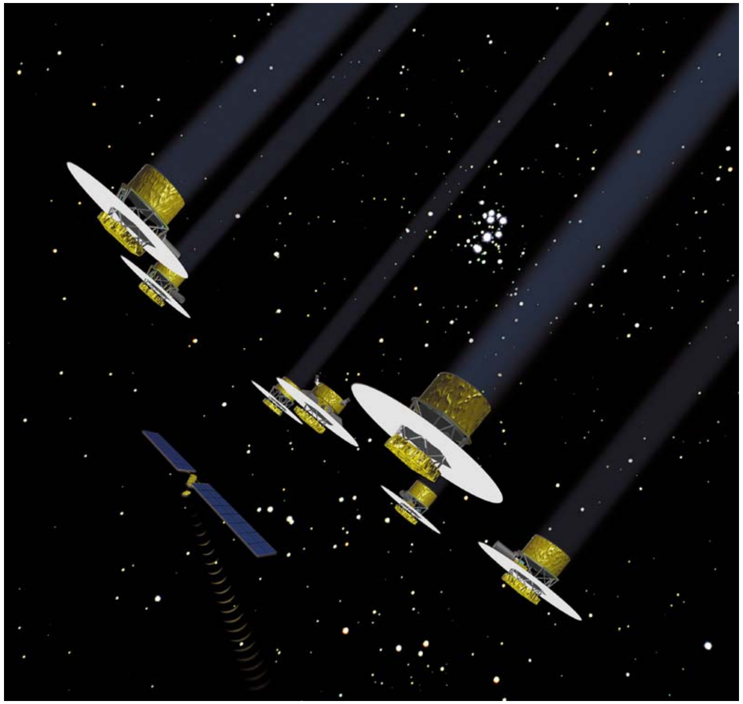
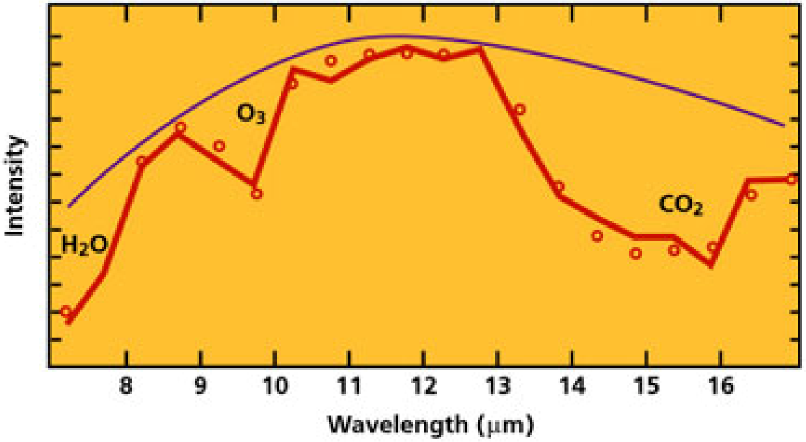
Follow-up spectroscopy would search for signatures of **life**:-



Spectral lines of oxygen, water carbon dioxide in atmosphere



Simulated 'Earth' from 30 light years

The Search for Extra-Solar Planets

- The field is still in its infancy, but there are exciting times ahead
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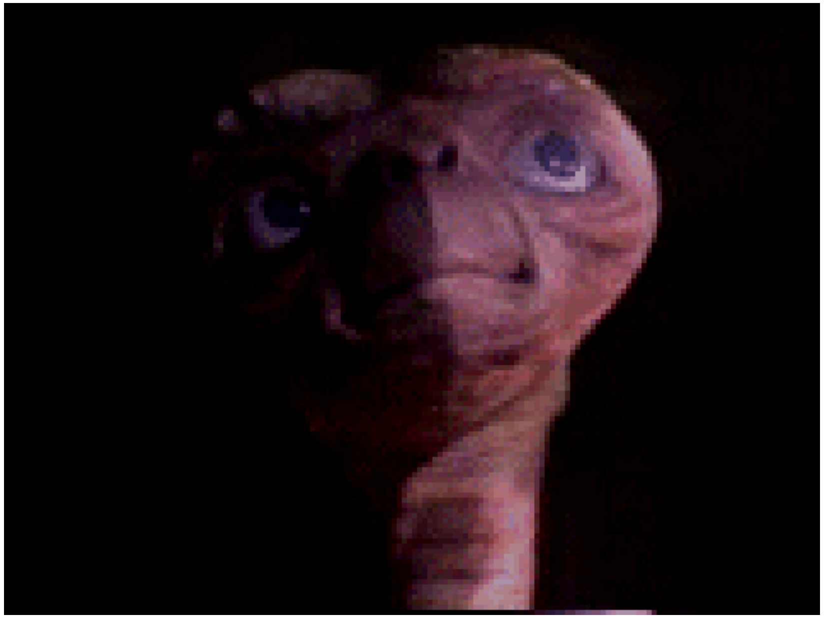
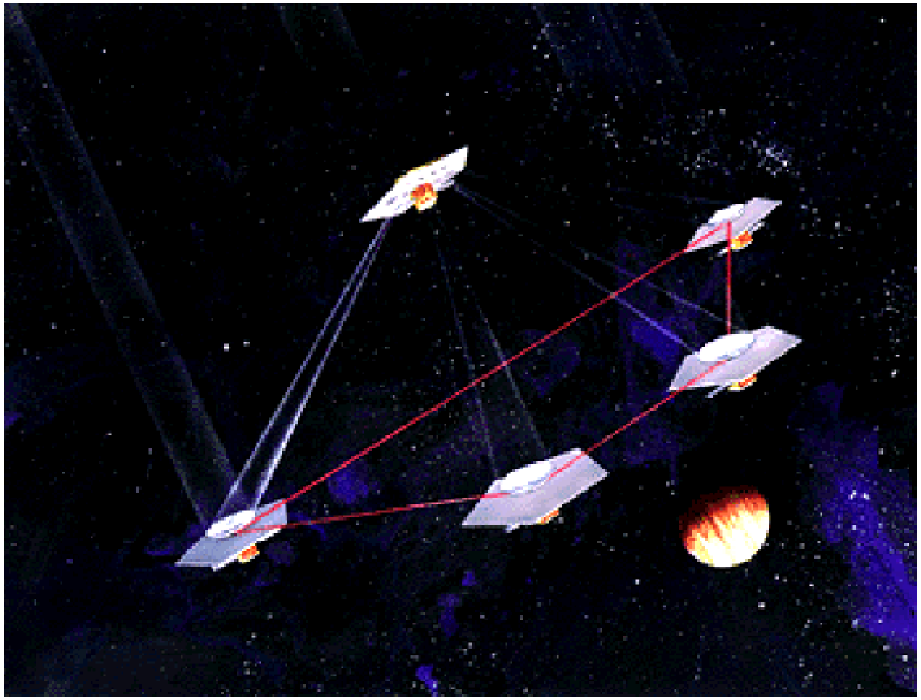
What (or who) will we find?…



Looking to the Future

4. NASA: Terrestrial Planet Finder
   ESA: Darwin
   } ~ 2015 launch

These missions plan to use *nulling interferometry* to 'blot out' the light of the parent star, revealing Earth-mass planets



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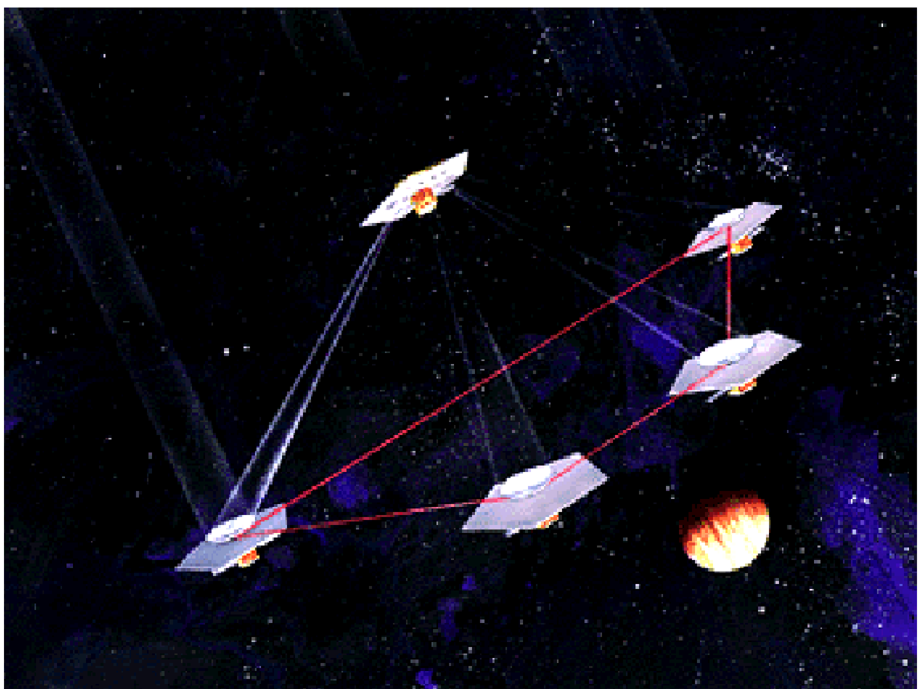
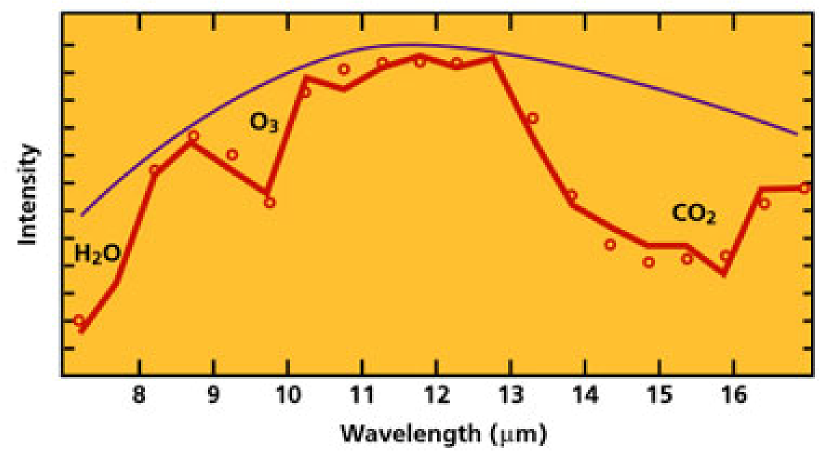
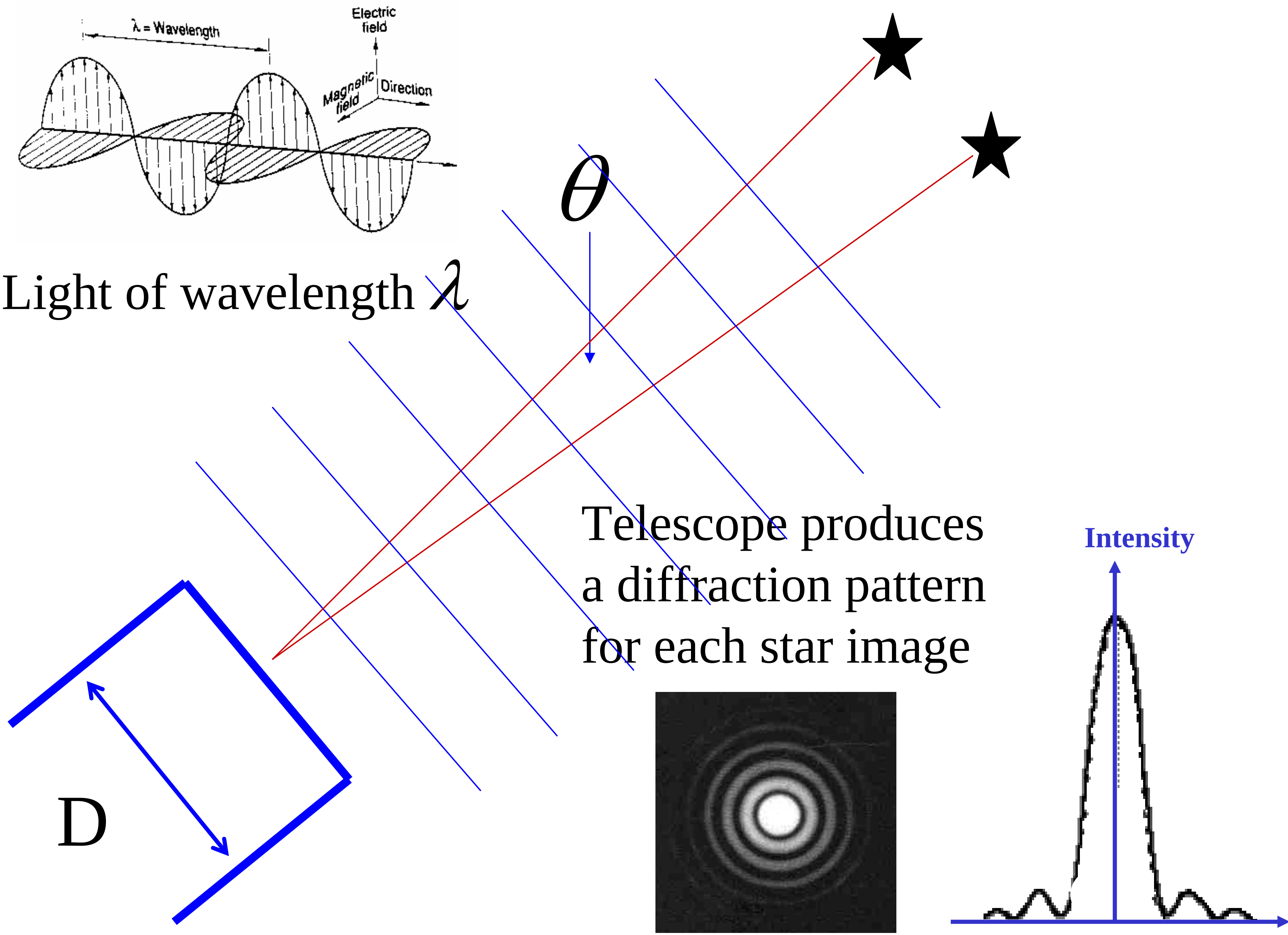
Follow-up spectroscopy will search for signatures of **life**:-



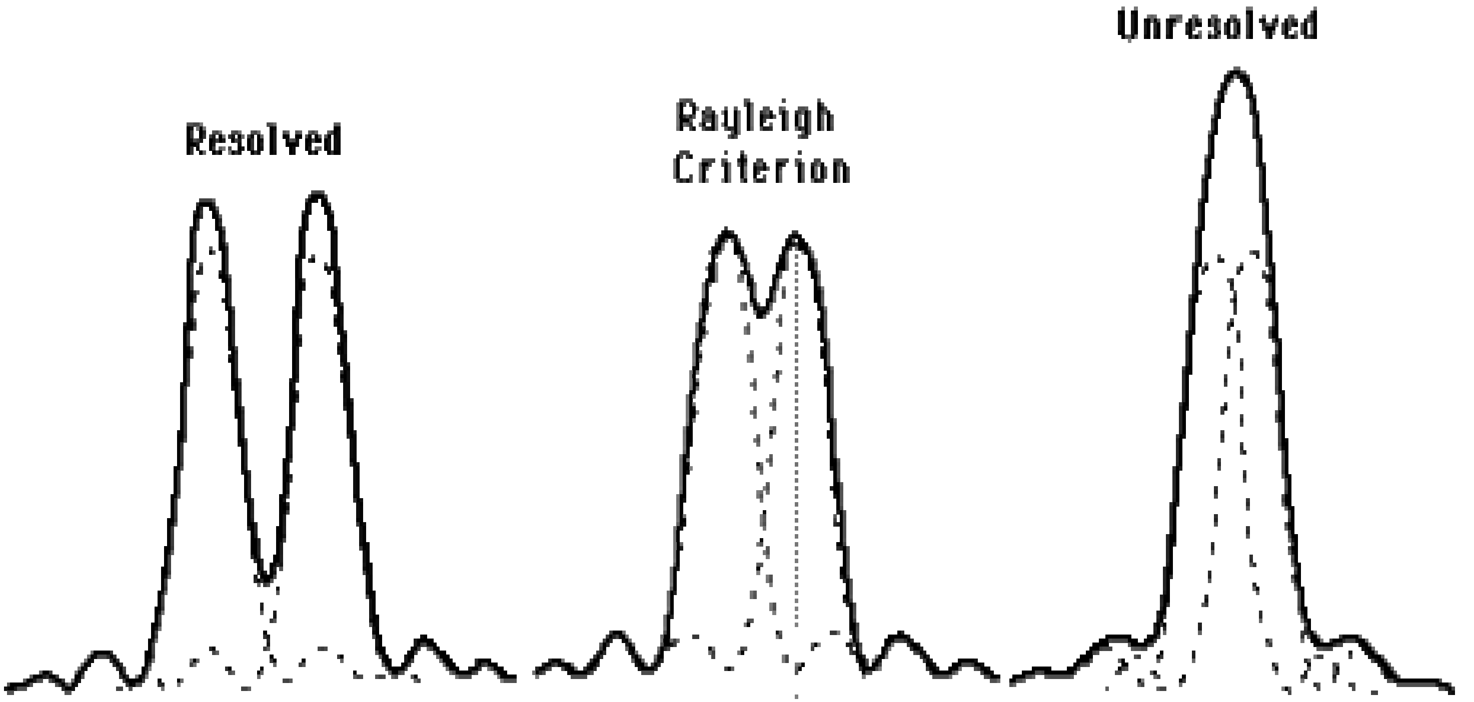
Spectral lines of oxygen, water carbon dioxide in atmosphere



Simulated 'Earth' from 30 light years

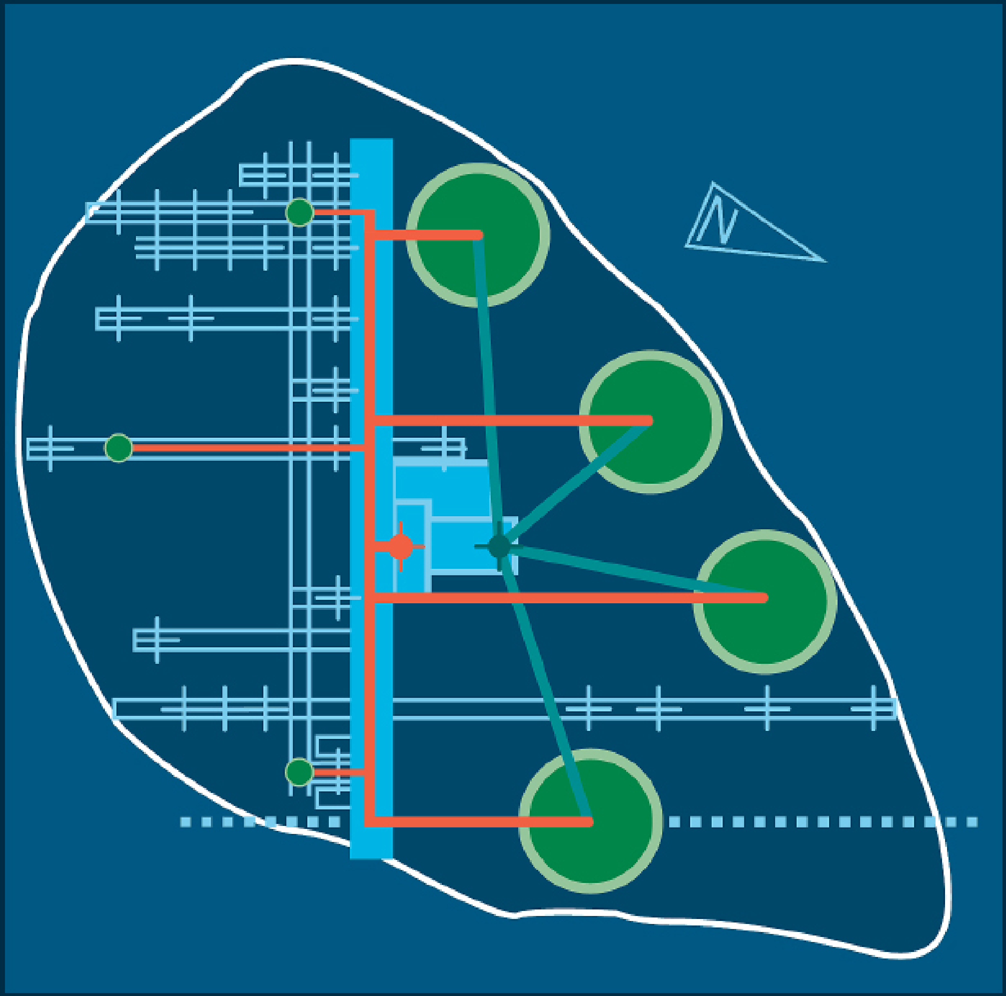


λ = Wavelength
Electric field
Magnetic field
Direction
Light of wavelength λ
θ
Telescope produces a diffraction pattern for each star image
Intensity
D



Rayleigh criterion for the minimum resolvable detail:

THE VLT INTERFEROMETER



No. of combined telescopes:
2 to 7 (8)

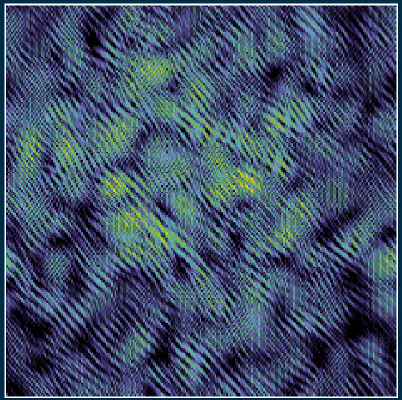
Baselines:
30 to 130 m (UTs)
8 to 200 m (ATs)

Delay line stroke:
60 m

Angular resolution:
0".001 at 1 μm

Wavelength coverage:
480 nm - 20 μm

INTERFEROMETRY WITH THE VLT

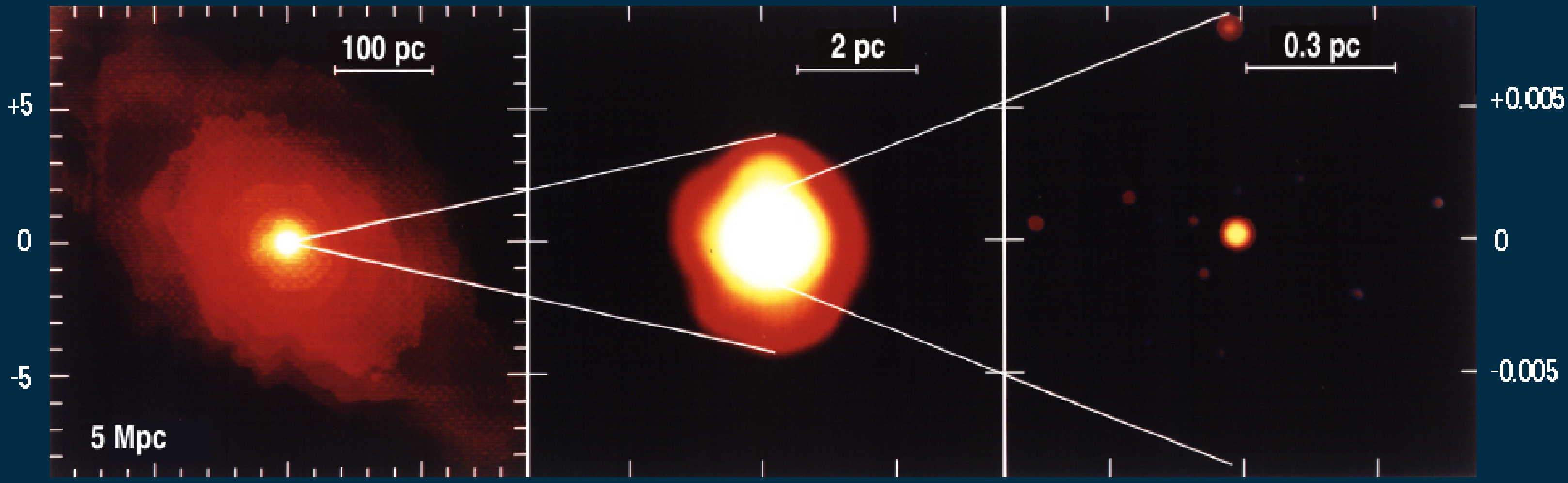


Coherent combination of light from two or more telescopes results in interference fringes.

Through computer analysis of the fringes, a high-resolution image of the source can be constructed.

The VLTI resolving power equals that of a 130 m telescope

Natural Seeing (0″.5 Res) Adaptive Optics (0″.06 Res) VLTI (0″.0024 Res)



Courtesy Max Planck Society

K-band (2.4 μm)

The Search for Extra-Solar Planets

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