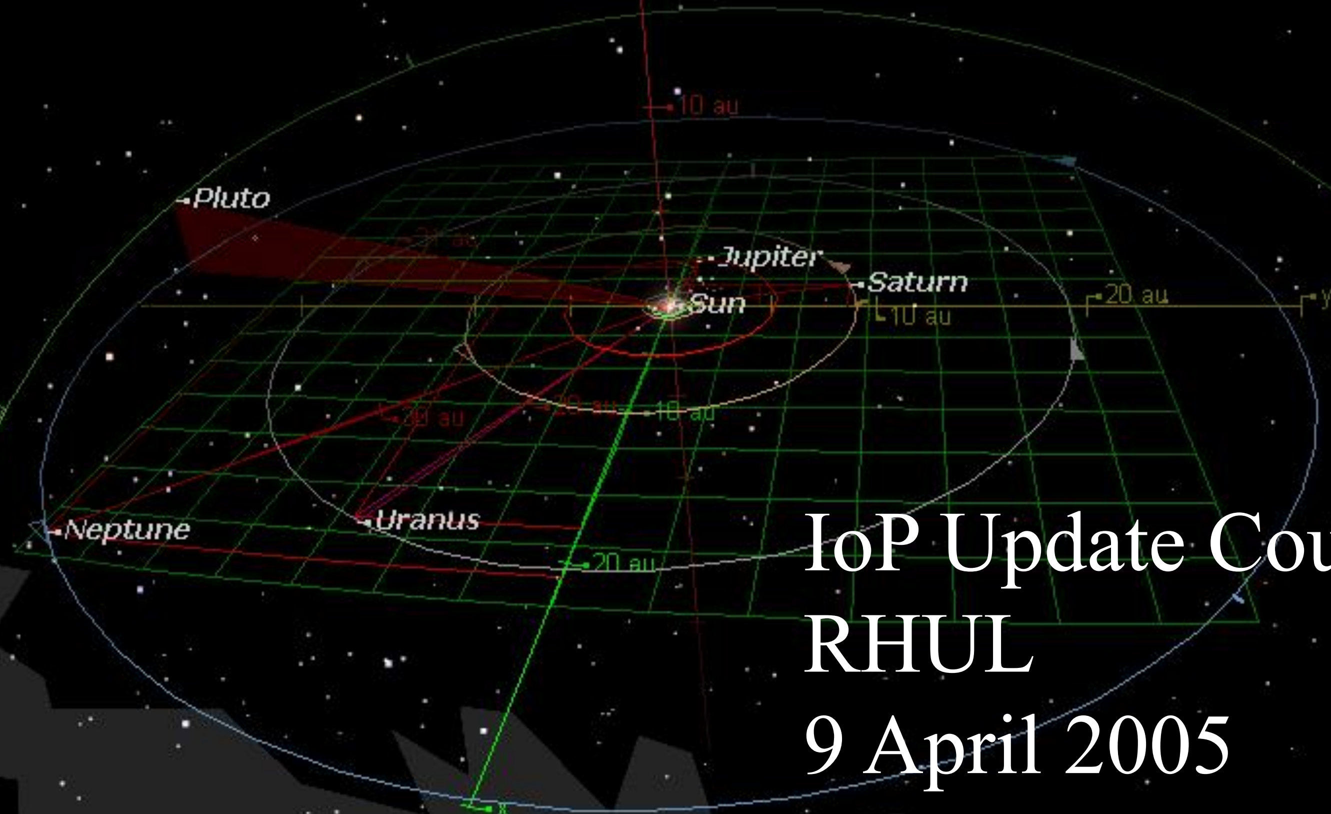
Measuring the Solar System

The role of the transit of Venus



IoP Update Course
RHUL
9 April 2005

Glen Cowan
RHUL Physics Dept.

Royal Holloway
University of London

Outline

Relative distances in the solar system (& somewhat beyond)

Absolute distances and the transit of Venus

Interlude on instrumentation

Viewing the 2004 transit and a few other student projects

The Planets

Terrestrial (Rocky):
- Mercury
- Venus
- Earth
- Mars
- (Pluto)

Jovian (Gas Giants):
- Jupiter
- Saturn
- Uranus
- Neptune

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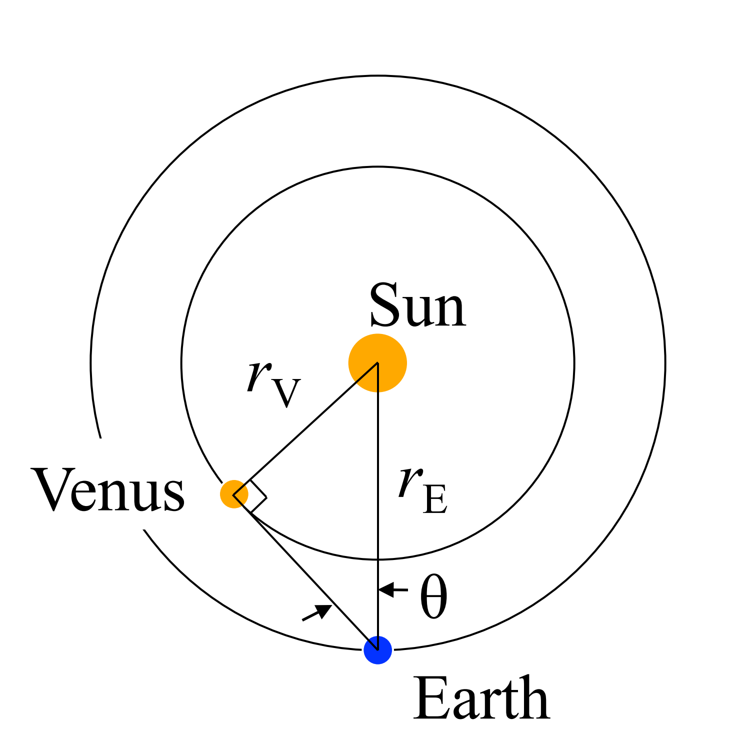
The size of the solar system

Ptolemy, Kepler, etc., only knew the ratios of orbital sizes, not the absolute distances (e.g. in km).

For Mercury and Venus (inside Earth's orbit), we can get ratios from measuring the maximum angle between planet and sun.

At "greatest eastern elongation" of Venus, for example,

$\sin\theta = r_V / r_E = 0.723$



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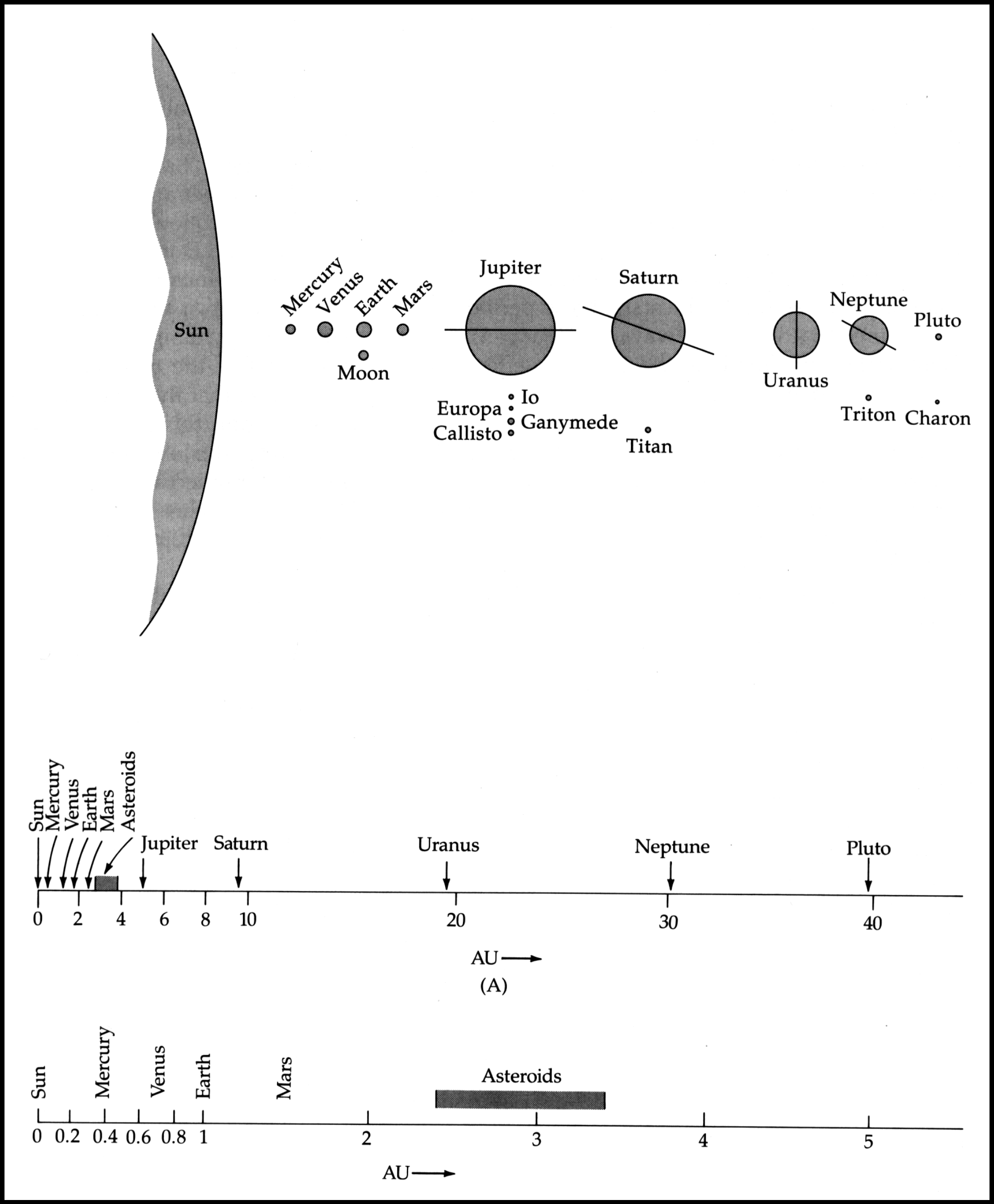
Planetary orbits

Planet	Period T	Semimajor axis a (A.U.)
Mercury	88 days	0.387
Venus	225 days	0.723
Earth	365 days	1.000 ← defines the A.U.
Mars	687 days	1.52
Jupiter	11.9 yrs	5.20
Saturn	29.5 yrs	9.54
Uranus	84 yrs	19.2
Neptune	165 yrs	30.1
Pluto	248 yrs	39.5

But how big is 1 Astronomical Unit (A.U.) in kilometres?

Solar System Sizes



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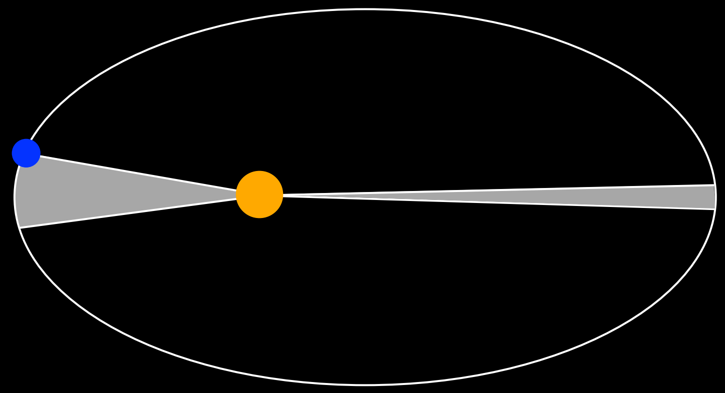
Kepler's Laws

Using data from Tycho Brahe, Kepler (1627) found that planetary orbits follow three mathematical laws:

I. The orbits are ellipses with Sun at focus
III. Equal areas swept out in equal times
V. Period T and semimajor axis a follow $T \sim a^{3/2}$



Third law based on *relative* size of orbits;
Kepler didn't know how big the orbits are in km.

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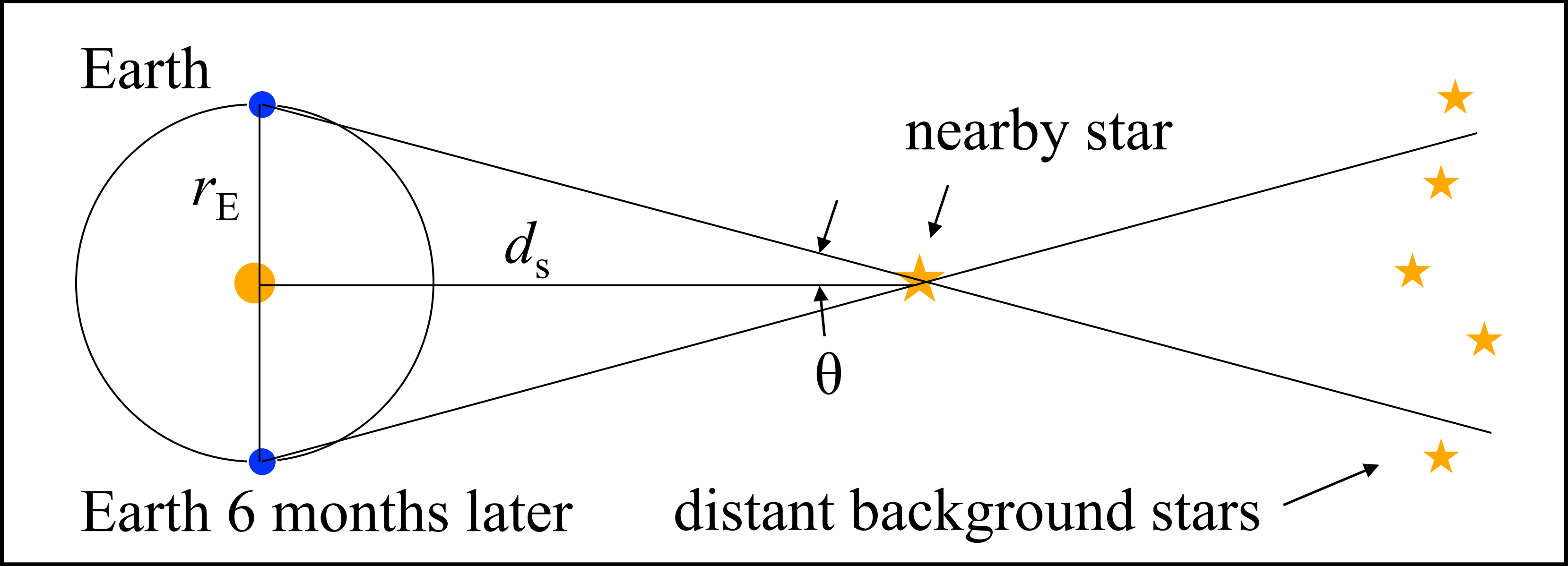
Why is knowing the A.U. so important?

All other distance measurements in astronomy depend on it!

For example, we find distances to nearby stars using stellar parallax:



Parallax angle only determines the ratio d_s/r_E.

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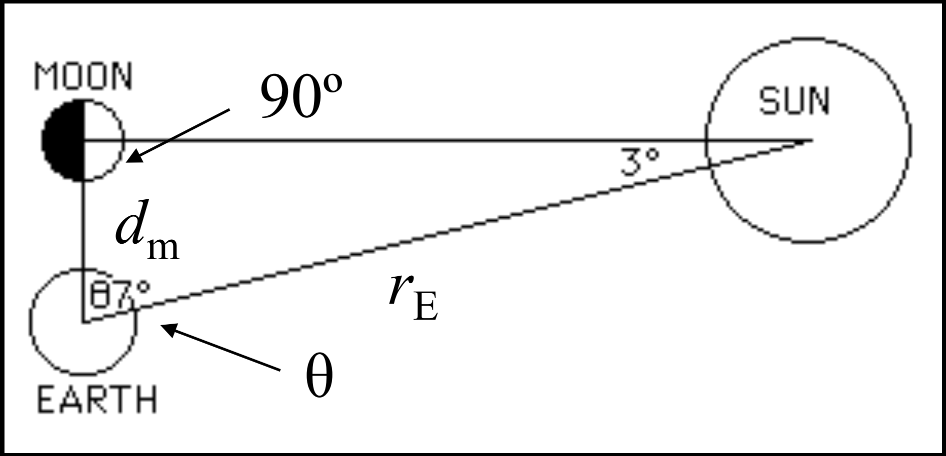
Aristarchus' method (3rd century BC)

Wait for half moon;

measure angle θ between Moon and Sun.

Distance to moon known: $d_m \approx 400{,}000$ km



$\cos\theta = d_m / r_E$

Aristarchus thought θ = 87º, therefore $r_E \approx 8{,}000{,}000$ km.
Actually θ = 89.8º, too difficult to distinguish from 90º.

Conclusion: $r_E \gg d_m$

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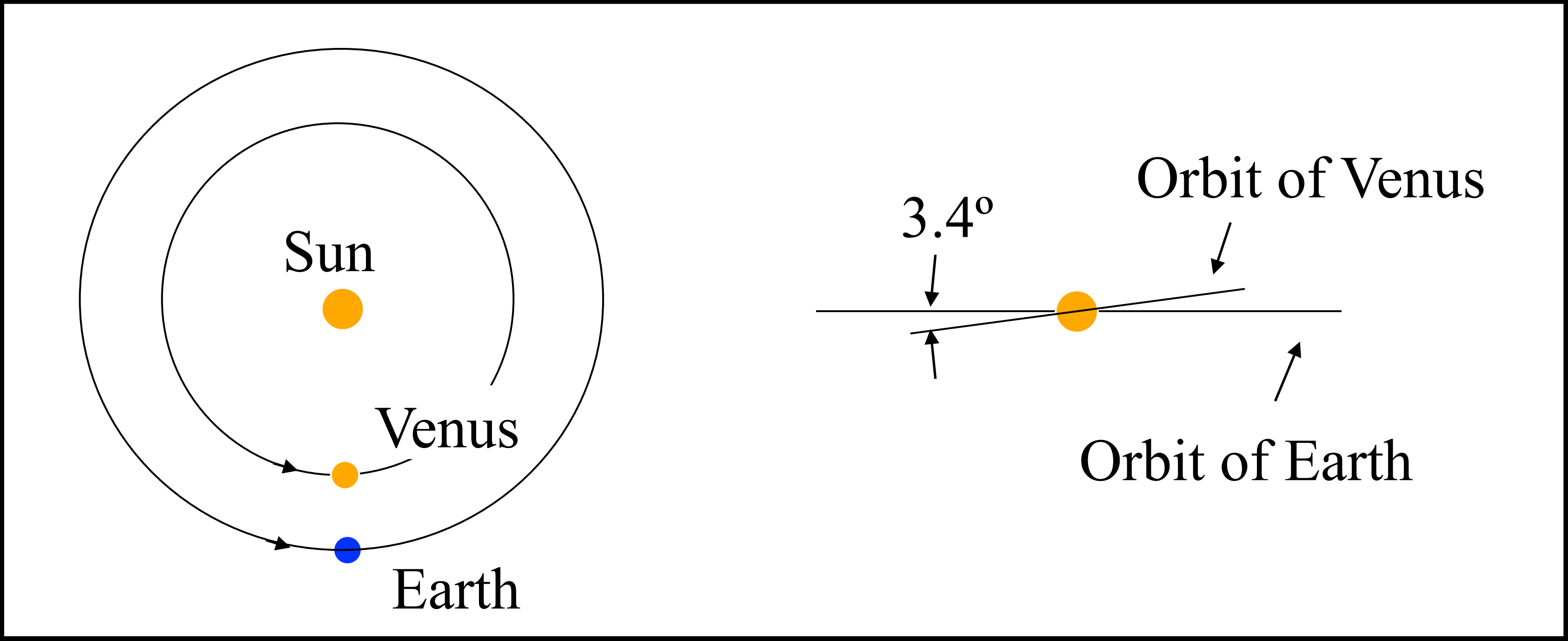
Venus Transit method

Venus passes (almost) between Earth and Sun every 584 days, but only crosses Sun's disc twice every 120 years.

Halley (1716) works out how transits can be used to determine the AU, but never saw one himself.



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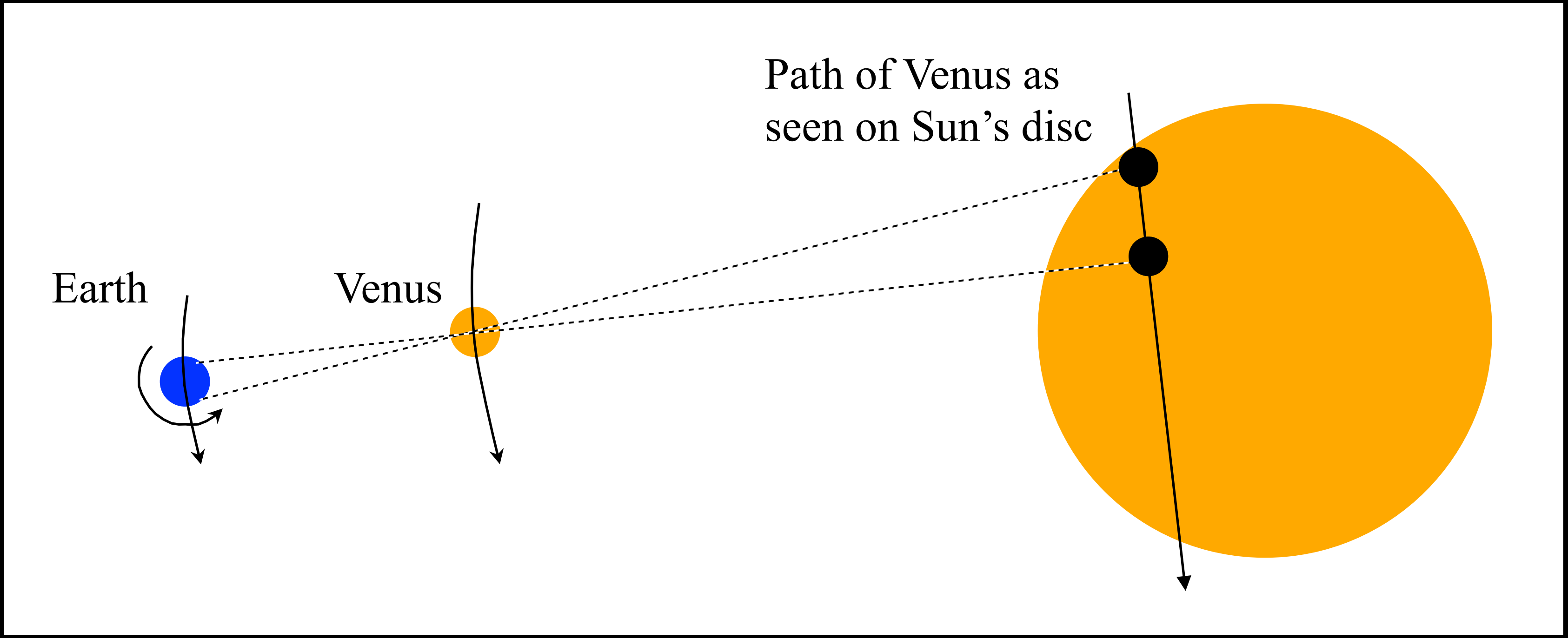
Halley's method

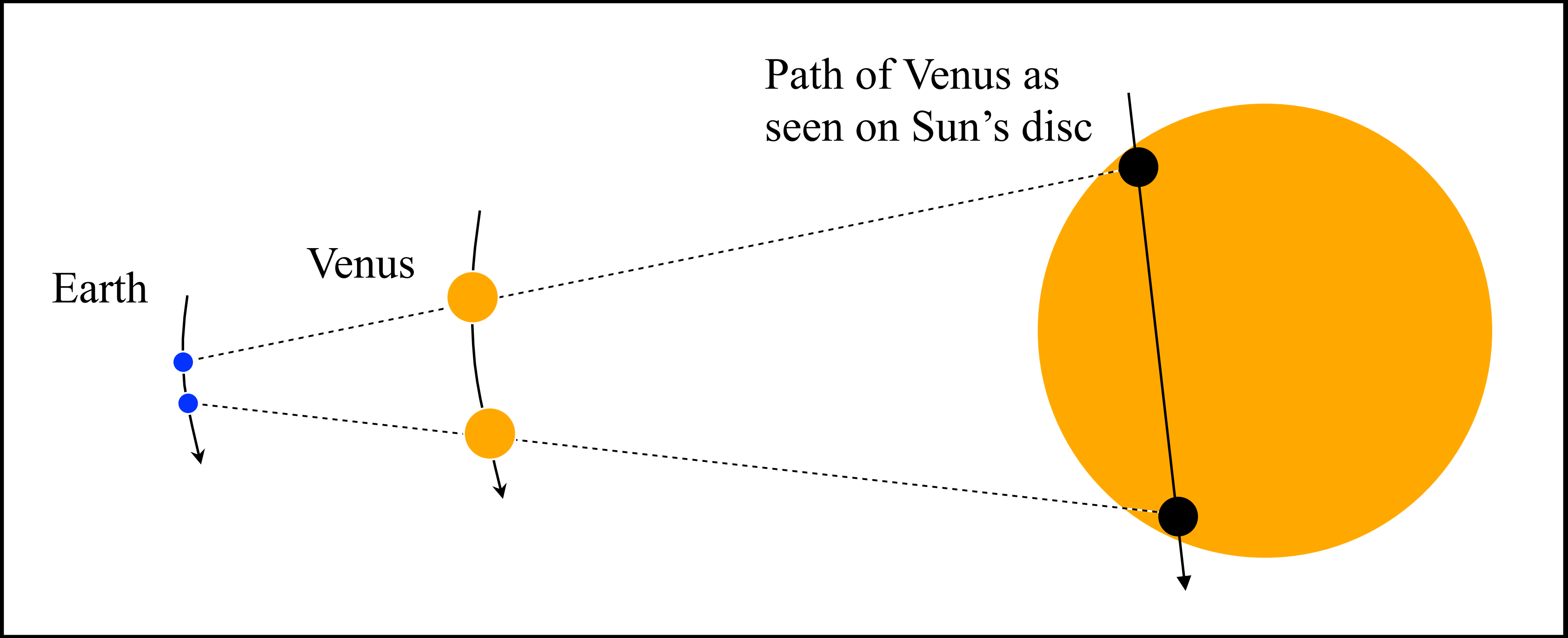
Exploit the parallax effect by observing the transit of Venus across the face of the sun from different places on the earth, or equivalently at different times.



Duration of transit (I)

If Earth were "point like", duration of transit would depend only on orbital motion of Earth and Venus (via Kepler's Laws).

No information on absolute distance to Sun.



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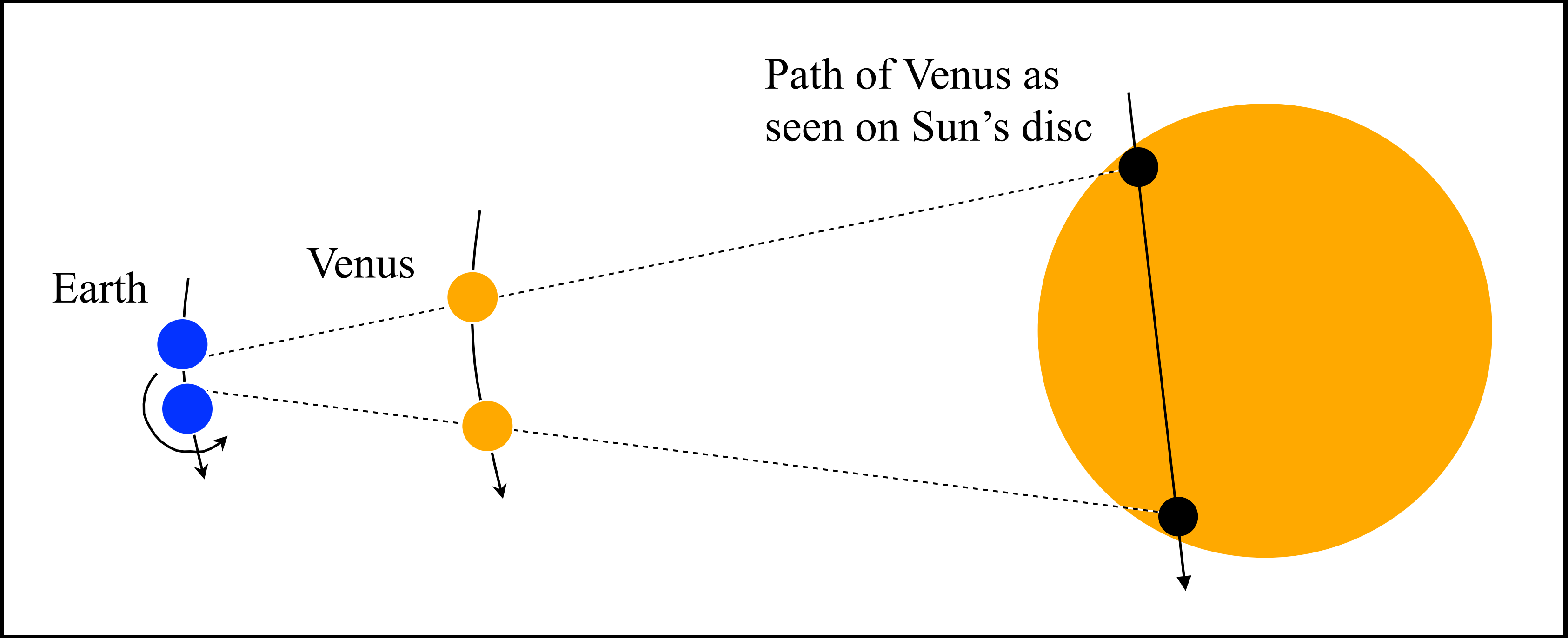
Duration of transit (II)

Earth has 12,800 km diameter and is rotating.

This additional motion shortens duration of transit (effect zero at poles, largest at equator).



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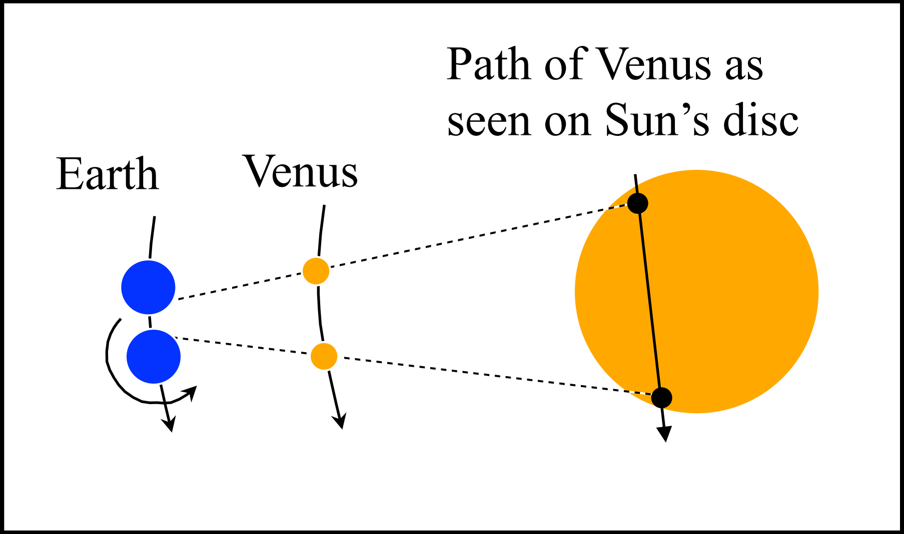
Duration of transit (III)

Magnitude of the effect of rotation on transit duration depends on absolute size of orbit (absolute size of Earth fixed).



If 1 AU were smaller, effect of earth's rotation would appear greater and Venus would cross the Sun's disc more quickly.

Measure transit duration → determine size of AU!

Venus transits of 1761 and 1769

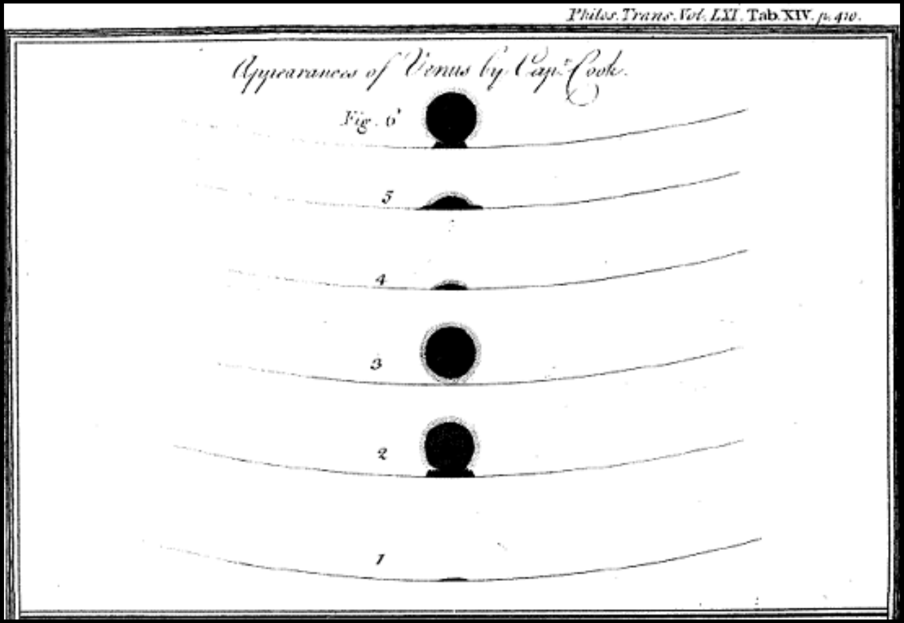
Many expeditions to different locations to observe the transits.

Measure time of ingress/egress (with 18th century clocks).

In 1761, several observations clouded over or otherwise botched, still, size of A.U. found with accuracy of around 20%.

Data from 1769 better – 1 A.U. = 150,000,000 km ± several %.

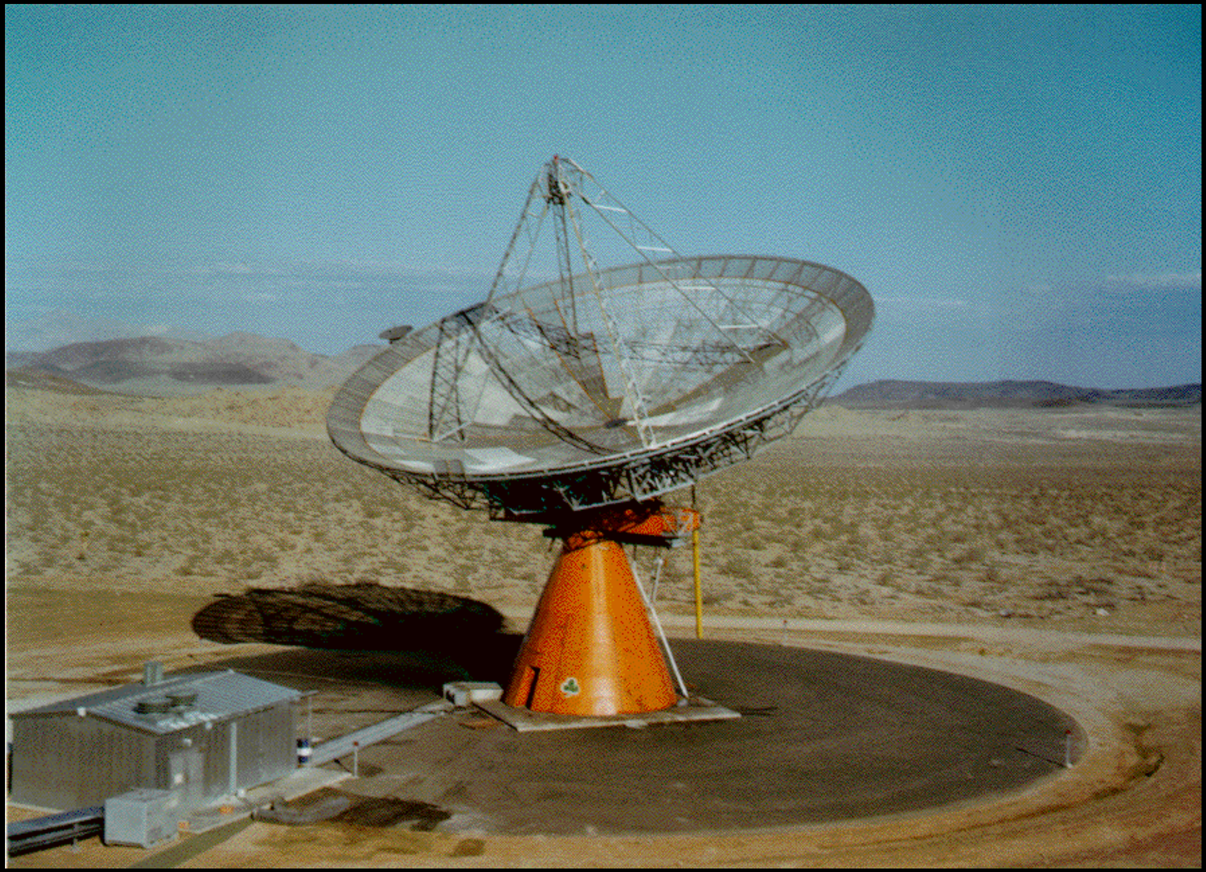
"Black drop" effect makes accurate timing difficult



Echo Station at Goldstone, California

In 1961, radar to Venus gives distance to Sun 149,599,000 km

Current best value: 149,597,870 km



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The 2004 Venus Transit

8 June 2004 from 6:19 to 12:24 BST.

Full transit visible from Britain (last time this happened was 1283).

Perfect weather in Egham for entire transit!

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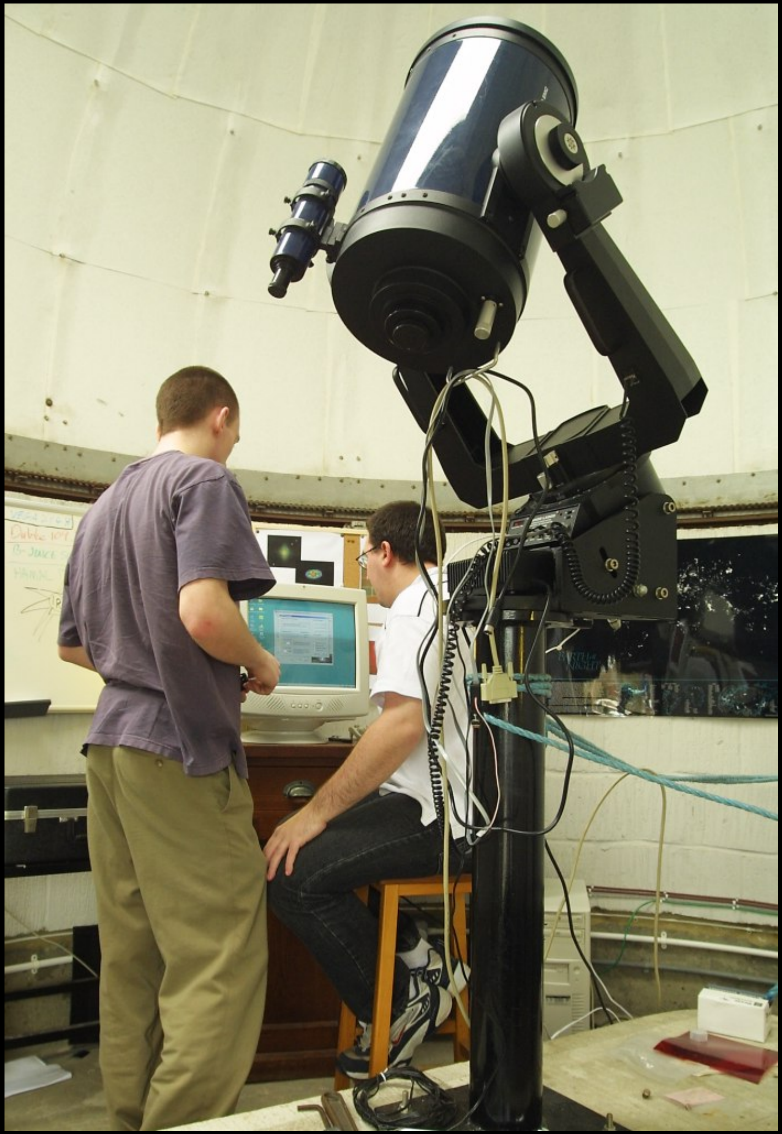
Interlude on telescopes



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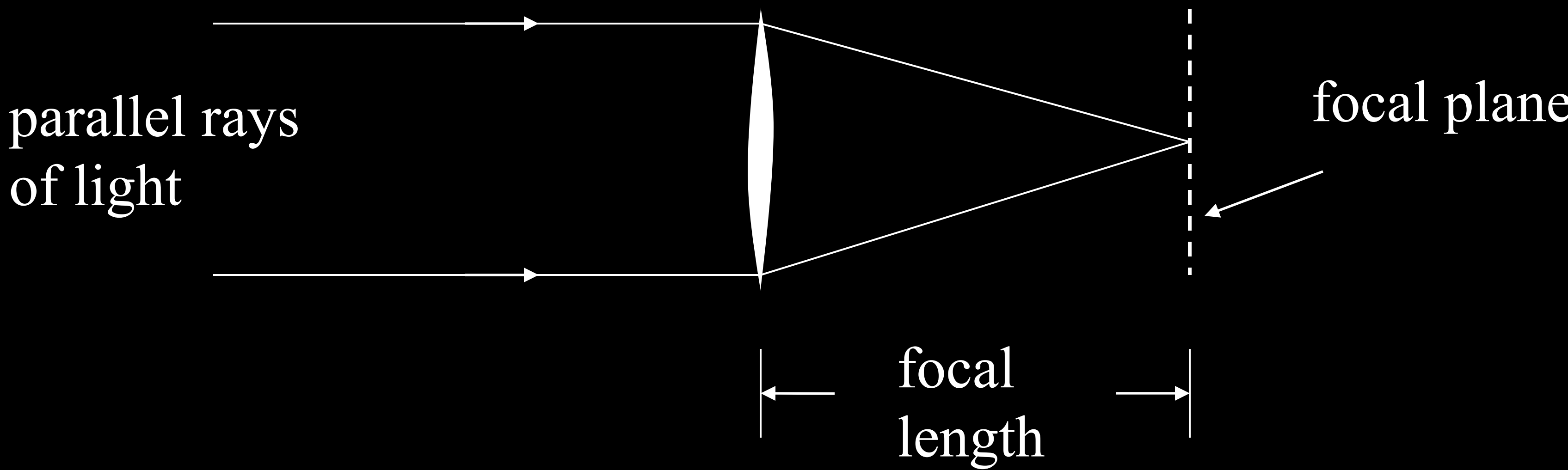
Refracting telescopes

First telescopes used lenses
Lippershey (1608)
Galileo (1609)



Problems: chromatic aberration, difficult to make large lenses

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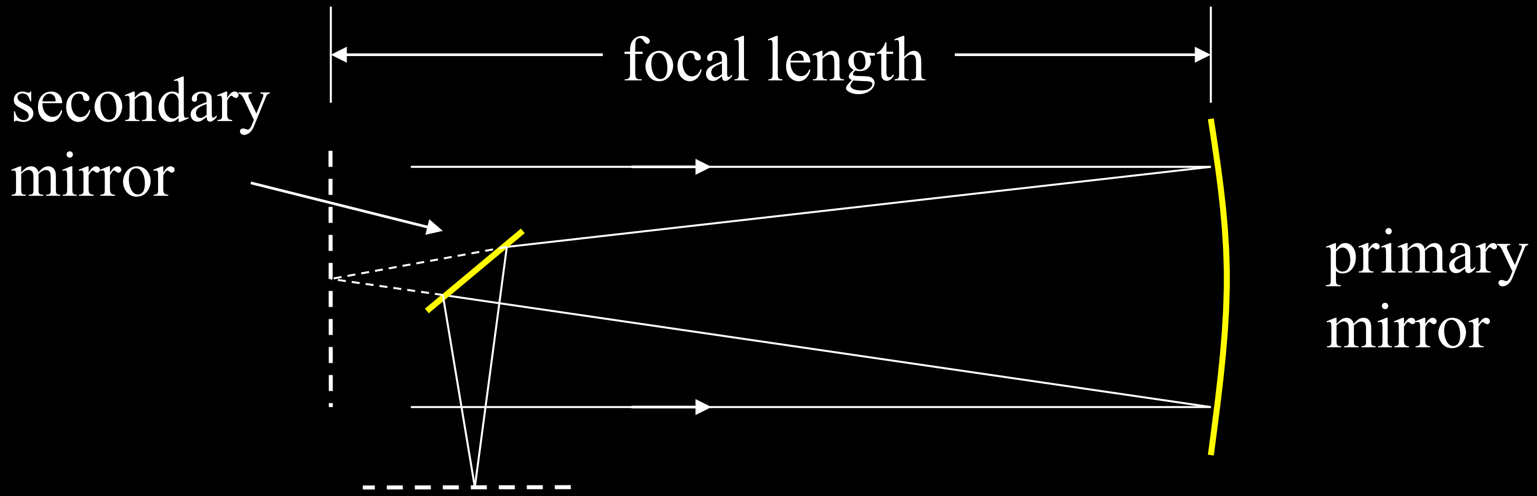
Reflecting telescopes

No chromatic aberration, since law of reflection independent of wavelength

Mirrors up to many metres in diameter

Newton (1668)



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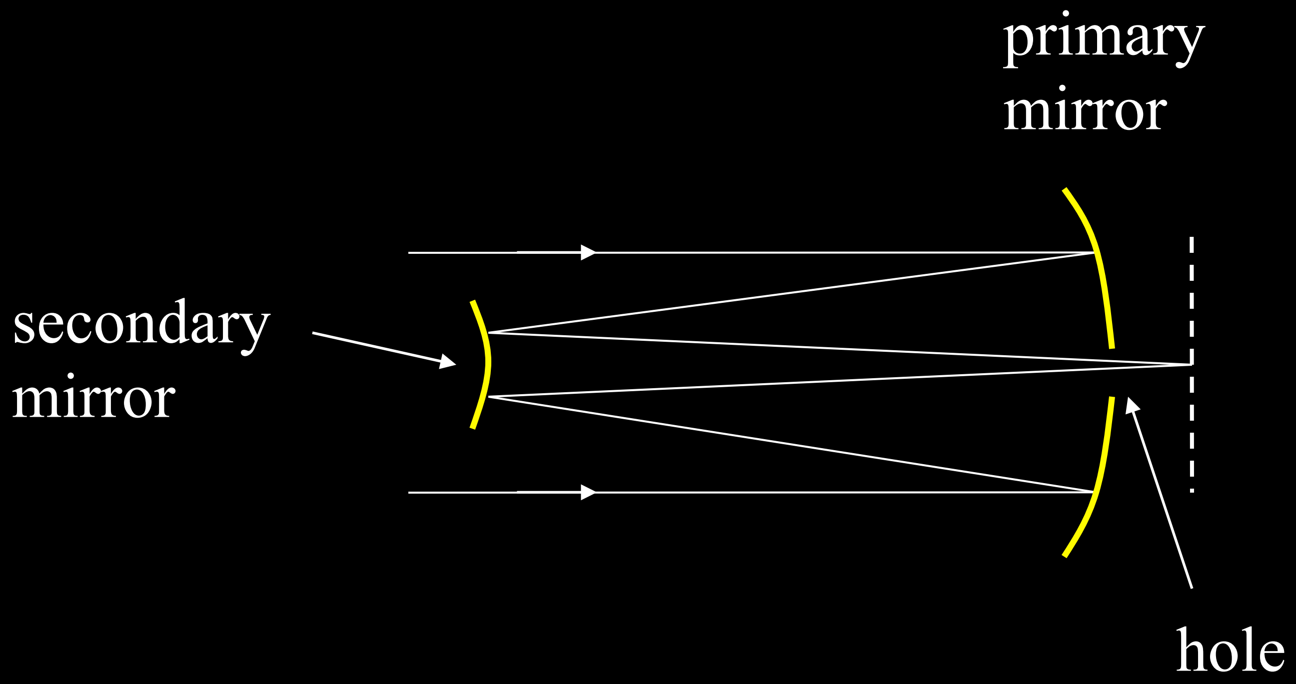
Cassegrain reflector



Long effective focal length in a short tube

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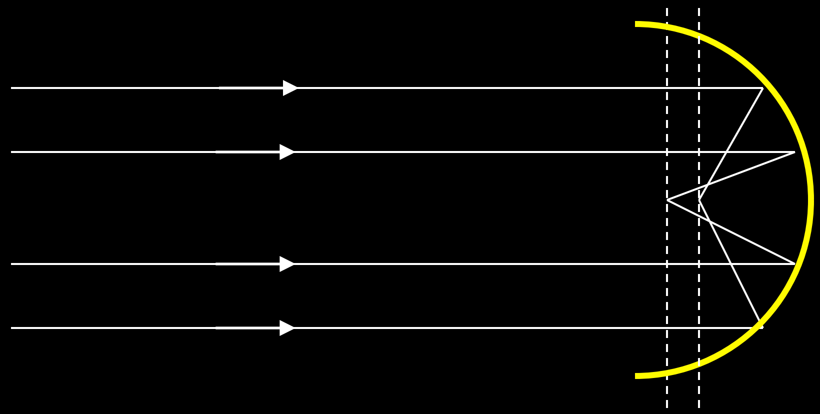
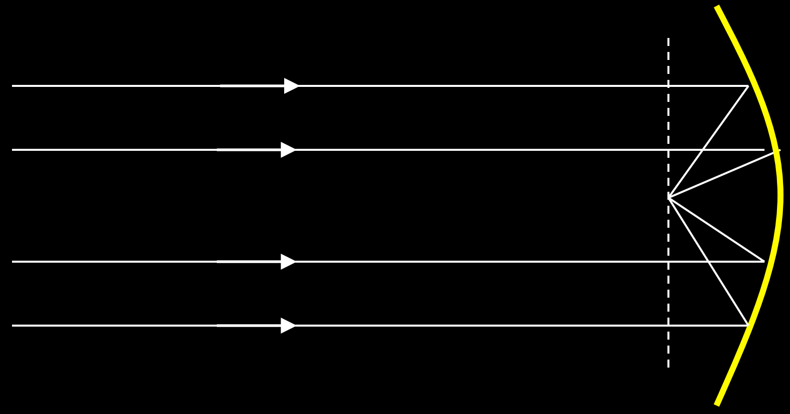
Problems with reflectors

spherical aberration



removed if mirror is parabolic



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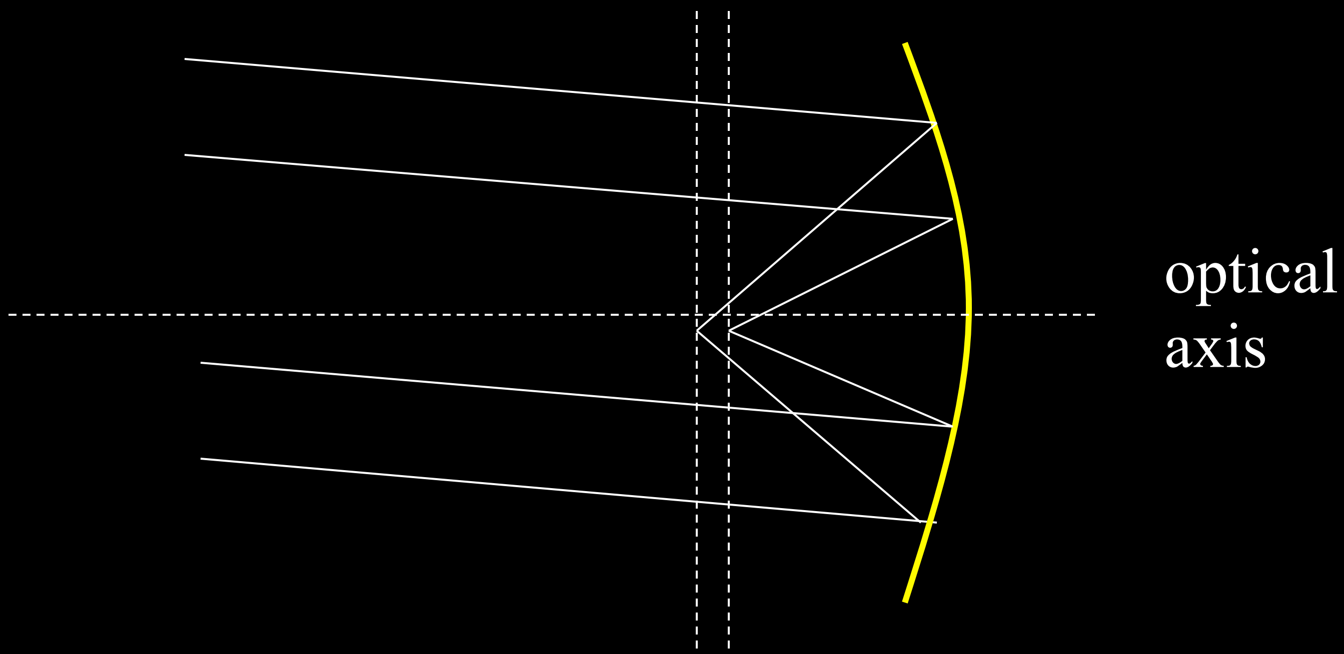
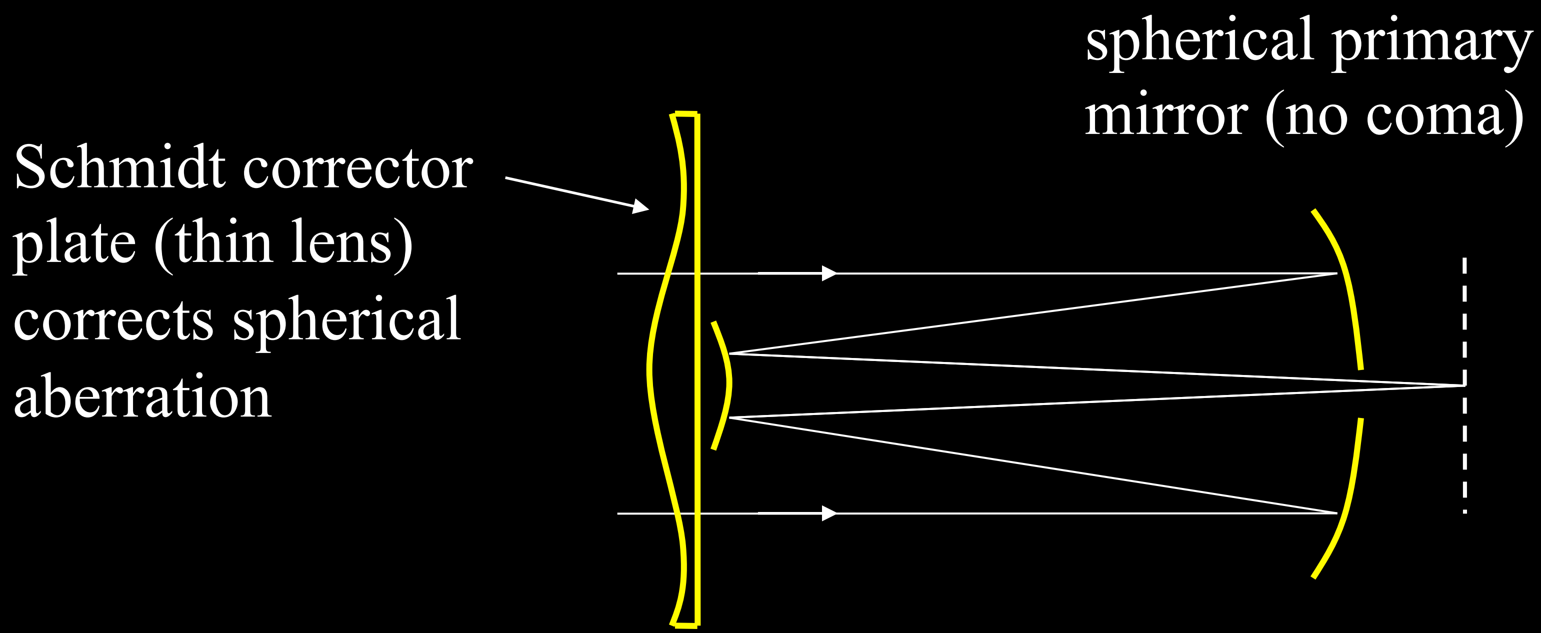
Coma



Parabolic mirror does not focus in single plane if incident rays not parallel to optical axis

Schmidt-Cassegrain reflector



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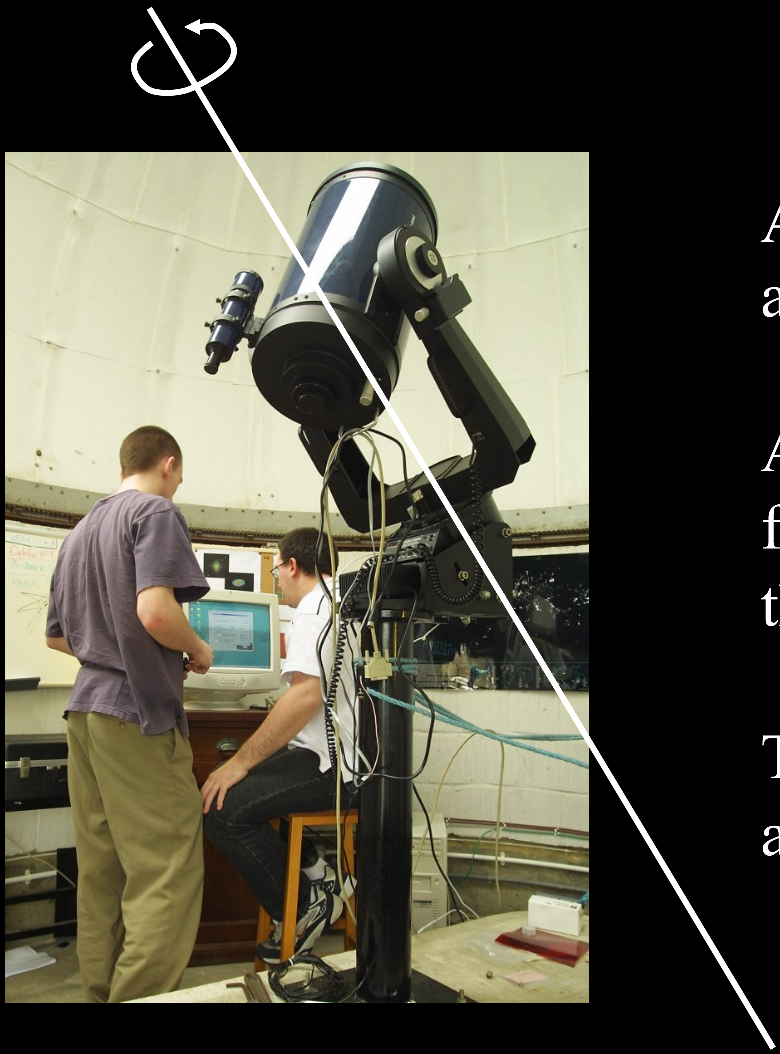
Equatorial mount



Axis of fork parallel to axis of the earth.

As earth rotates to the east, fork rotates to the west at the same rate.

Telescope stays pointing at a fixed direction in space.

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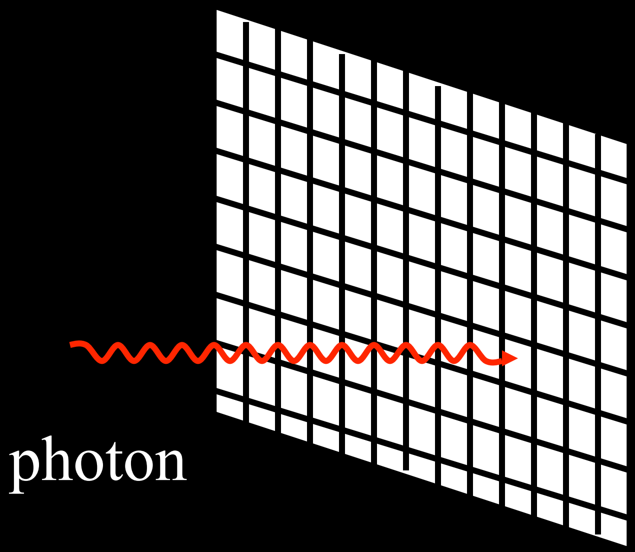
Detecting the light



Charge coupled device (CCD)

E.g. 480 x 640 pixels
on a 3 mm x 4 mm silicon chip

Photon liberates e^-,
stored until readout.

10 to 20 times more sensitive
than photographic film

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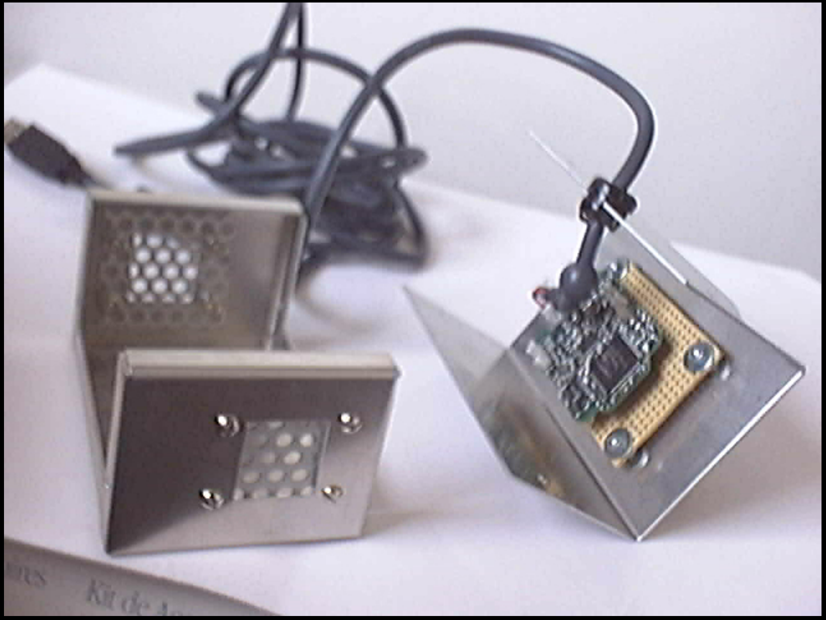
QuickCam CCD



Solar filter

AstroSolar film from Baader Planetarium GmbH

Rejects all but ~10^{-5} of incident light

The diffraction limit

Diffraction places a lower limit on smallest resolvable angle

$$\theta = 1.22 \frac{\lambda}{D}$$

wavelength of light (λ)

diameter of objective mirror (D)

E.g. $\lambda = 500$ nm, $D = 25$ cm:

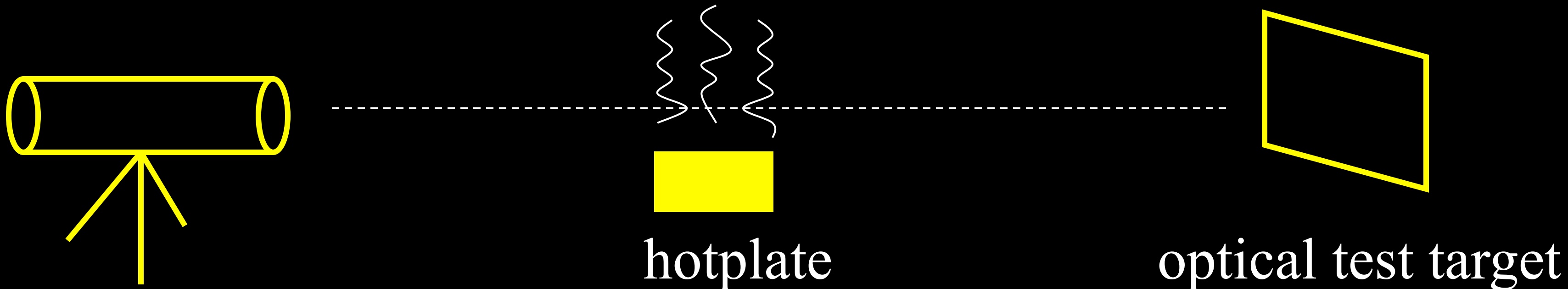
$$\theta = 1.22 \times \frac{500 \times 10^{-9}\ \text{m}}{25 \times 10^{-2}\ \text{m}} \times \frac{180^\circ}{\pi} \times \frac{3600''}{1^\circ} = 0.5''$$

Seeing

Turbulence in atmosphere typically limits resolution to > 1 ″

- optimize site (high mountain on an island, e.g., Hawaii)
- Hubble Space Telescope
- adaptive optics

Try this:



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VT observations at RHUL

Two telescope/CCD systems

Monitoring the transit

Timing of video streams synchronized to about 0.1 s

Not all of sun visible in scope, so we had to work out where to look for ingress.

7:44:58.2

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7:44:58.3

7:44:58.4

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7:44:58.5

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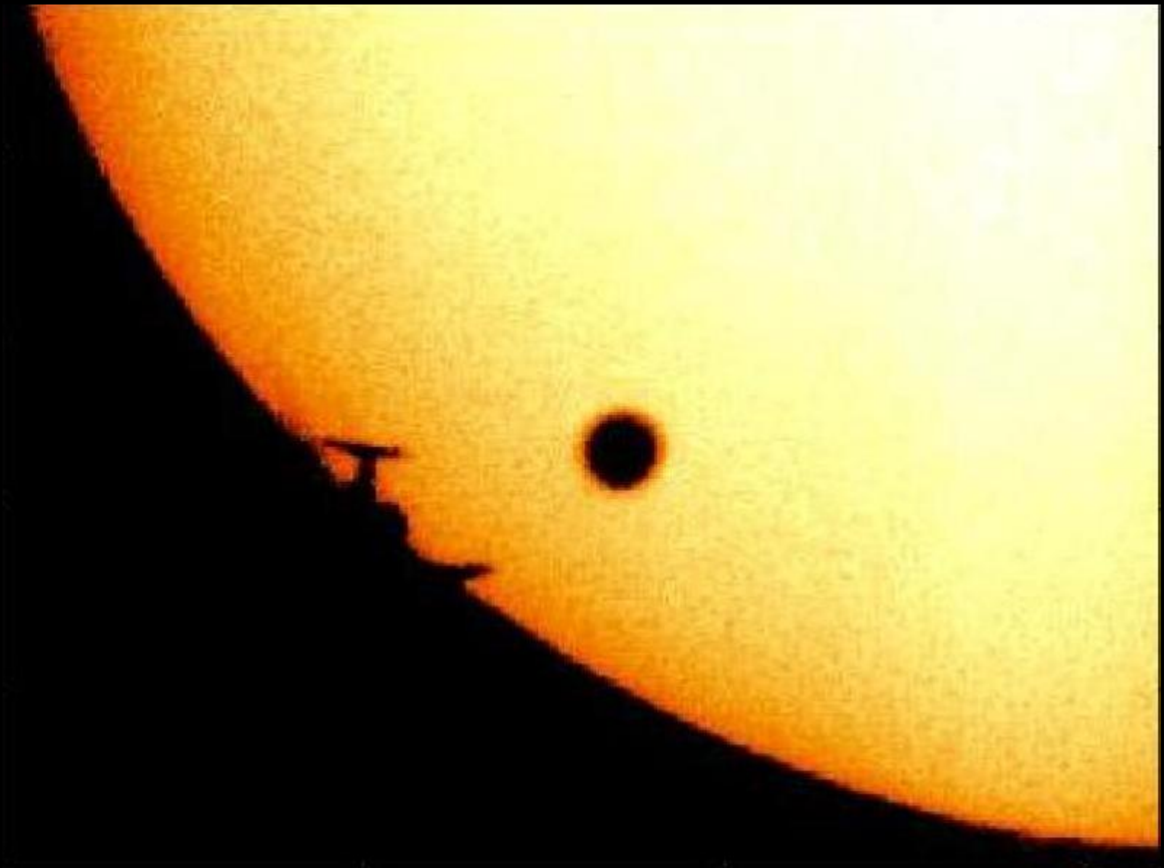
7:44:58.6



7:44:58.7

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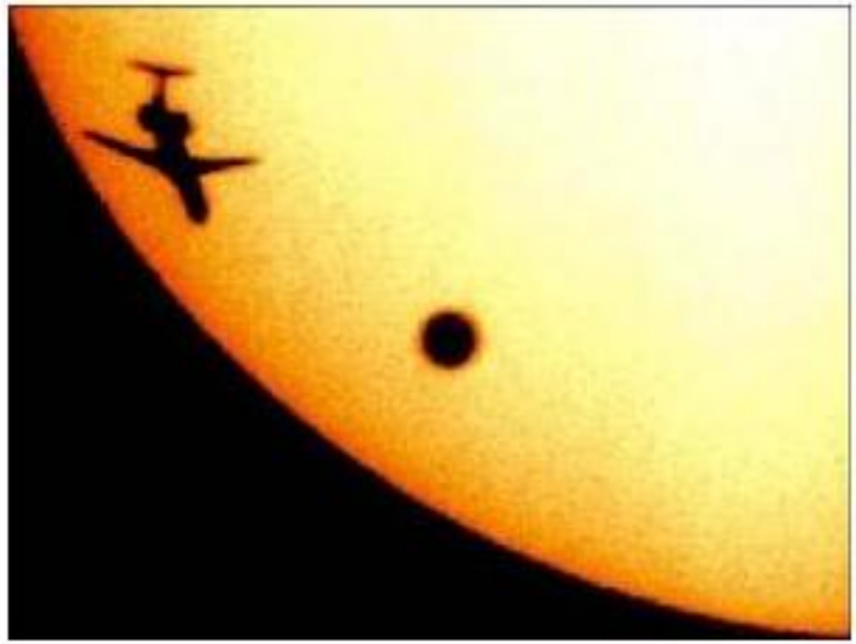
The Jet

GuardianUnlimited index ›

09.06.04: The transit of Venus

Britain
An aircraft flies across the field of view at the Royal Holloway observatory as Venus is in transit.

Photograph: Royal Holloway, University of London
[Royal Holloway, Department of Physics]
[Royal Holloway: more on Venus transit]



Analysing the video data

Java program written for analysis of video data (ImageJ plugin)

JMF_Edge_Analyzer.java - WordPad

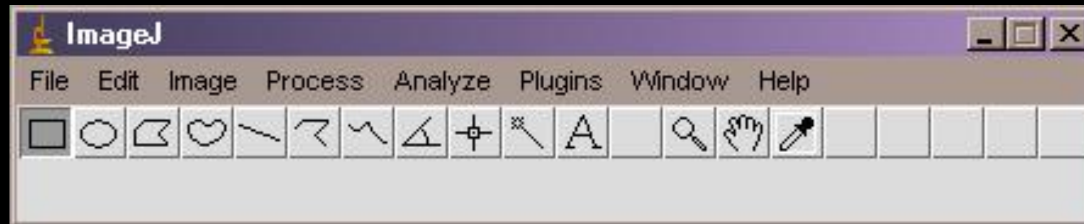
File Edit View Insert Format Help

```
// loop over frames

    for (int i=0;i<totalFrames; i++) {

      int currentFrame = fpc.mapTimeToFrame(p.getMediaTime());
      IJ.showStatus((currentFrame+1)+"/"+totalFrames);
      IJ.showProgress((double)(currentFrame+1)/totalFrames);

      System.out.println("frame " + currentFrame);
      if ( saveData ) {
        out.println("# frame " + currentFrame);
      }

//  Analyze frame here.
//  Unpack pixel contents into array; reorder vertical direction to increase upwards.

      Image img = frameConverter.createImage(frame);
      ImageProcessor ip = new ColorProcessor(img);
      int ncol = ip.getWidth();
      int nrow = ip.getHeight();
      int[] pixels = (int[])ip.getPixels();
      int[][] intensity = new int[nrow][ncol];
      int c, r, g, b;
      for(int k=0; k<ncol; k++){
        for (int j=0; j<nrow; j++){
          int l = j*ncol + k;
          c = pixels[l];
          r = (c&0xff0000)>>16;
          g = (c&0xff00)>>8;
          b = c&0xff;
          intensity[nrow-j-1][k] = r + g + b;
        }
      }
```

For Help, press F1

Locating Sun and Venus frame by frame

Analyse each frame of video separately.



Edges are detected where the image intensity changes rapidly.
Coordinates written to data file for further analysis.

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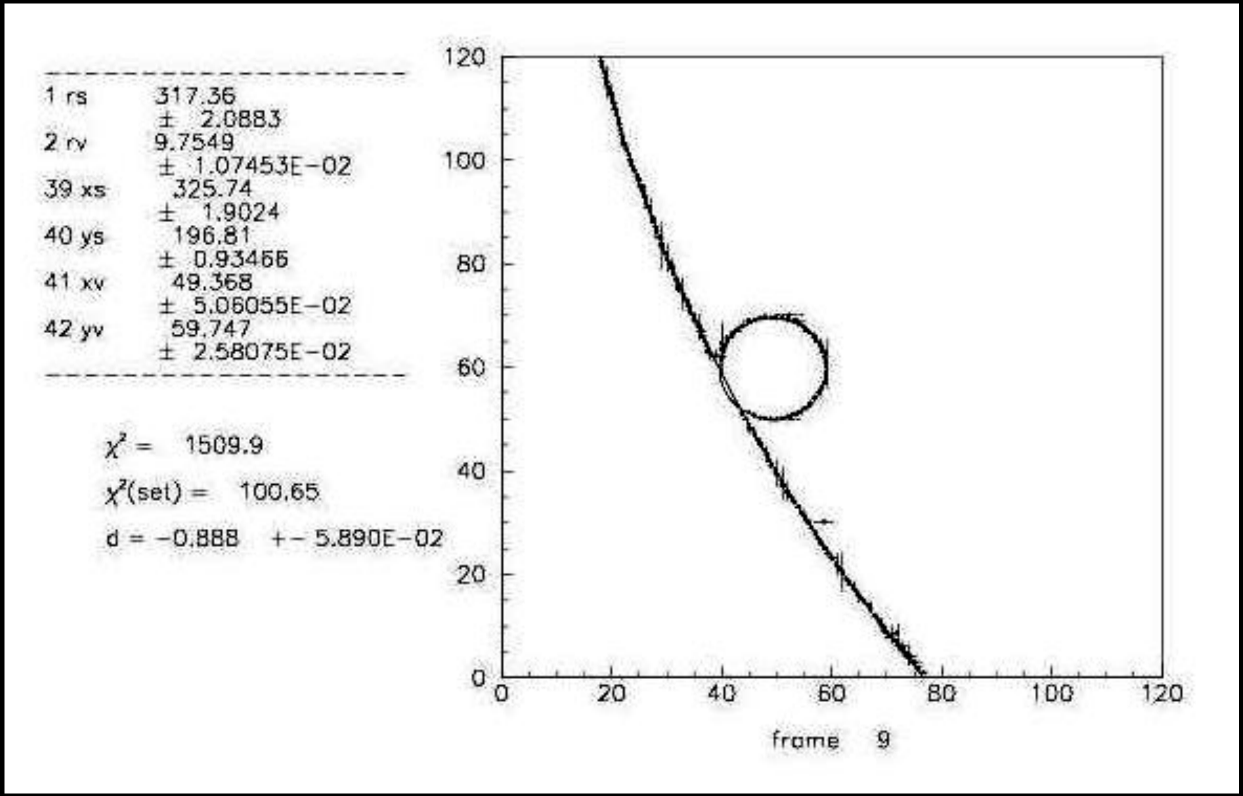
Determining position of Sun and Venus

Apply statistical procedure to estimate separation of Sun and Venus frame by frame.



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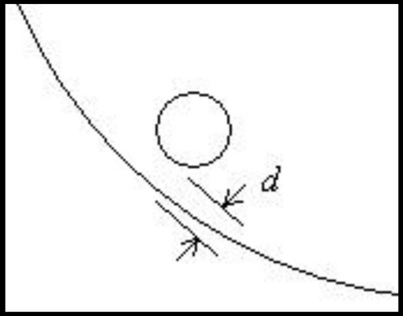
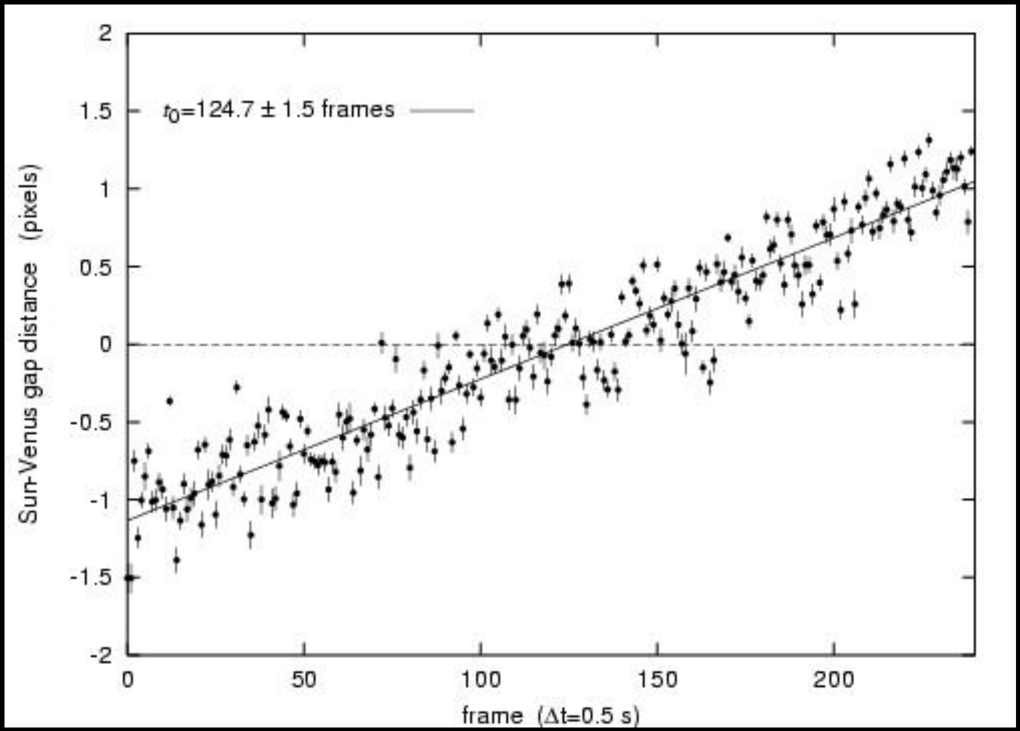
Sun-Venus gap versus time

Sun-Venus gap distance in two-minute interval about ingress (internal contact).





Time of internal contact from fitted line:

t_2 = 5:39:42.6 ±0.8 UT

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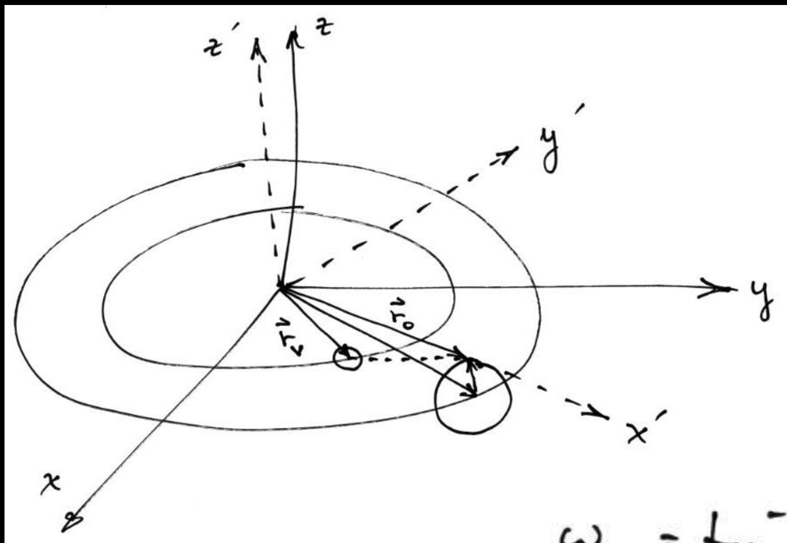
Calculating Sun-Venus gap vs time



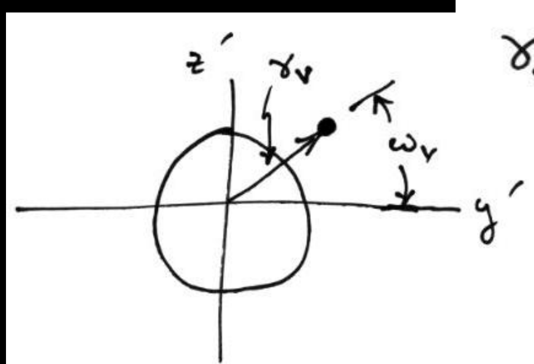
$$\hat{x}' = \cos\lambda_0\,\hat{x} + \sin\lambda_0\,\hat{y}$$

$$\hat{y}' = -\sin\lambda_0\,\hat{x} + \cos\lambda_0\,\hat{y}$$

$$\hat{z}' = \cos\beta_0\,\hat{z} - \sin\beta_0\,\hat{x}'$$

$$\omega_v = \tan^{-1}\frac{\vec{\delta}\cdot\hat{z}'}{\hat{\delta}\cdot\hat{y}'}$$

$$\gamma_v = \cos^{-1}\left[\frac{(\vec{r}_0-\vec{r}_v)\cdot\vec{r}_0}{|\vec{r}_0-\vec{r}_v|\,|\vec{r}_0|}\right]$$



Ongoing effort!

Goal is to adjust AU's value so that calculation and data agree.

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Observing the Sun

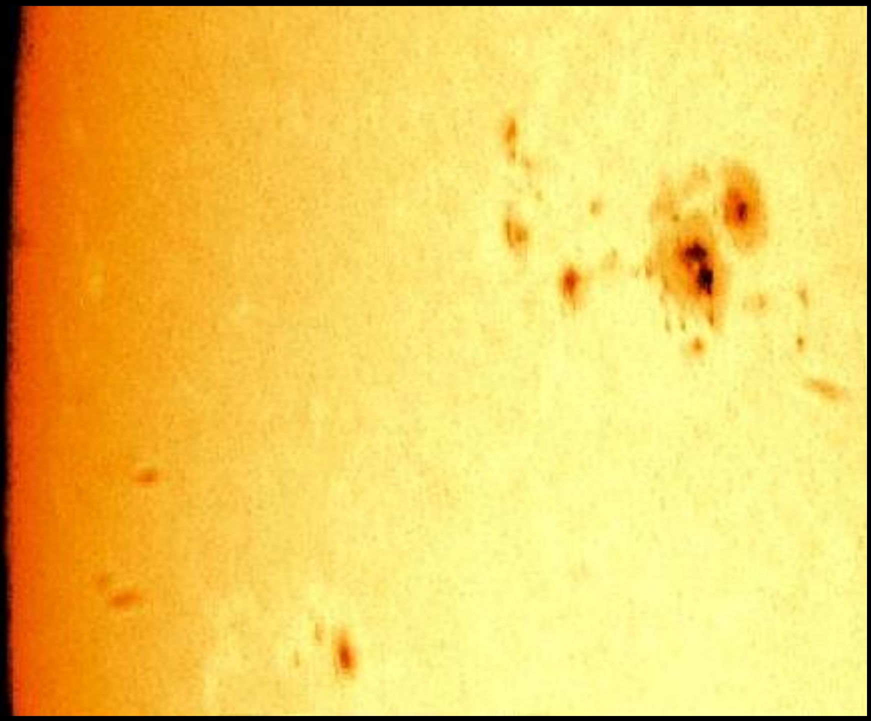

Photo B. Scott

No night time staff needed!

Crucial safety issue: proper filter.

Lots of interesting surface features: sunspots, solar flares, etc.

Limb darkening gives information on temperature profile.

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The true colour of the Sun?

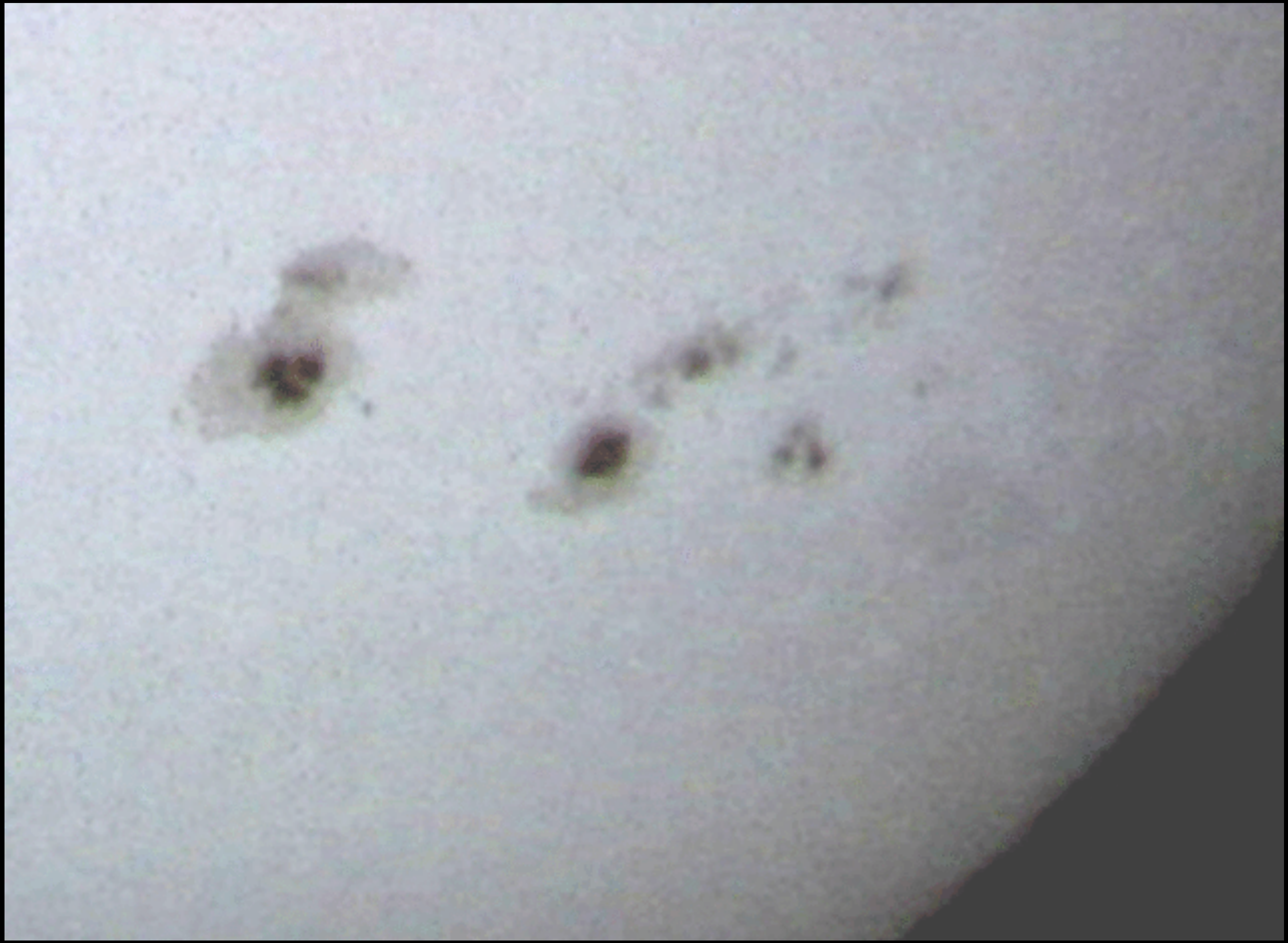

Photo GDC

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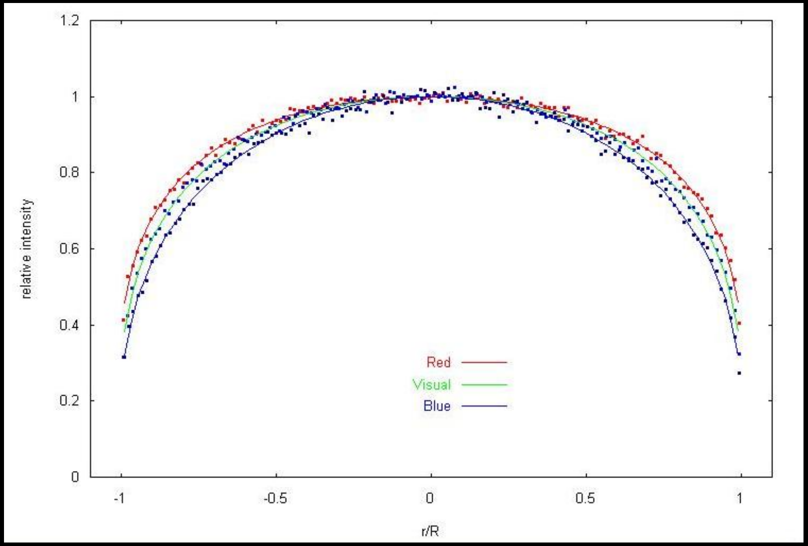
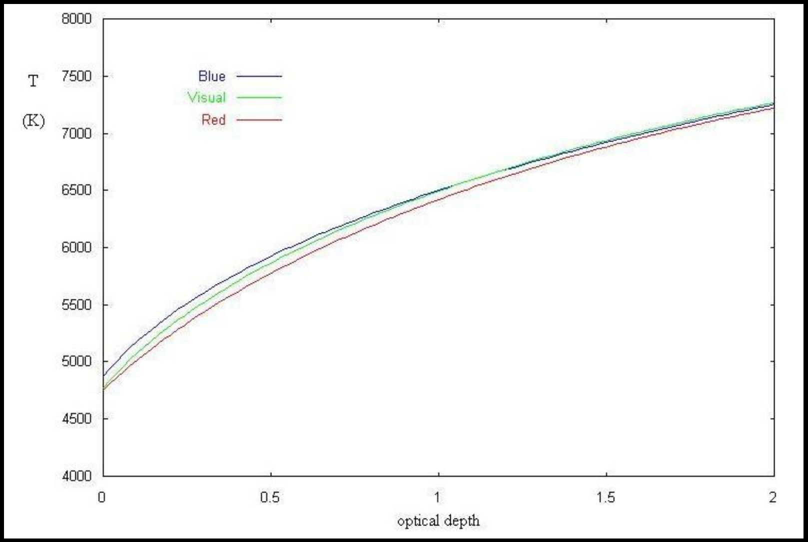
Analysis of solar limb darkening





Measurements of sun’s intensity as a function of position on disc give temperature as a function of depth.

Photo GDC

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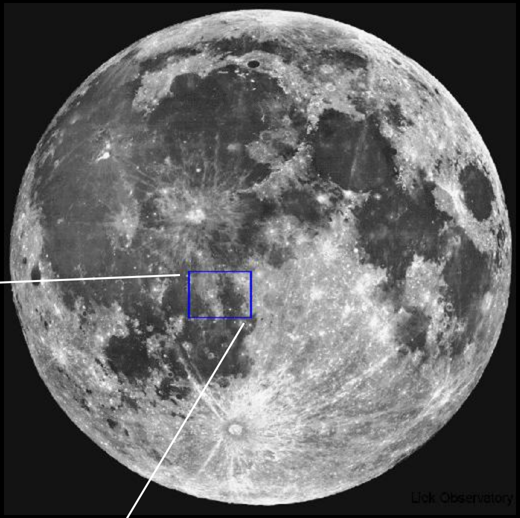
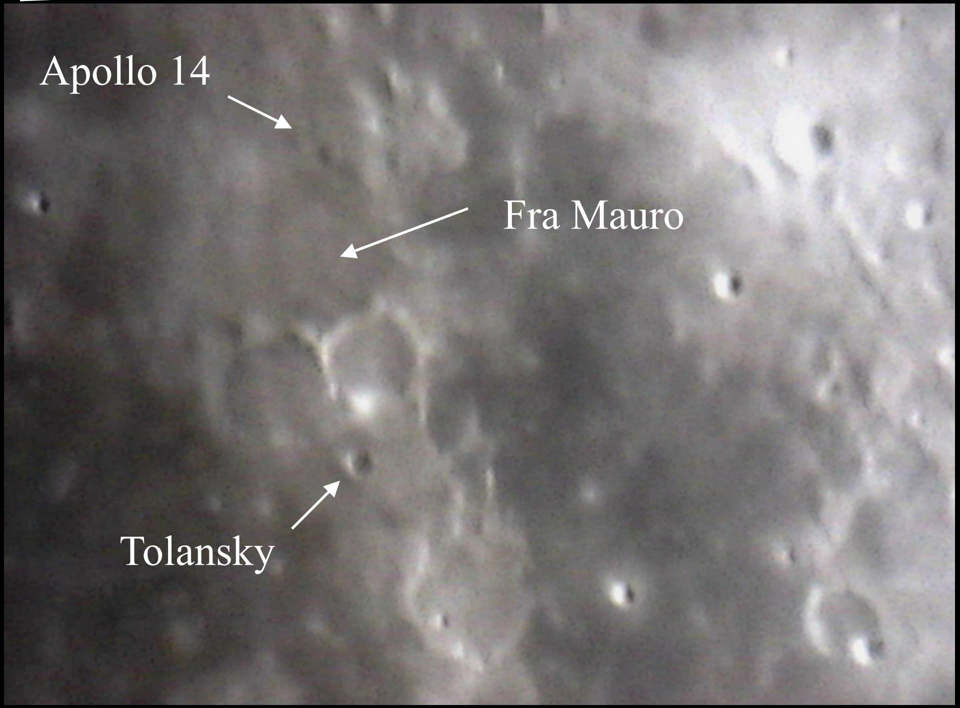
Tolansky Crater





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Galaxies

Whirlpool galaxy M51

Difficult to see owing to light pollution but long time exposure with CCD effectively allows one to subtract the background.

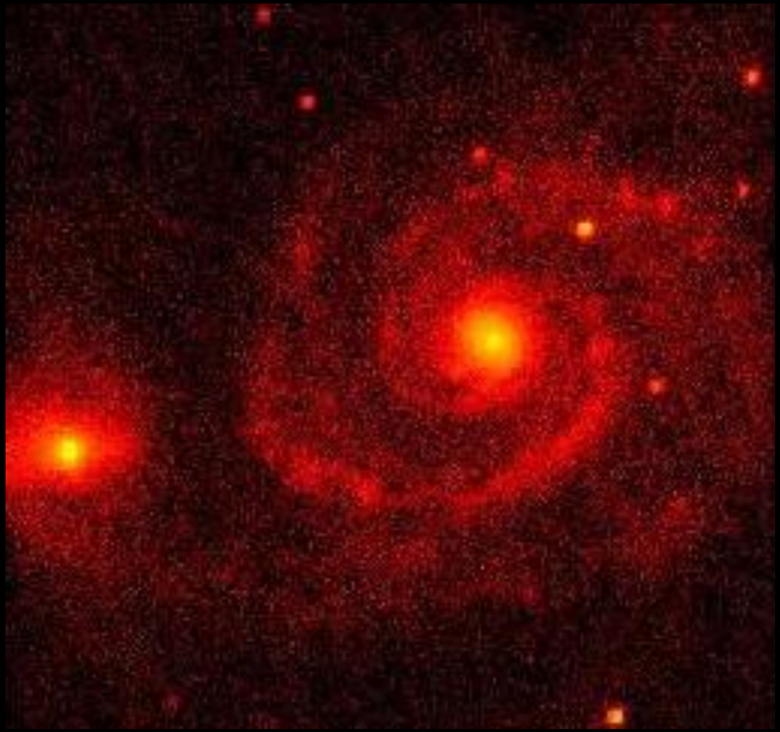

Photo R. Emerson

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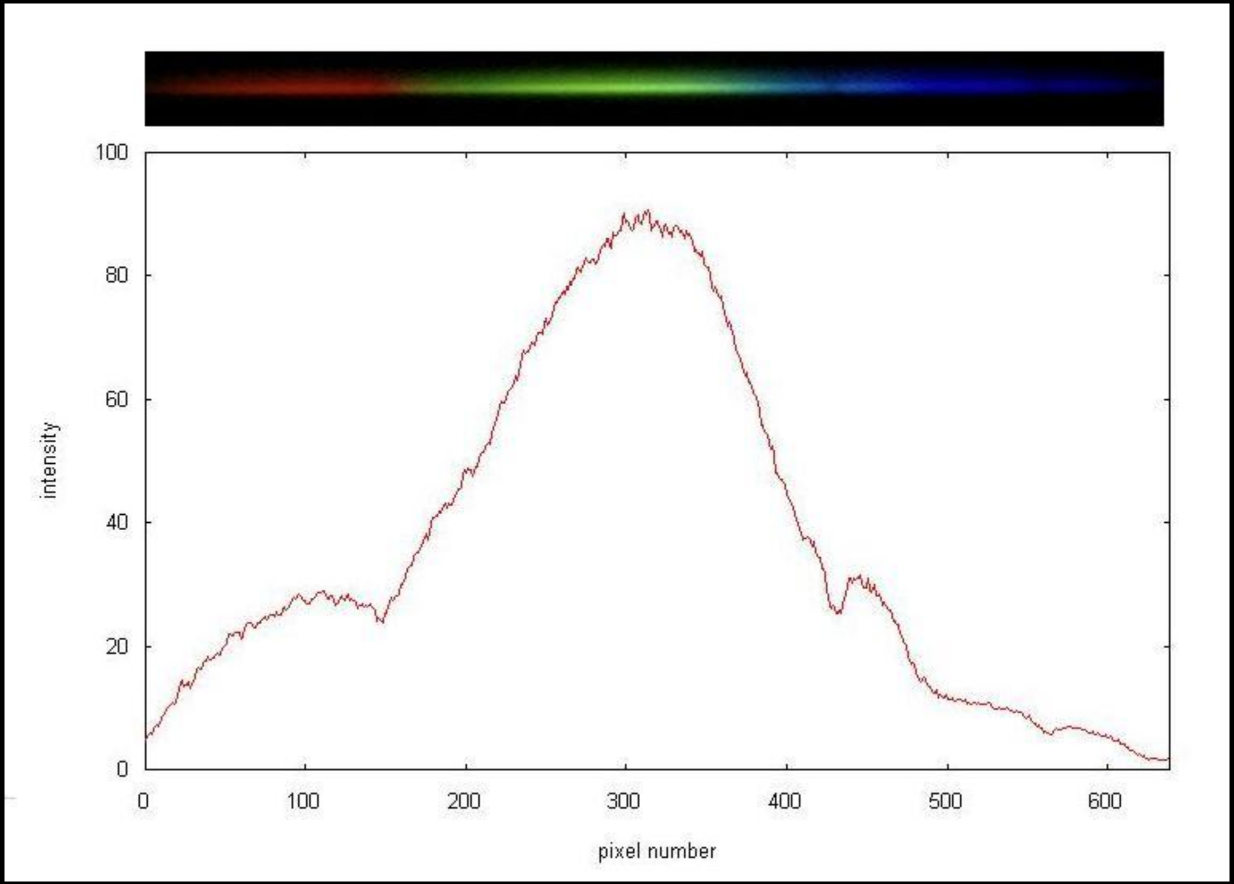
Colour and spectroscopy



Balmer absorption lines in Vega

Comets

Icy bodies (~dirty snowballs), mixtures of dust and ices (water, $C0_2$, ammonia)

Short period (<200 yr) from Kuiper Belt (30 to 100 AU), in plane of Solar System.

Long period (>200 yr) from Oort Cloud, ~50,000 AU, isotropic.

Nucleus of Comet Halley by Giotto spacecraft.

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Comet Machholz

13 January 2005
Photo M. George
RHUL Physics

Motion ~5”/min

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Asteroids

Rocky bodies mainly
found between
orbits of Mars and Jupiter
(the asteroid belt).

Size ranges from dust
grains to small planetoids
(930 km diameter for
Ceres).

Gaspra: 19 x 12 x 11 km

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Wrapping up

We can ask a lot of questions about the solar system:

How big is it?
What's it made of?
How did it form?
Are there other solar systems?

Today I've really only touched on the first of these points.

The Venus transit was a nice example of an astronomical event that led to student projects, but it's over. Now try e.g.

comets, asteroids, other transits (Hawaii trip in 2012?)

Equipment requirements in hundreds, not thousands of GBP;

lots of good free software, e.g., ImageJ, fv, CLEA