Experiment 244: Hubble space telescope

Aim

The purpose of this experiment is to analyze some Hubble Space Telescope (HST) images to identify the change in luminosity of a star during a gravitational microlensing event.

Reference

1. Perryman, M., *The Exoplanet Handbook*. Cambridge University Press, 2011

2. Microlensing Observations in Astrophysics (MOA) website,
`http://www.phys.canterbury.ac.nz/moa/`

Useful Data

Name	Symbol	Value
Astronomical Unit	AU	1.496×10^{11} m
Gravitational Constant	G	6.6742×10^{-11} m^3 kg^{-1} s^{-2}
Light Year	ly	9.4605×10^{15} m
Mass of Earth	$M_\oplus$	5.97219×10^{24} kg
Parsec	pc	3.0857×10^{16} m
Solar Mass	$M_\odot$	1.989×10^{30} kg
Solar Luminosity	$L_\odot$	3.84×10^{26} W
Speed of Light	c	2.99792458×10^{8} m s^{-1}

Introduction

Microlensing is the time-dependent magnification of a background object, usually a star, by the gravitational field of a foreground object, usually another star. The light from the background star is split into two or more separate images, which cannot be resolved by normal telescopes. The only observed effect is an overall magnification of the background (source) star to a maximum, and then a return to the baseline intensity as the source, lens and observer become temporarily aligned. For microlensing where the source and lens are in the Galaxy, events have a typical duration of around 30 days.

MOA-2007-BLG-379, or MB07379 for short, was the 379th gravitational microlensing event found by the MOA group (Microlensing Observations in Astrophysics) in 2007. Several hundred images of the event were taken from observatories in New Zealand, South Africa, Hawaii, Chile, Australia and California. In addition, 20 images were taken by the Hubble Space Telescope (HST). In this experiment, you will analyse 10 HST images that were taken in the I passband, two on 8 October 2007 (epoch 1) and eight on 4 May 2008 (epoch 2). Aperture photometry will be carried out using supplied software.

Two of the HST images are shown in Figure 2, one from epoch 1 and one from epoch 2. MB07379 is arrowed on both images. It is apparent that the luminosity of MB07379 decreased significantly between the two epochs. The decrease can be used to help identify the lens of MB07379. A finder chart of the event by MOA is also shown below, in Figure 3. This was taken in 2006 when the magnification was unity.

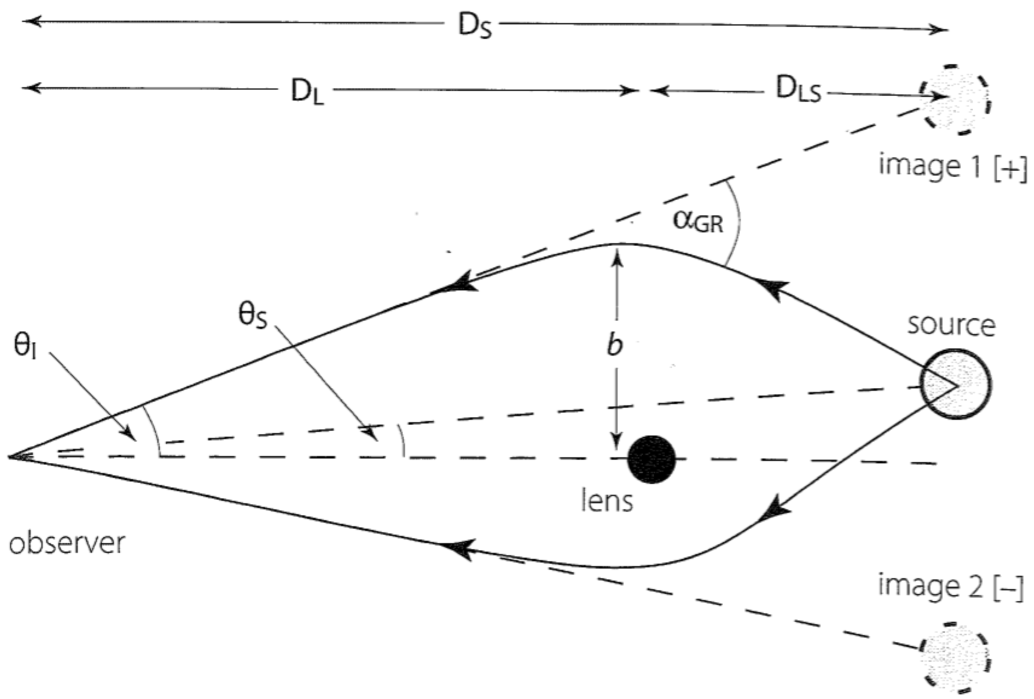


Figure 1: Geometry of a microlensing event. From Perryman (2011).

Theory

Microlensing Details Figure 1 shows the geometry of a microlensing event. Light from a background source star is deflected through an angle α_{GR} by the gravitational potential of a foreground lens object. The source star therefore appears at a different position to where it would have been seen had the lens object not deflected the light from the source. For a single point-like lens mass, the light from the source is in general split into two images of the source star, shown in Fig. 1 as images 1 and 2. The *lens equation* describes the mapping between the *source plane* and the *lens plane.*

D_S and D_L are the distances from the observer to the source and lens respectively. D_{LS} is the distance between the lens and the source and, for microlensing in the Galaxy, $D_{LS} = D_S - D_L$[1]. The angle subtended at the observer between the source star and the lens object is θ_S, the angle subtended at the observer between the lens and the image of the source star is θ_I. b is the position of the image in the lens plane.

The lens equation can be written as:

$$\theta_I^2 - \theta_S\theta_I - \theta_E^2 = 0 \tag{1}$$

where θ_E is the angular Einstein ring radius:

$$\theta_E = \left(2Rs\frac{D_{LS}}{D_S D_L}\right)^{1/2} \tag{2}$$

where R_s is the Schwarzschild radius: $R_s = 2GM_L/c^2$ and M_L is the mass of the lens object, G is the gravitational constant and c is the speed of light.

A convenient rescaling of the lens equation is to take $r_s \equiv \theta_S/\theta_E$ and $r \equiv \theta_I/\theta_E$.

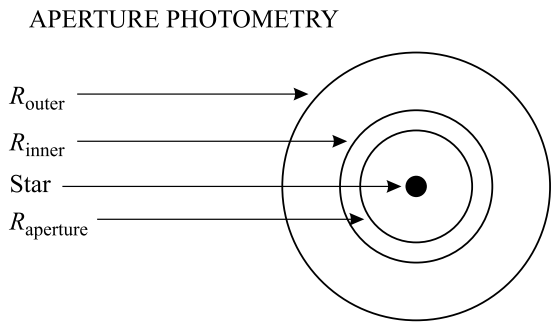
$$r^2 - r_s r - 1 = 0 \tag{3}$$

Solving Eq. 3 for r gives us the angular positions of the two images of the source, in units of the angular Einstein ring radius.

[1]Note, this is not true when D_S and D_L are on cosmological scales.

Aperture Photometry Aperture photometry is a technique for measuring the brightness of objects in astronomical images. A point source of light – such as a star – will not usually appear as a single bright pixel on a digital image. The light from the object will be spread out over a patch of pixels due to the effect of the telescope and camera optics, the effect of any turbulent atmosphere, or for many other reasons. The goal of aperture photometry is to collect all the light from the object, and subtract the background light from the surrounding sky.

In order to perform aperture photometry of an object, we define three circles centred on the object. The diagram below shows the three radii that need to be set to perform aperture photometry — R_{outer}, R_{inner} and R_{aperture}. R_{aperture} is the radius within which the values in all pixels are summed to determine the luminosity of the star. R_{outer} and R_{inner} define an annulus for the subtraction of the sky background. R_{inner} needs to be large enough to allow for point spread function changes across the field of view. R_{outer} and R_{inner} need to be large enough to measure the sky accurately, but small enough to exclude neighbouring stars. Appropriate values of the three radii can be found by demanding that comparison stars have the same measured luminosities at the two epochs.



Equatorial Co-ordinates Astronomers use a set of co-ordinates to map the celestial sphere. These co-ordinates are analogous to latitude and longitude values that are used to map positions on the surface of the Earth. Moving from the north pole on Earth to the south pole, we move from positive to negative values of latitude. Similarly, moving from the north celestial pole (the point on the sky directly above the north pole on Earth) to the south celestial pole, we move from positive to negative values of *declination.* Moving east from the Greenwich meridian, which is defined as zero degrees longitude, we move to larger values of longitude. Similarly, *right ascension* is the name given to the direction on the sky analogous to terrestrial longitude. Note that while the equatorial co-ordinate system is defined with respect to the Earth's poles and equator, it remains fixed on the sky – it doesn't rotate with the Earth.

Like latitude, a celestial object's declination, δ is in the range $[-90°, 90°]$. Right ascension, α, is either measured in hours, minutes and seconds – e.g. 18:05:33.0 – or in degrees from 0 to 360 degrees.

The angular distance, d, between two equatorial co-ordinates (α_1, δ_1) and (α_2, δ_2) is

$$\cos d = \sin \delta_1 \sin \delta_2 + \cos \delta_1 \cos \delta_2 \cos(\alpha_1 - \alpha_2) \tag{4}$$

The images listed in the table below are loaded onto the PCs in the central room in the stage I laboratory on the ground floor. They are in files labeled `visit0102` (epoch 1, on 8 Oct 2007) and `visit0304` (epoch 2, on 4 May 2008). Also loaded on the PCs is a piece of software for carrying out photometry, called Aperture Photometry Tool, or APT for short.

Image	Date	Start	Stop	Exposure	Instrument	Filter
UA550101M	8 Oct 07	12:49:16	12:51:56	160.000	WFPC2	F814W
UA550102M	8 Oct 07	12:53:16	12:55:56	160.000	WFPC2	F814W
UA550302M	4 May 08	18:18:17	18:20:57	160.000	WFPC2	F814W
UA550303M	4 May 08	18:25:17	18:27:57	160.000	WFPC2	F814W
UA550304M	4 May 08	18:29:17	18:31:57	160.000	WFPC2	F814W
UA550305M	4 May 08	18:36:17	18:38:57	160.000	WFPC2	F814W
UA550306M	4 May 08	18:40:17	18:42:57	160.000	WFPC2	F814W
UA550307M	4 May 08	18:47:17	18:49:57	160.000	WFPC2	F814W
UA550308M	4 May 08	18:51:17	18:53:57	160.000	WFPC2	F814W

Procedure

(1) Identify stars on the MOA image with brighter ones on one of the HST images. Note the clearly superior quality of the space-based images.

(2) Open and watch the screen-cast entitled "Using APT in Experiment 244"[2]. Re-run the screen-cast as often as required, pausing it as necessary if you want to follow along with the instructions as you perform the tasks below.

(3) Start the APT software if you haven't already[3]. Open[4] image UA550101M and identify the location of event MB07379 using the finding charts in Figure 2. Make a note of the right ascension and declination of the event.

(4) Use the right ascensions and declinations given by APT to determine the pixel size on the sky (in arcseconds per pixel) of the HST WFPC2 camera.

(5) Use APT to carry out aperture photometry on MB07379 on the two epoch 1 images, and also on at least two images of MB07379 from epoch 2. Note that the orientation of the HST was flipped 180° between the two epochs.

(6) Carry out aperture photometry (see procedure as above) on at least three nearby, comparison, uncrowded stars of similar luminosity on the same images. Confirm that the luminosities of the comparison stars did not change appreciably between the two epochs.

(7) Use your results to determine the ratio of the luminosities of MB07379 at epoch 1 to epoch 2.

(8) Estimate one standard deviation limits on the luminosity ratio.

(9) Write up your results, including answers to the questions below.

Questions

Can HST resolve the separate images in a microlensing event? Hint: work out an expression for the angle between images from the lens equation, in units of the angular Einstein ring radius. Assume that the lens and source are closely aligned. Compare your value with your computed resolution for HST. Assume a typical microlensing event with $D_L = 6$ kpc, $D_S = 8$ kpc and $M_L = 0.3 M_\odot$.

[2]Start Menu → All Programs → Physics → Aperture Photometry Tool → Using_APT_in_Exp_244.ogv
[3]Start Menu → All Programs → Physics → Aperture Photometry Tool → Aperture Photometry Tool
[4]C:\Program Files (x86)\Aperture Photometry Tool\hstimages\HST Images\

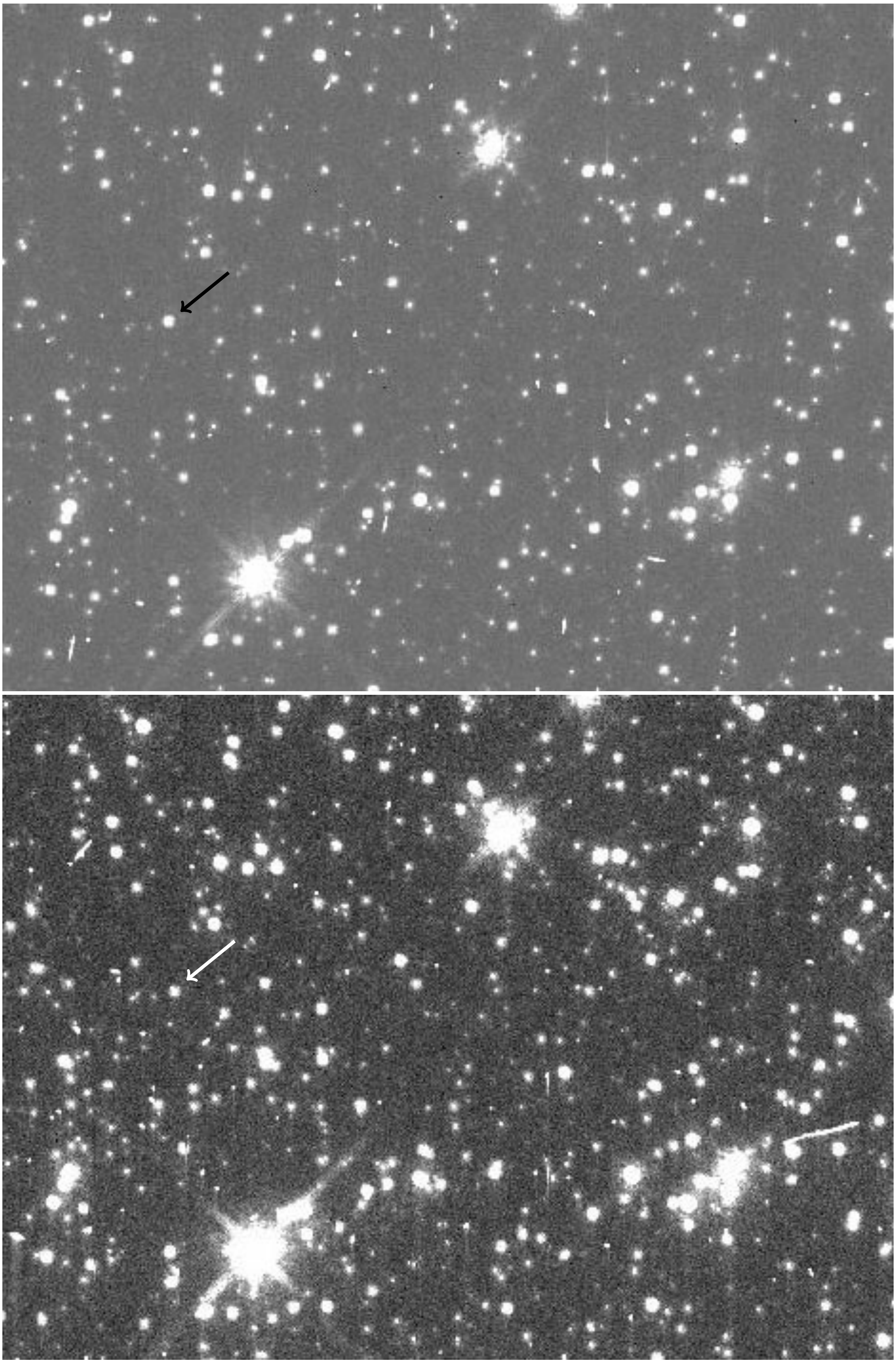


Figure 2: Top: HST image of MB07379 on epoch 1 (N is 45° below the x-axis, E is 45°. Bottom: HST image of MB07379 on epoch 2. Event MB07379 is indicated with an arrow.

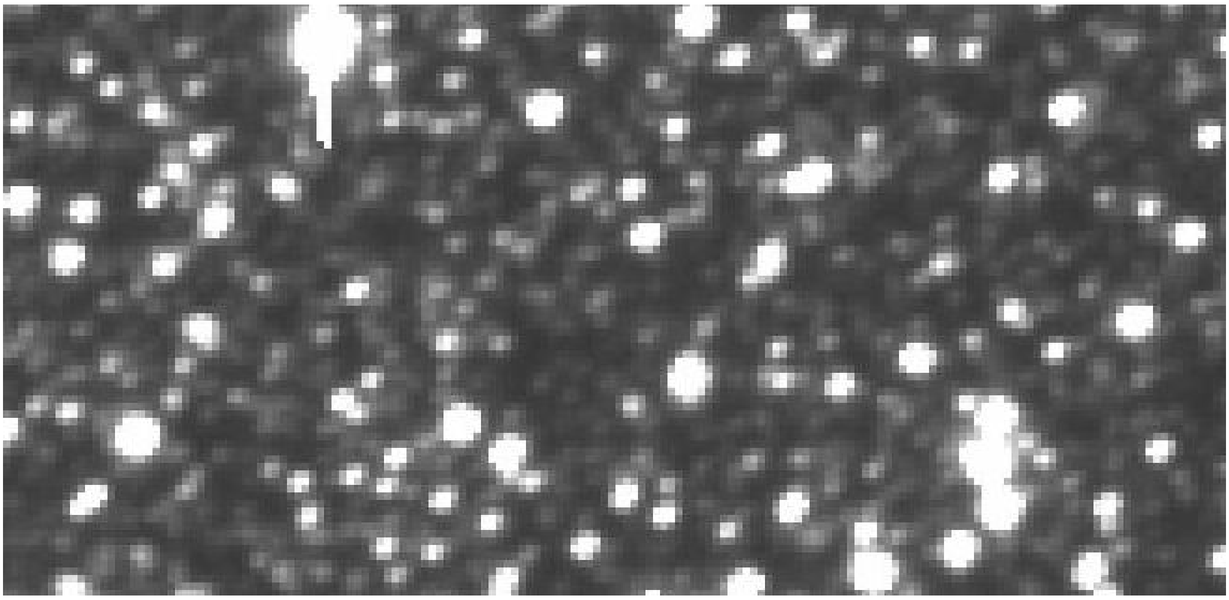


Figure 3: Finder chart by MOA of MB07379 from 2006 when the magnification was unity. E is up and N is right.

List of Equipment

Images loaded onto the PCs in the central room in the stage I laboratory on the ground floor, with the APT software to analyse them, and a screen-cast explaining how to use the APT software.

Phil Yock
Nicholas Rattenbury
March 2015