MICROlensing Search for EXoplanets

A Gravitational Microlensing Pro-Am Project - Version 5

Updated 2021 November 27

Introduction

This project is still evolving so your participation and comments would be most welcome. You will notice that the required frequency of observations is, typically, every few hours so it should quite easily fit with any other observing program you may be following.

There are likely to be just a handful of targets available at any on time and possibly only one or two which have the potential to detect exoplanets so the amount of observing time that needs to be devoted to this project should not unduly impinge on other observing activities.

The advantage over comet and supernovae hunting is that we do know where to look.

For all things Microlensing please do visit [Microlensing Source](#)

Contents

1.0   What is Gravitational Microlensing?

Gravitational microlensing is an observational effect that was predicted in 1936 by Einstein using his General Theory of Relativity. When one star in the sky appears to pass nearly in front of another, the light rays of the background source star become bent due to the gravitational "attraction" of the foreground star. This star is then a virtual magnifying glass, amplifying the brightness of the background source star, so we refer to the foreground star as the lens star. If the lens star harbours a planetary system, then those planets can also act as lenses, each one producing a short deviation in the brightness of the source - Figure 1.1.
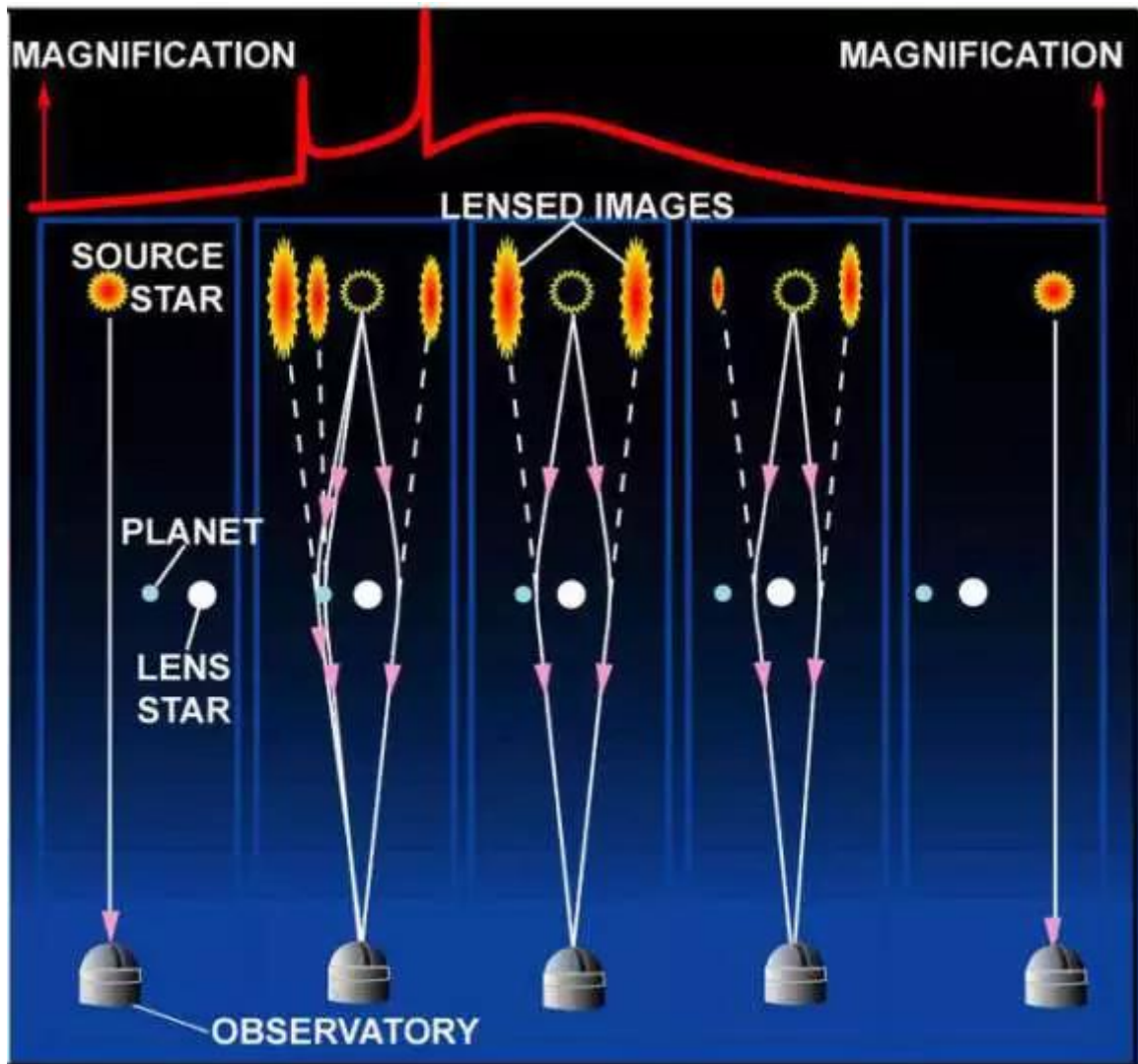
Figure 1.1. Planet detection through microlensing

Thus, we discover the presence of each exoplanet, and measure its mass and separation from its star. This technique will tell us how common Earth-like planets are and will guide the design of future exoplanet imaging missions.

164 planets have been discovered from the ground using this technique (2021 November 26). For updates go to the Exoplanet.eu catalog and select Microlensing in the Detection drop-down box.

The Nancy Grace Roman Space Telescope microlensing survey will detect many more such planets, including smaller mass planets since the planet "spike" will be far more likely to be observed from a space-based platform. This will lead to a statistical census of exoplanets with masses greater than a tenth of the Earth's mass from the outer habitable zone out to free floating planets. The results from the Roman Space Telescope microlensing survey will complement the exoplanet statistics from Kepler, and will provide answers to questions about planet formation, evolution, and the prevalence of planets in the galaxy.

An animation can be viewed at https://svs.gsfc.nasa.gov/20242 from which the above text was taken.

See also;
https://en.wikipedia.org/wiki/Gravitational_microlensing#:~:text=Gravitational%20microlensing%20is%20an%20astronomical,of%20the%20light%20they%20emit

Other objects can mimic lensing events e.g., Be stars, Young Stellar Objects (YSOs), Active Galactic Nuclei (AGNs) AGNs and Quasars (Quasi Stellar Objects, QSOs).
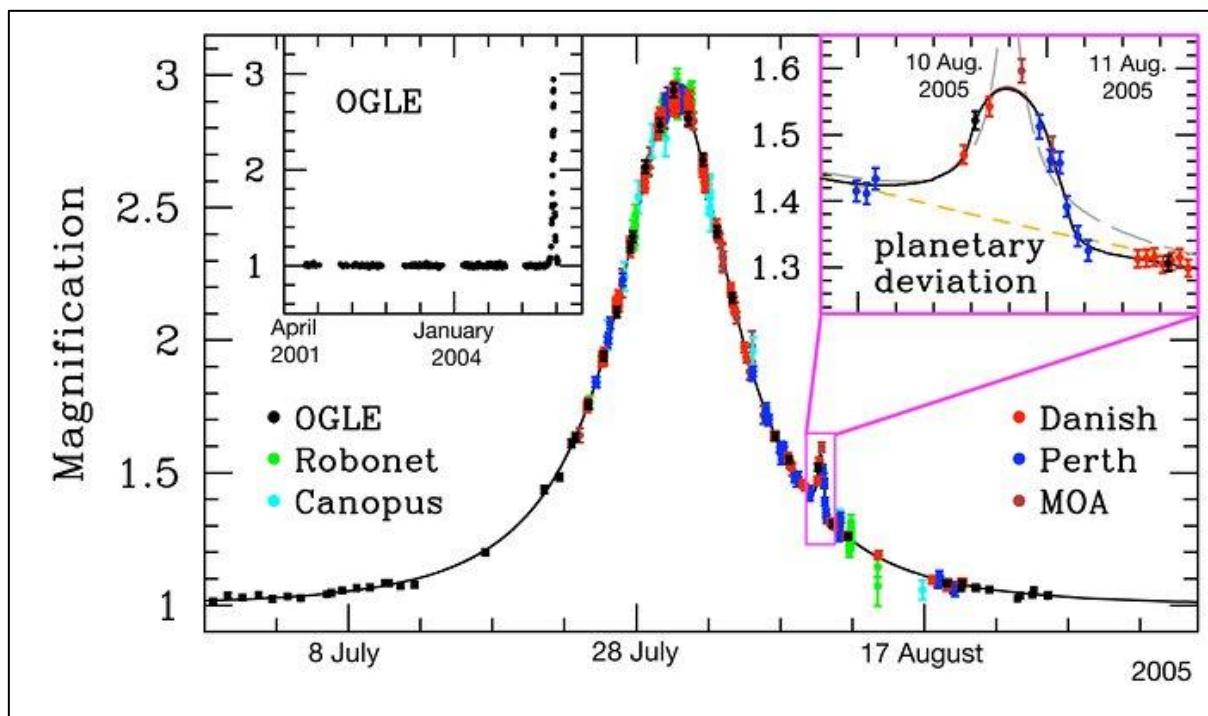
2.0   Detection of exoplanets

Figure 2.1 Light curve of microlensing event OGLE-2005-BLG-390   Credit ESO

Data obtained by PLANET/RoboNet, OGLE, and MOA on the microlensing event OGLE-2005-BLG-390 together with a model light curve, showing the planetary deviation on its falling part, lasting about a day – Figure 2.1. Also shown are best-fitting models with a single lens and a binary source (long-dashed) and a single-source-single-lens light curve (short-dashed). Each point represents the brightness in a single image and the data are colour-coded in order to indicate the telescope: Danish 1.54m at ESO La Silla (Chile), Perth 0.6m (Bickley, Western Australia), Canopus 1.0m (Hobart, Tasmania, Australia), Faulkes North 2.0m (Haleakela, Hawaii, USA), OGLE 1.3m (Las Campanas, Chile), and MOA 1.8m at Mt John Observatory (New Zealand). The regular cycle of colours shows how observing is taken over by the next telescope in turn as the night ends at each site. An enlargement of the planetary deviation is shown as inset in the top right.

Typically, the exoplanet 'blip' (formally known as a planetary anomaly) can last for a few hours (Earth mass planet) to a few days (Jupiter mass planet) – its duration being proportional to the square root of the mass of the planet.

An explanation of how gravitational microlensing can detect exoplanets is at Microlensing Searches for Exoplanets and at The Use of High-Magnification Microlensing Events in Discovering Extrasolar Planets

Of more relevance to amateur observers is the paper ['Detecting Exoplanets by Gravitational Microlensing using a Small Telescope'](#) by Grant Christie

While not strictly exoplanets, free-floating or rogue planets have been discovered using gravitational microlensing. A list can be seen at https://en.wikipedia.org/wiki/Rogue_planet If the lens were a black hole, we would in principle be able to detect a planet orbiting a black hole as a planetary binary lens event.

3.0   The Project
3.1   How did we get into this?
In 2021 January we were approached by Dr. Siegfried Vanaverbeke he commented 'I have viewed your webpage on the relatively new exoplanets section of the BAA. I see that gravitational microlensing is listed as one of the possible interests of the section. Cambridge University has been actively involved in Gaia alerts, a project to follow up candidate gravitational microlensing events and other transients – [project webpage](#) We have observed some objects from astrolab IRIS observatory in Ypres, but I think some coordination with other interested observers would be welcome. I don't know many BAA members are already involved or would be willing to do so'.

If you are wondering about the title of the webpage Lukasz Wyrzykowski notes 'We are trying to cover broad science cases and are not limited to black holes - that was just a catchy title to attract attention'.

The rest of this document describes where we are and so your involvement in this project would be most welcome.

3.2   Project overview

The flowchart, Figure 3.2.1, gives an overview of the project from the point of view of both coordinator and observers.
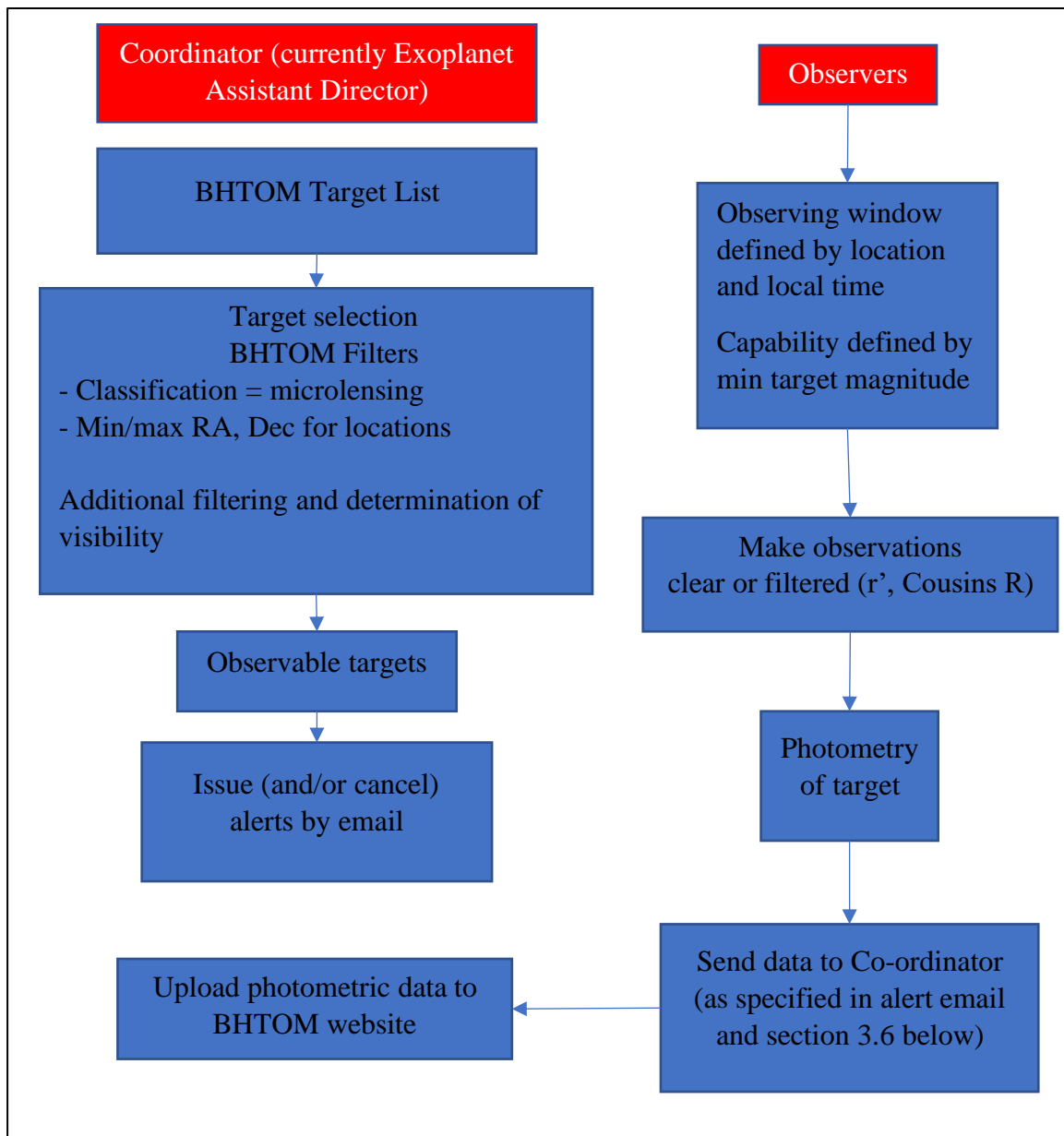

Figure 3.2.1 Project overview

Please note that alerts will be issued fortnightly and, by following the process shown in Figure 3.2.1, there is no need to register your observatory with BHTOM. At present this is the easier route to log observations and allows a record to be kept by the BAA.

3.3 Target selection

Observers will be provided with a (very short) list of targets via email so need not go through this activity themselves.

The various surveys produce very large numbers of transient events only some of which may be exoplanet related thus target selection and follow-up observations are essential for this project.

The BHTOM target list is updated every Monday but there is no plan to provide email or text alerts but I have requested such a facility. There is also a Gaia Alerts app for; iOS and Android but is out of date and there are no plans to keep it current.

The target lists, example in Figure 3.3.7 below will be updated regularly, placed on the Exoplanet website and circulated to interested members. The ARPS low-phase angle project could act as a template for this project in that observations would be concentrated on a few specific targets which might possibly result in the detection of an exoplanet.

What we are interested in are high magnification microlensing events which might indicate a more distant object lensed by a star hosting an exoplanet – see 2.0 above. By high magnification I mean microlensing events where the magnitude is increasing rapidly and significantly – for example Gaia21bfr, Figure 3.3.1.

The target selection process described below is primarily for the use of the project coordinator who will the issue alerts but is included to explain how the selection of targets is arrived at.
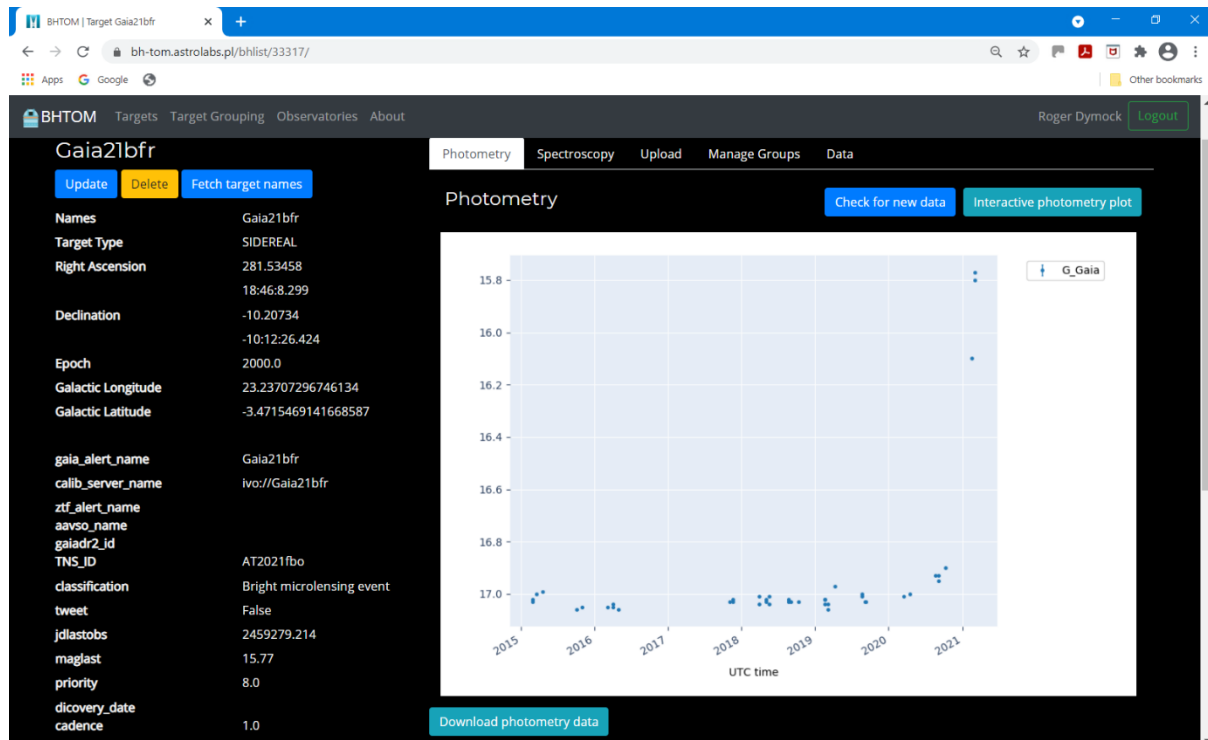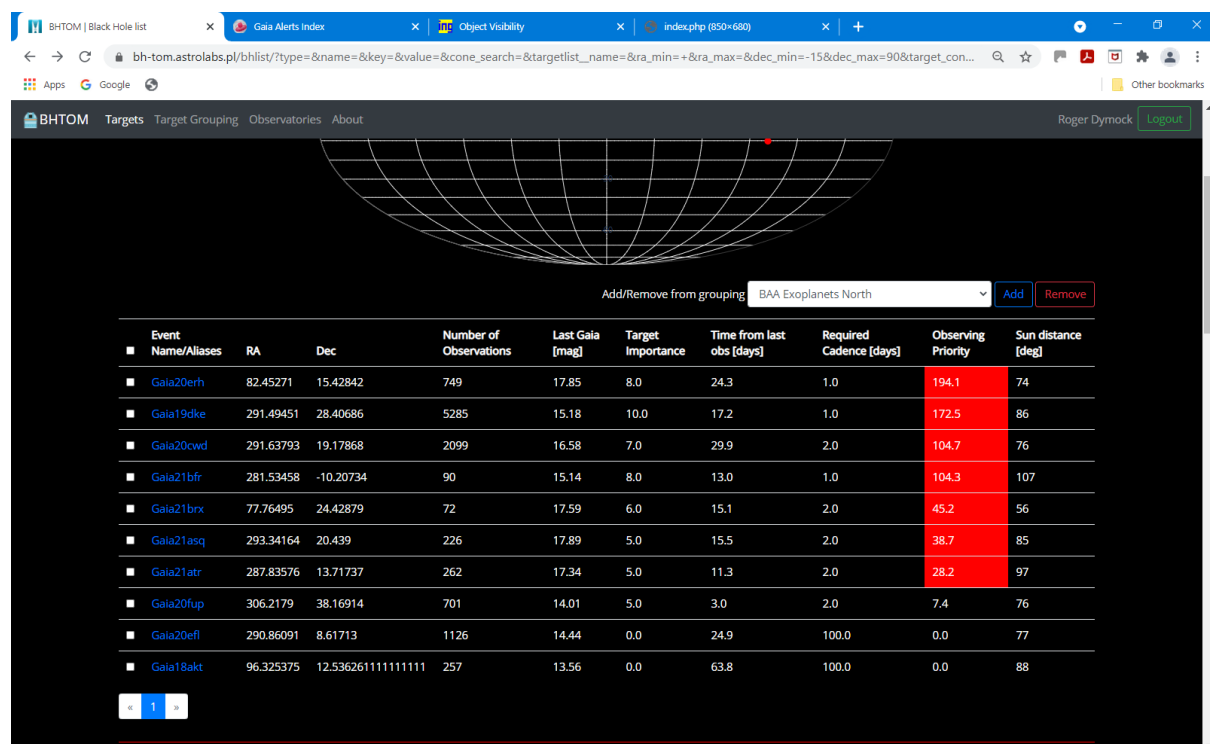

Figure 3.3.1. Example of a high magnification microlensing event

3.3.1   Target selection process for Northern hemisphere observers (Lon 0° E, Lat 54° N, 100 m) (Targets selected 2021 April 21 in these examples).

Note; specific requests for observations should be given special attention and flagged as such on email alerts

a) On the BHTOM website select Targets and then under Filter Targets input;
- Name; Gaia21 (to select most recent events)
- Dec min; -15 (ensures targets are at least 20° above the horizon at culmination)
- Dec max; +90
- Classification; microlensing
- Include only those targets with a quiescent mag of >= 18
A list of filtered targets is produced, Figure 3.2.5

Figure 3.3.2 Filtered targets

b) Then include only the following
- bright microlensing event
- possible ditto
- potential ditto
- microlensing event
- long microlensing event
- potential ditto
- Observing Priority; All
c) Review each candidate on BHTOM

d) On the Gaia Alerts page enter each prospective target in turn to confirm potential lensing status and review associated documentation. Example in Figure 3.3.3.

e) Review each candidate on LCO MOP website

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f) Omit those which have returned to their base magnitude or which could be stellar outbursts. Of particular interest will be those where the brightness is rising rapidly
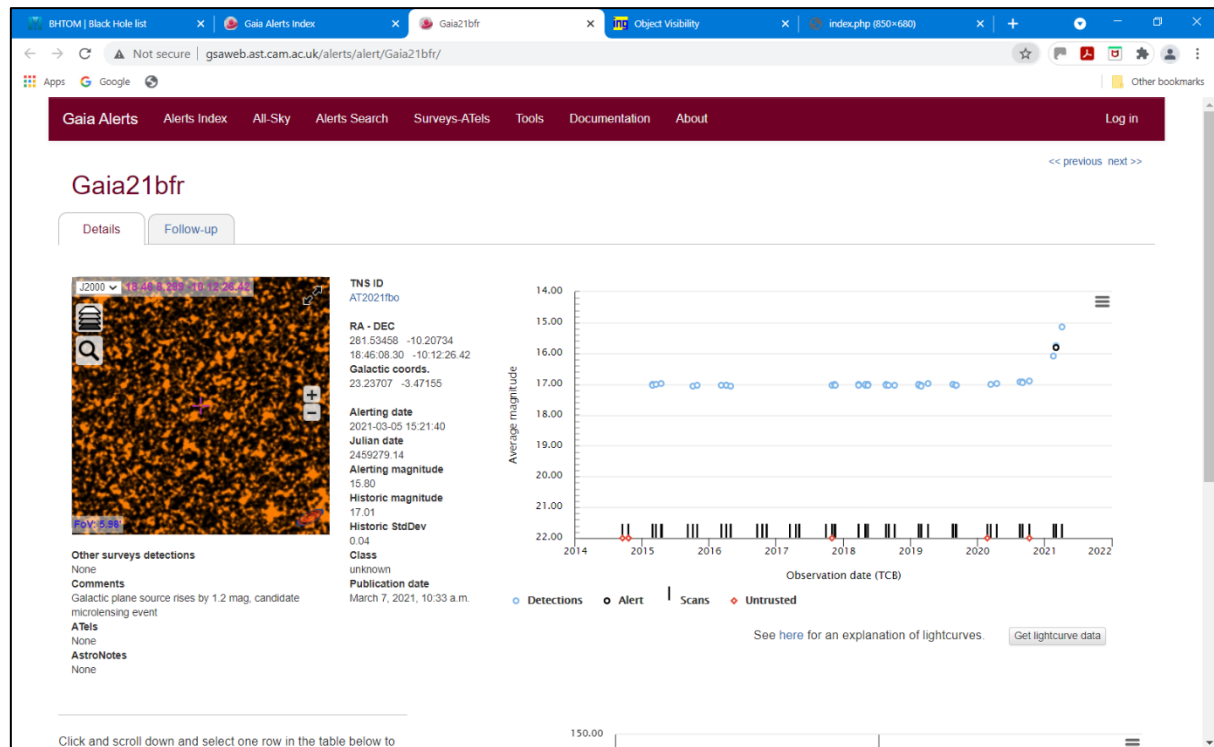

Figure 3.3.3. Gaia Alerts page for Gaia21bfr

g) An aid to determining visibility is Object Visibility – STARALT at
http://catserver.ing.iac.es/staralt/

Using the Staralt feature as shown in Figure 3.3.4, input, and Figure 3.3.5, output for date of issue of alert email to determine those targets which are currently observable. The RA and Dec decimal data are copied from the BHTOM target list.

Figure 3.3.4. Staralt input
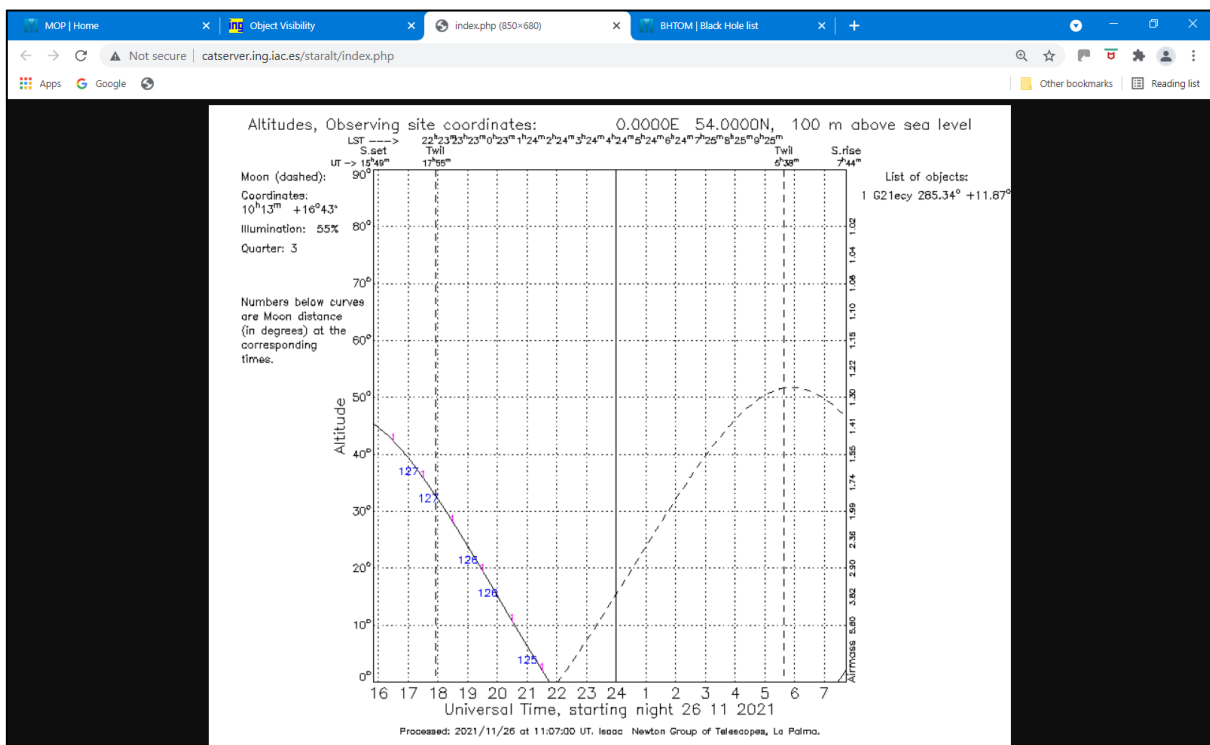
Figure 3.3.5. Staralt output

h) Check Staralt output using a planisphere for the relevant latitude

i) Check all data.

j) Review previous alerts

k) Issue email alert to Exoplanet and ARPS (x2) Simplelists and copy Siegfried Vanaverbeke, Lukasz Wyrzykowski and Franky Dubois.

l) Save as Word doc and pdf then upload pdf to Exoplanet website

Light curves can be obtained from the BHTOM website – Figure 3.3.6 is an example.

Finder charts are available on both the BHTOM and Gaia Alerts pages for the subject target. They can Finder charts can also be generated using STSci Digitized Sky Survey at https://archive.stsci.edu/cgi-bin/dss_form, example shown in Figure 3.3.7 and/or the Gaia Alerts index for the particular target.
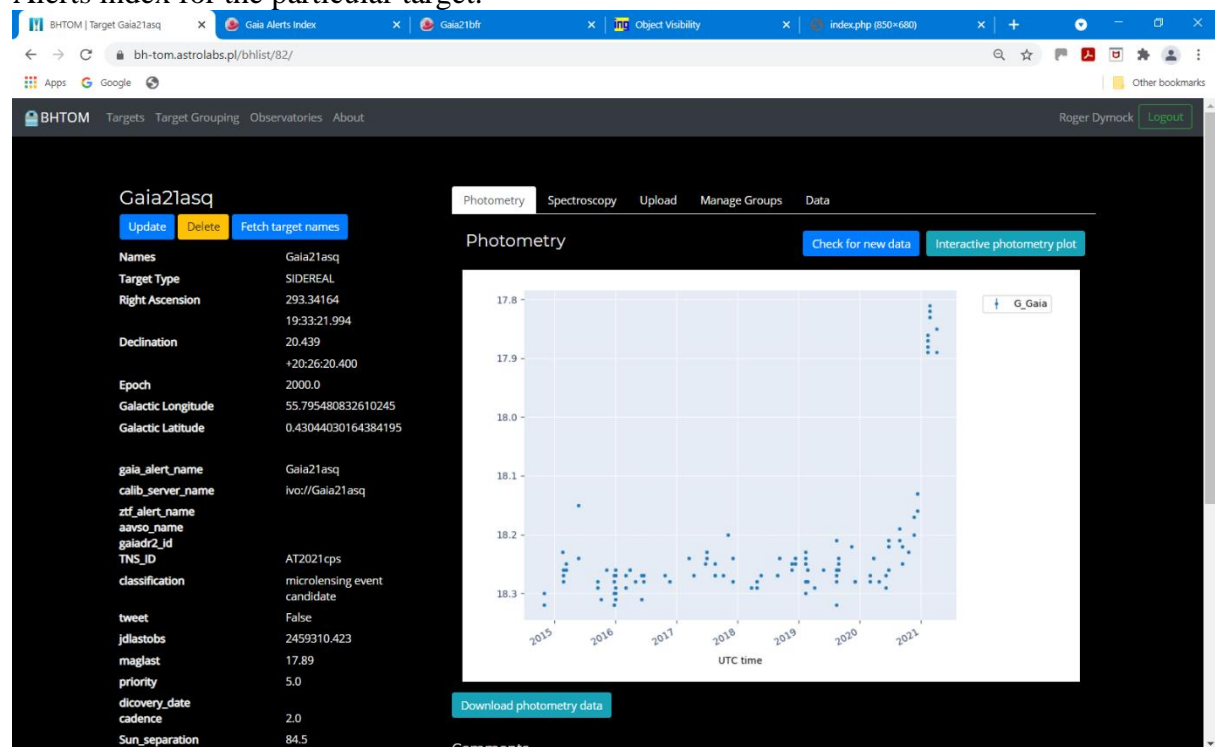
Figure 3.3.6. BHTOM light curve for Gaia20asq
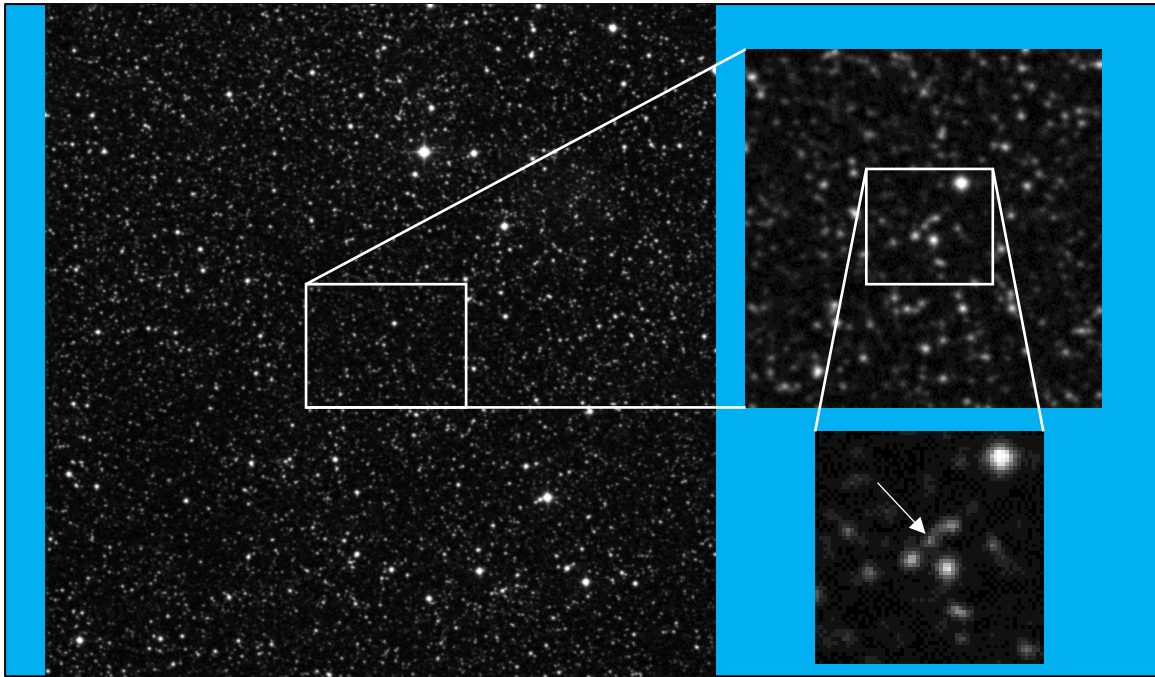
Figure 3.3.7. STSci DSS charts for Gaia20cwd

3.3.2   Target selection process for Southern Hemisphere observers or UK observers with access to robotic telescopes in that region. The coordinates used are; Lon 149.2° E , Lat 31.3° S, Alt 548 m, UT offset +11 hrs (Warrumbungle Observatory, Australia)

On the BHTOM website select Targets and then under Filter Targets input;
- Name; Gaia21
- Dec min; -90
- Dec max; +35 (ensures targets are at least 20° above the horizon at culmination)
- Classification; microlensing event

Other filtering and visibility determination as for Northern hemisphere targets.

3.3.4   Microlensing email alert format
Method of publication is via email. Example text is shown below.

<div align="center">

Microlensing Search for Exoplanets

</div>

Change to frequency of observations
Typical exoplanet 'spikes' on a microlensing light curve last for a day so a higher cadence than previously advised is requested – every 2 or 3 hours would be ideal.

Advice to imagers
To obtain the best approximation to Gaia magnitudes;
1) Use a Sloan r' filter
or
2) Use a Cousins R filter but ensure target is above 20 degrees altitude
or
3) If imaging unfiltered ensure target is above 45 degrees altitude
and

4) Use Gaia DR2 data for obtaining magnitudes of comparison stars -
https://www.cosmos.esa.int/web/gaia/data-release-2

If using Astrometrica select;
1) Filter r', R (Cousins) or Clear/None depending on filter used
2) Color Band G
3) Star Catalog Gaia DR2

Current alerts

Note; Gaia21efs is a priority target which we have been specifically requested to observe

Gaia21efs
Region; Northern hemisphere
RA 20:29:41.9 Dec +31:17:43
Quiescent (Gaia) magnitude; 15.8
Gaia alerts link (includes data and finder chart)
http://gsaweb.ast.cam.ac.uk/alerts/alert/Gaia21efs/

Please send observations to Roger Dymock. Data required;

Observing site
Observer, name
Photometric software
Photometric Catalogue used
Catalogue magnitude band
Date and time (JD) e.g., 59403.391447
Target e.g., Gaia21bfr
Filter used
Magnitude
Error

Data from BHTOM and Gaia Photometric Alerts websites

Alerts can also be viewed at https://britastro.org/node/25935

3.5   Imaging
The required cadence (frequency of observations) is typically every few hours. This means that observations could fit in with exoplanet transit runs by taking a few images before or after those sessions. Exoplanet 'spikes' on the microlensing light typically last for a day – se Figure 2.1 above.

Check that you have the correct RA and Dec for the selected target (silly mistake which I have made but at least it gave me the opportunity to practice using Astrometrica in crowded fields)

Typical amateur telescopes used by the MicroFUN project range from 10 to 16 ins, 25 to 41 cms

To obtain the best approximation to Gaia magnitudes;
1) Use a Sloan r' filter

or
2) Use a Cousins R filter but ensure target is above 20 degrees altitude
or
3) If imaging unfiltered ensure target is above 45 degrees altitude
and
4) Use Gaia DR2 data for obtaining magnitudes of comparison stars -
https://www.cosmos.esa.int/web/gaia/data-release-2

If using Astrometrica select;
1) Filter r', R (Cousins) or Clear/None depending on filter used
2) Color Band G
3) Star Catalog Gaia DR2

Filtered images will need a much longer exposure time (typically x4), or shorter exposure ones stacked, than unfiltered.

Examples of photometry.
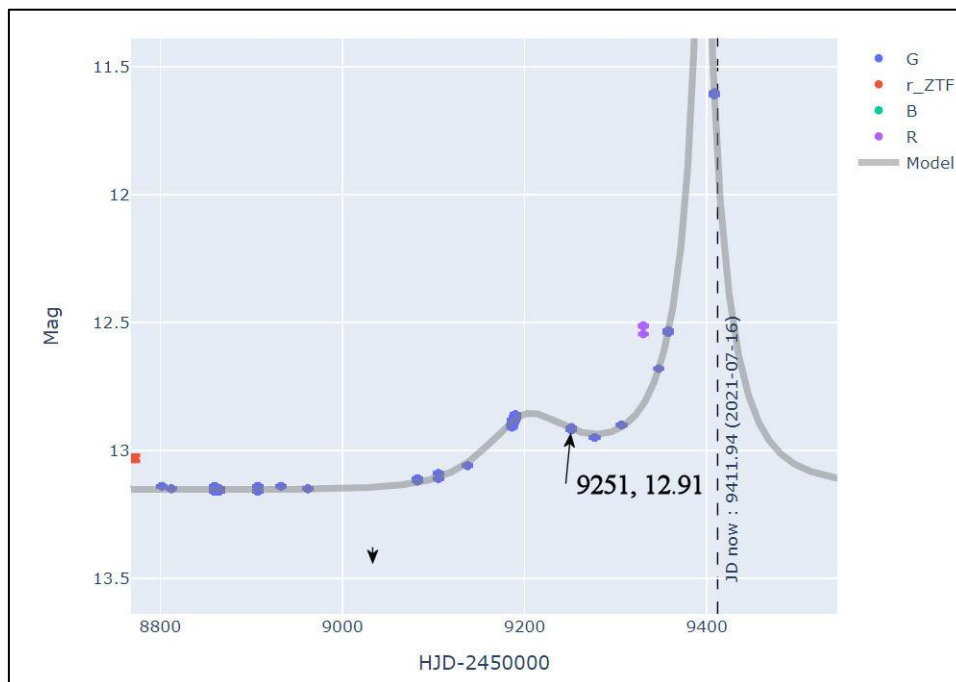
Figure 3.5.1 Chart of Gaia20fnr from Las Cumbres Observatory Microlensing Observing Platform with Gaia observation noted (date, mag).

3 images were measured with Astrometrica using the Gaia DR2 catalogue and selecting Filter Clear/None and Gaia Broadband (G) Color band. Target altitude was 64 degrees. Results below.

```
---------------------------------------------------------------
      JD         mag     Flt   SNR     ZeroPt     Cat    Design.
---------------------------------------------------------------
2459249.03231   12.912 G   C   432.27   26.136 Gaia DR2   g20fnr
2459249.03359   12.916 G   C   429.66   26.140 Gaia DR2   g20fnr
2459249.03487   12.907 G   C   432.39   26.134 Gaia DR2   g20fnr
```

There is a very good match with the Gaia data

1 image was measured with Astrometrica using the Gaia DR2 catalogue and selecting Filter Filter R (Cousins) and Gaia Broadband (G) Color band. Target altitude was 47 degrees. Result below

```
-----------------------------------------------------------------
     JD          mag     Flt   SNR     ZeroPt      Cat   Design.
-----------------------------------------------------------------
2459260.05958   12.913 G  R   416.05   26.056 Gaia DR2   g20fnr_R
```

There is also a very good match with the Gaia data

Typical light curves may have a base magnitude of between 12 and 18, vary by 1 to 2 magnitudes with 'exoplanet spikes' ranging from 0.2 to 0.7 magnitudes. A precision of +/- 0.05 magnitudes would seem appropriate which approximately equates to an SNR of 20. Such measurements should be well within the capabilities of a reasonably competent imager.

An example of the change in magnitude due to the presence of an exoplanet is shown in Figure 3.5.1
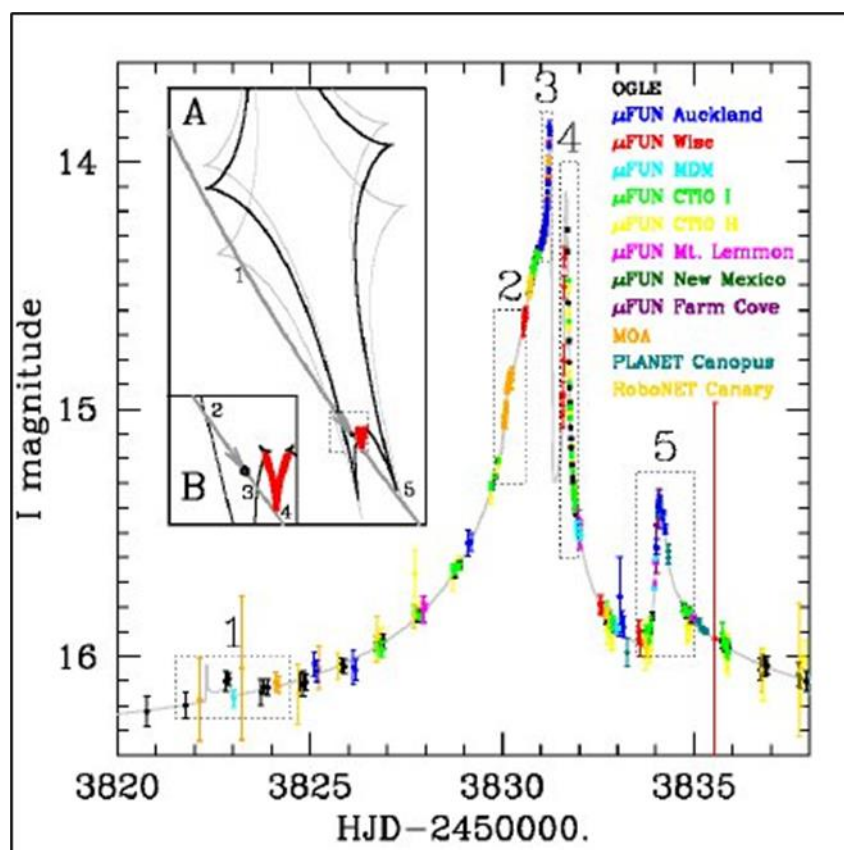

Figure 3.5.1. Light curve showing the change in magnitude for the exoplanet is approx. 0.6

Accurate timing; 1-2 secs

If you are going to upload images to the BHTOM website they must be calibrated. Curently it is much easier just to send your magnitude measurements to the co-ordinator as mentione din Figure 3.2.1. Figure 3.5.2 is an image processed with Astrometrica of Gaia20fnr obtained with the Warrumbungle robotic telescope on 2021 February 3rd using a V filter

When using Astrometrica in crowded fields select Background from PSF under the Program Settings/Program tab

Check that the filter; used, identified in the FITS header and any software you use to process images are all the same
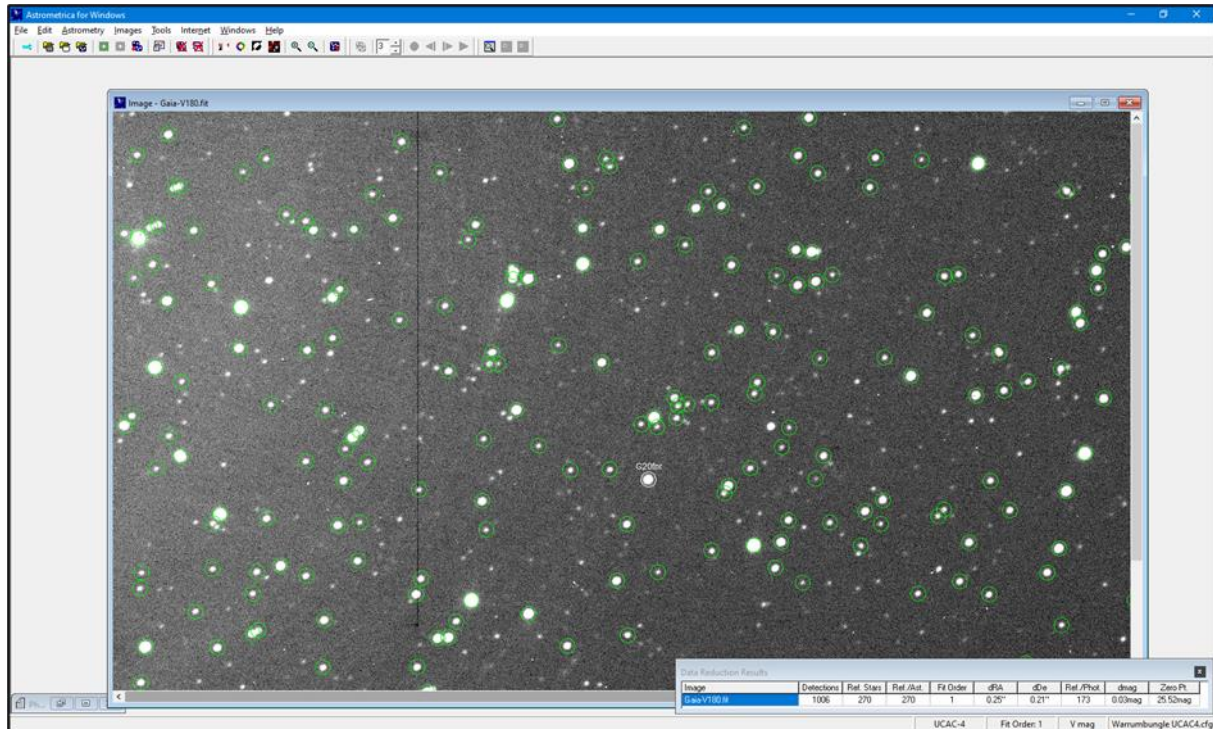

Figure 3.5.2 Image of Gaia20fnr obtained with the Warrumbungle telescope

3.6   Data input to coordinator

For each observation the following data is required;

Observing site
Observer, name
Photometric software
Photometric Catalogue used
Catalogue magnitude band
Date and time (JD) e.g., 59403.391447
Target e.g., Gaia21bfr
Filter used
Magnitude
Error

4.0 Links

ASASSN – All-Sky Automated Survey for Supernovae

BlackHole TOM - https://bh-tom.astrolabs.pl/ This platform allows for target selection and processing of the data/images. The project has a Slack channel at Slack which you can join by emailing bhtom@astrouw.edu.pl

BlackHole Help; bhtom@astrouw.edu.pl or the Slack channel

Gaia - http://www.esa.int/Science_Exploration/Space_Science/Gaia/Gaia_overview

Gaia Alerts Workshop - 2021 January 18-22
https://web1.ast.cam.ac.uk/ioa/wikis/gsawgwiki/index.php/Workshop2020:main
Talks available on YouTube;
2021 Jan 18 - https://youtu.be/BpNbkseqUBI
Black Hole TOM presentations at;

- 2 hrs 8 mins to 2 hrs 28 mins	Introduction to the Black Hole TOM
- 2 hrs 30 mins to 2 hrs 37 mins	Black Hole TOM Features
- 2 hrs 46 mins to 3 hrs 00 mins	Uploading data to Black Hole Target Observation Manager
- 3 hrs 1 mins to 31hrs 12 mins	CCDPhot, Precision Photometry and Astrometry made easy

2021 Jan 19 - https://youtu.be/8GNIXyMLGyc

- 0 hrs 34 mins to 0 hrs 48 mins	Classification of Gaia Alerts (Spectroscopy)

2021 Jan 20 - https://youtu.be/d88hjDmHX04
2021 Jan 21 - https://youtu.be/Wylsoi_nUOU
2021 Jan 22 - https://youtu.be/K2HIIKAfut8

Hands-on sessions 19 Jan, 18:00 CET and 20 Jan, 15:00 CET

12th Gaia Science Alerts and First Time-Domain Astronomy Workshop 2021 November 8 - 12
The BAA gets a mention during this video between 1:24 and 1:32

Archive of slides, videos from previous mtgs –
http://www.ast.cam.ac.uk/ioa/wikis/gsawgwiki

Gaia in the UK - https://www.gaia.ac.uk/mission

Gaia Photometric Science Alerts - http://gsaweb.ast.cam.ac.uk/alerts/home

Gaia Photometric Alerts - http://gsaweb.ast.cam.ac.uk/alerts/alertsindex   (Use the search box to look for "lens")

Korea Microlensing Telescope Network (KMT) - https://kmtnet.kasi.re.kr/kmtnet-eng/

Las Cumbres Observatory - https://lco.global/spacebook/exoplanets/gravitational-microlensing/
LCO Microlensing Observing Platform

MicroFun - http://www.astronomy.ohio-state.edu/~microfun/

Microlensing Source – all things microlensing

Mt John Observatory, MOA telescope - https://en.wikipedia.org/wiki/Mount_John_University_Observatory#MOA_Telescope

Nancy Grace Roman Space Telescope
The Roman Space Telescope is a NASA observatory designed to unravel the secrets of dark energy and dark matter, search for and image exoplanets, and explore many topics in infrared astrophysics. It will perform a microlensing survey of the inner Milky Way to find ~2,600 exoplanets. The Coronagraph Instrument will perform high contrast imaging and spectroscopy of individual nearby exoplanets.

OGLE-IV - http://ogle.astrouw.edu.pl/
The Optical Gravitational Lensing Experiment (OGLE) is a Polish astronomical project based at the University of Warsaw that runs a long-term variability sky survey (1992-present). The main goals are the detection and classification of variable stars (pulsating and eclipsing), discovery of microlensing events, dwarf novae, and studies of the structure of the galaxy and the Magellanic Clouds. Since the project began in 1992, it has discovered a multitude of extrasolar planets, together with the first planet discovered using the transit method (OGLE-TR-56b) and gravitational microlensing. The project has been led by professor Andrzej Udalski since its inception

Tomo-e Gozen Project
Tomo-e Gozen is an optical wide-field video observation system composed of a mosaic CMOS camera on the 1.05 m Kiso Schmidt telescope, real-time data analysis software, and automated operation software. When receiving alerts of gravitational wave events, automated follow-up observations of a few 100 deg2 start quickly. The high-speed, high-cadence, and wide-field observations with Tomo-e Gozen will open new windows for astronomy on short time-scale phenomena including faint meteors, near-earth asteroids, stellar occultations, early-phase supernovae, black hole binaries, optical counterparts of gravitational wave sources and FRBs, and unknown flashes in the Universe.

University of Warsaw Astronomical Observatory - http://www.astrouw.edu.pl/index.php/english-front

Vera C. Rubin Observatory (previously LSST)
Rubin Observatory will operate on an automated cadence, capturing an area the size of 40 full moons with each pair of 15-second exposures and returning to the same area of sky approximately every three nights. Over ten years of operations, hundreds of deep exposures will be acquired for every part of the visible sky. Dedicated computer facilities will process Rubin Observatory data in real time, issuing worldwide alerts within 60 seconds of detected changes in the sky. A subset of data will be widely available through the Rubin Observatory Education and Public Outreach (EPO) dynamic website portal, offering tools and activities for formal educators, citizen scientists, informal science centers, and the general public to engage, explore, and discover.
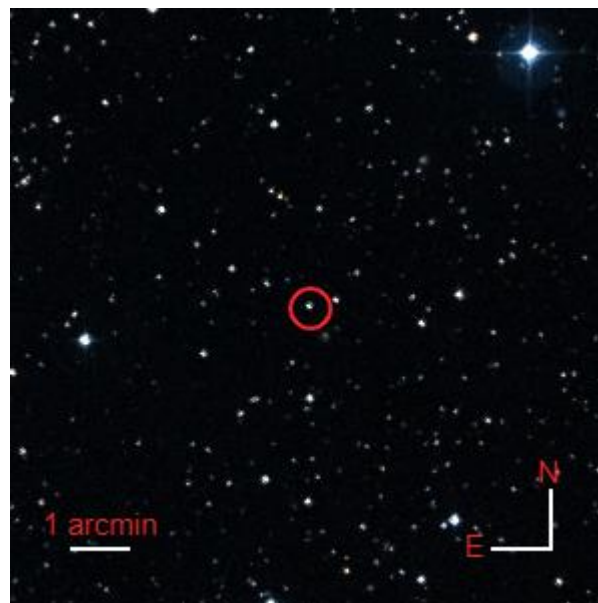
Zwicky Transient Facility (ZTF) - https://www.ztf.caltech.edu/

5.0   Acknowledgements

Appendix 1   Example of image processing using Astrometrica
A1.1   Target – Gaia21dnc
Finder chart from BHTOM is shown in Figure A1.1

A1.1. Finder chart for Gaia21dnc

A1.2   Program Settings
Under CCD tab set Color Band to match Filter – example in Figure A1.2
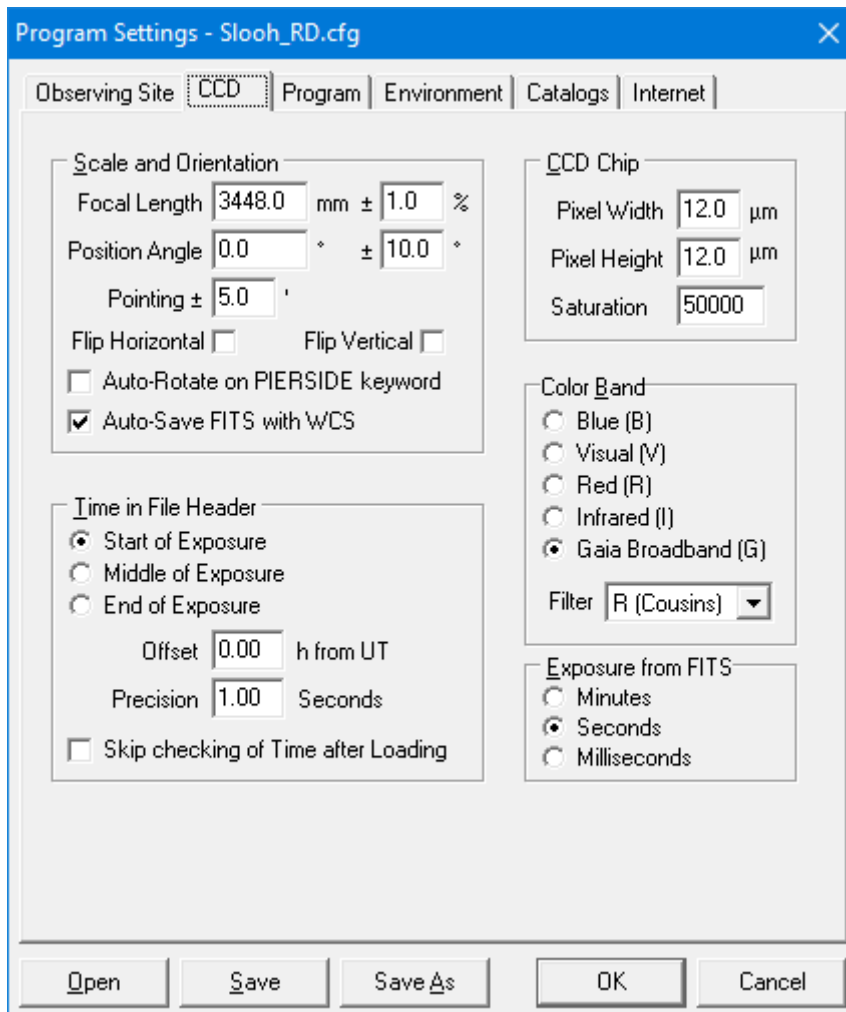
Figure A1.2. Program Settings/CCD tab

For crowded fields such as in this example under Program tab set Background from PSF – Figure A1.3. Otherwise set Background from Aperture.

Figure A1.3. Program Settings/Program tab

A1.3 Astrometric reduction
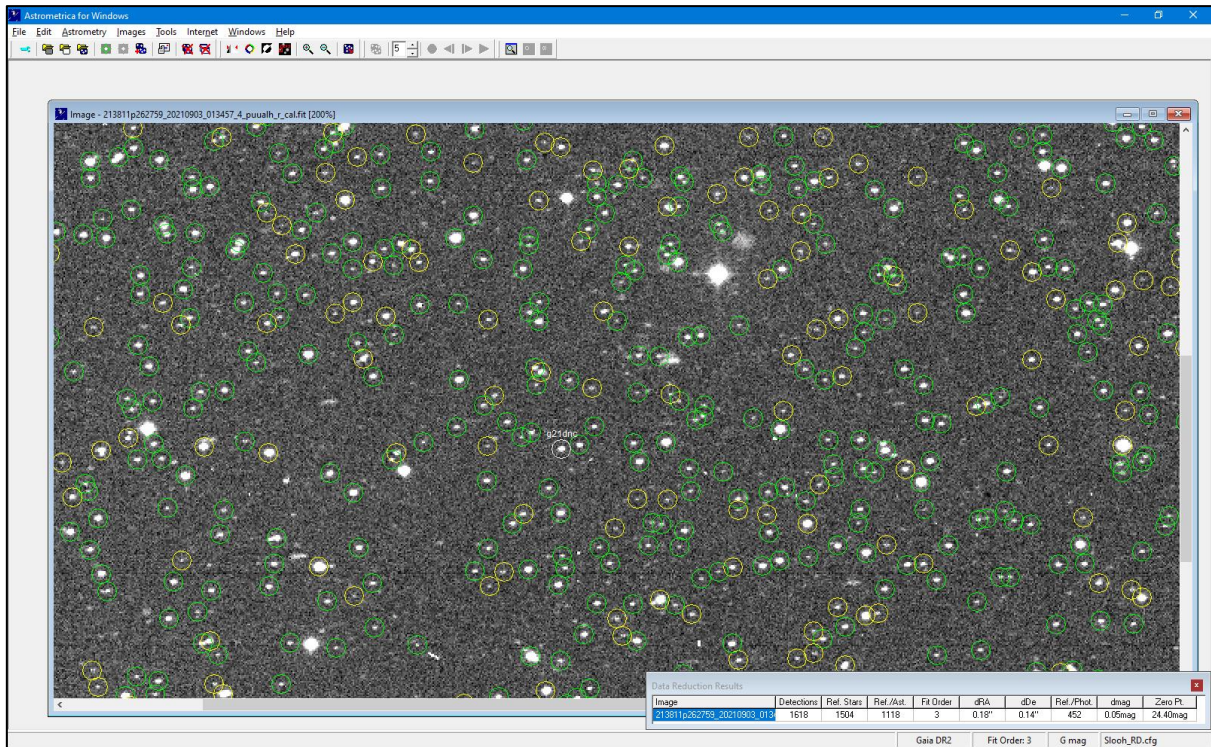
Figure A1.4. Screen shot after astrometric reduction

Figure A1.4 shows the results of astrometric reduction – note that dmag = 0.05mag

The end result of the reduction is shown in Figure A1.6.
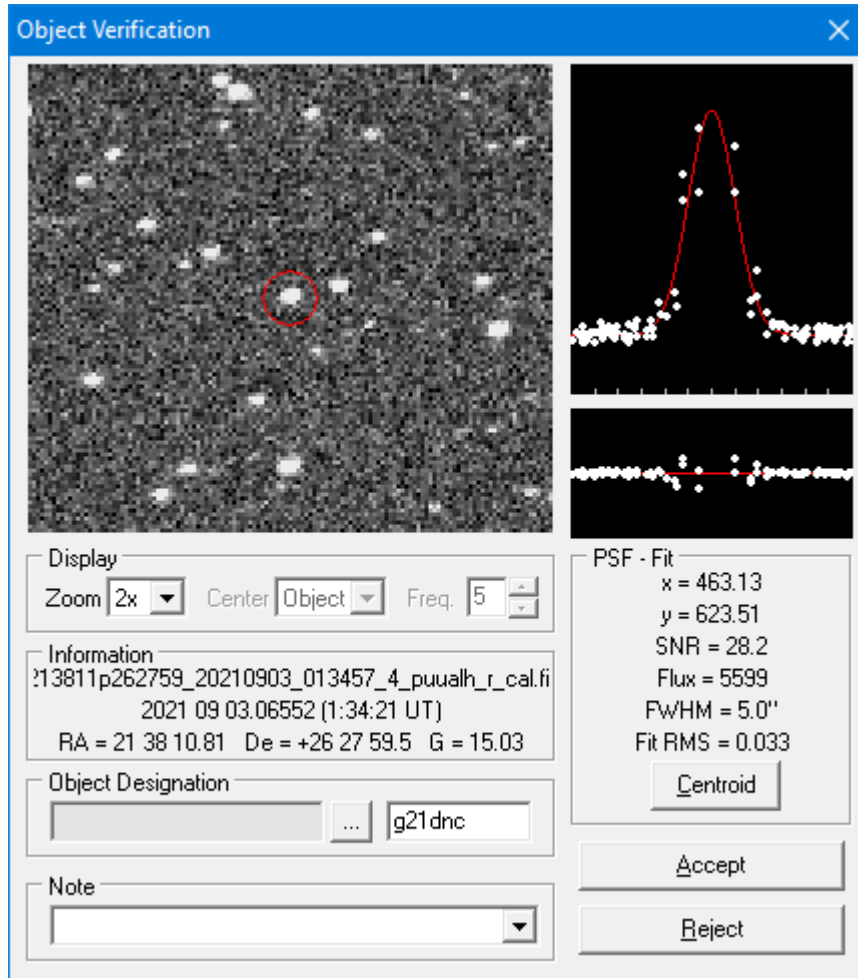
Figure A1.6. Astrometric reduction result

The Photometry file is shown below

```
OBSERVER:     R.Dymock
TELESCOPE:    0.51-m f/6.8 reflector + CCD
EXPOSURE JD: Mid-exposure, not corrected for light time
----------------------------------------------------------------
     JD          mag     Flt   SNR    ZeroPt     Cat    Design.
----------------------------------------------------------------
2459460.56552   15.029 G  R    46.45  24.399 Gaia DR2   g21dnc
----- end -----
```

A1.4   Error calculation

Error = $\sqrt{(4/SNR^2 + dmag^2)}$

= $\sqrt{(4/46.45^2 + 0.05^2)}$

= 0.07

Reported R magnitude would therefore be 15.03 +/- 0.07

Appendix 2   BHTOM website

A2.1   Overview

A manual is available at http://visata.astrouw.edu.pl/~wyrzykow/2021.01-BHTOM-manual-v.1.1.pdf

A2.2   Uploading data to the BHTOM website

Included for information only. The current process is to send your measurements to the co-ordinator (currently the ARPS Assistant Director Exoplanets) who will upload them to the BHTOM website rather than each observer uploading to the BHTOM website.

A2.3   Uploading photometric data

Photometric data can be uploaded as a CSV table – Figure A2.3.1.
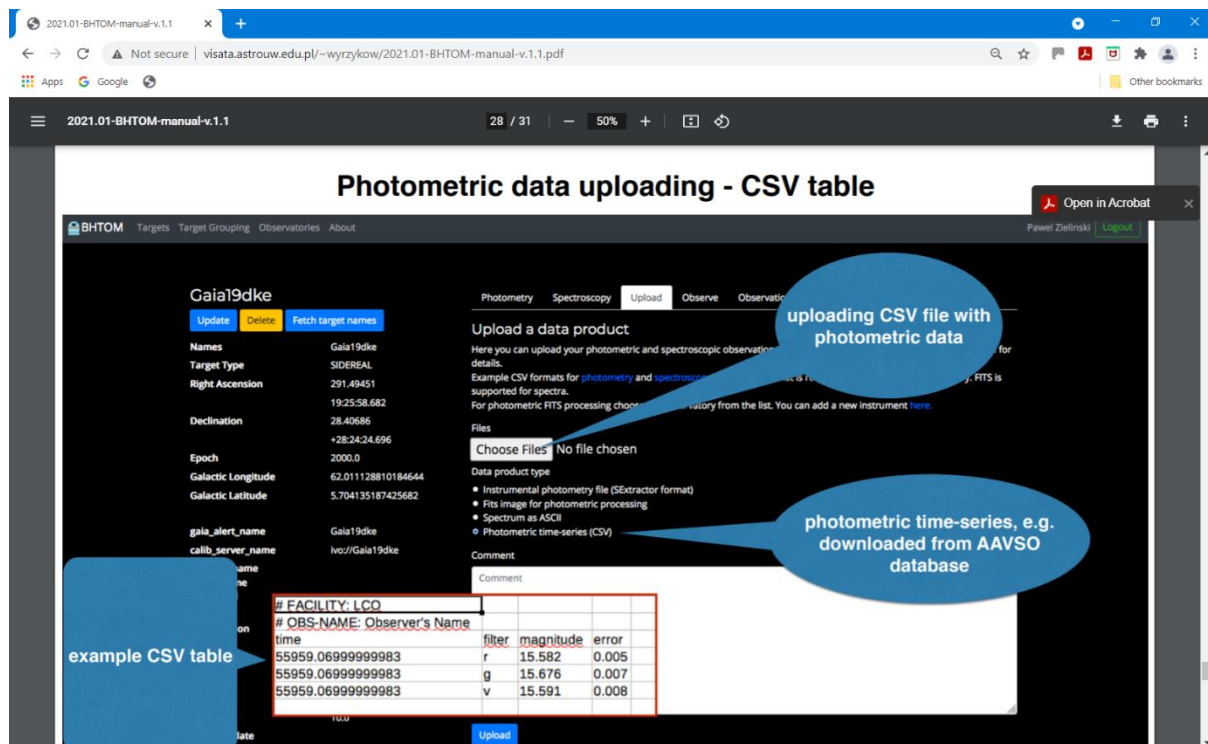
Figure A2.3.1. Photometric data upload

Please note that the header line starting with 'time' must be formatted exactly as shown in the example below (i.e., all lower case). The data can be tabulated in Excel, Table A2.3.2, and then saved as a .csv file, Figure A2.3.3. The two header lines starting with # can be included but are not necessary. The Status column for the particular target will be blank as opposed to 'Finished' when an image is uploaded. In the Interactive Photometry plot the Owner and Facility are not indicated but a future update may allow this.

# FACILITY: Warrumbungle Observatory			
# OBS-NAME: Roger Dymock			
time	filter	magnitude	error
59329.85846	R	12.545	0.003
59329.86115	B	14.033	0.007
59329.86672	B	14.014	0.007
59329.86959	R	12.515	0.003
59329.87226	B	14.031	0.006
59329.88066	R	12.511	0.003
59329.88336	B	13.992	0.006

Table A2.3.2. Photometry input in Excel format

Figure A2.3.3. Photometry input in csv format

A2.4 Checking input
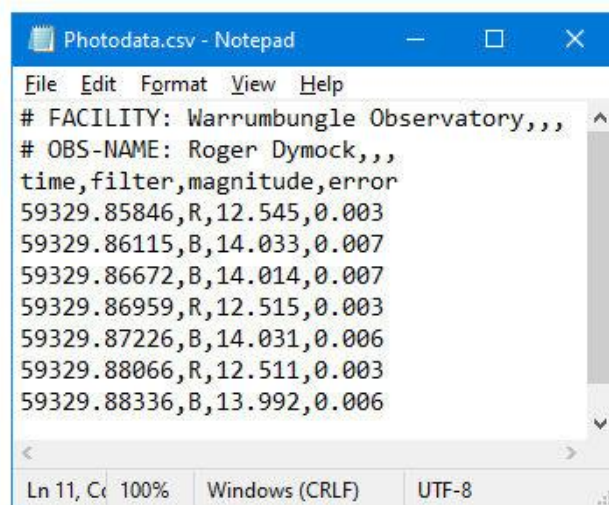
Input can be reviewed by selecting;

- target from the Targets list
- Data
- Your file
- Detail

Appendix 3   Microlensing light curve examples
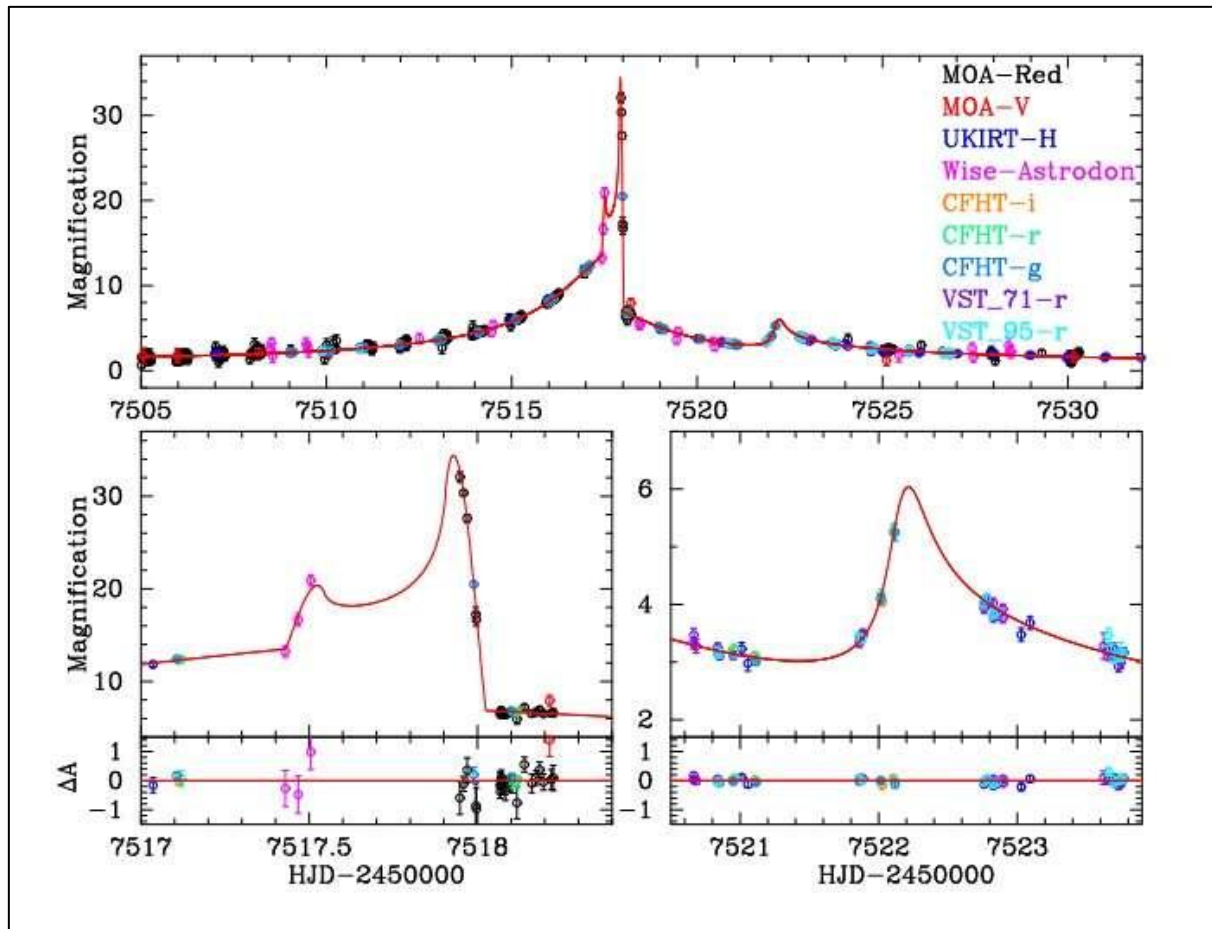

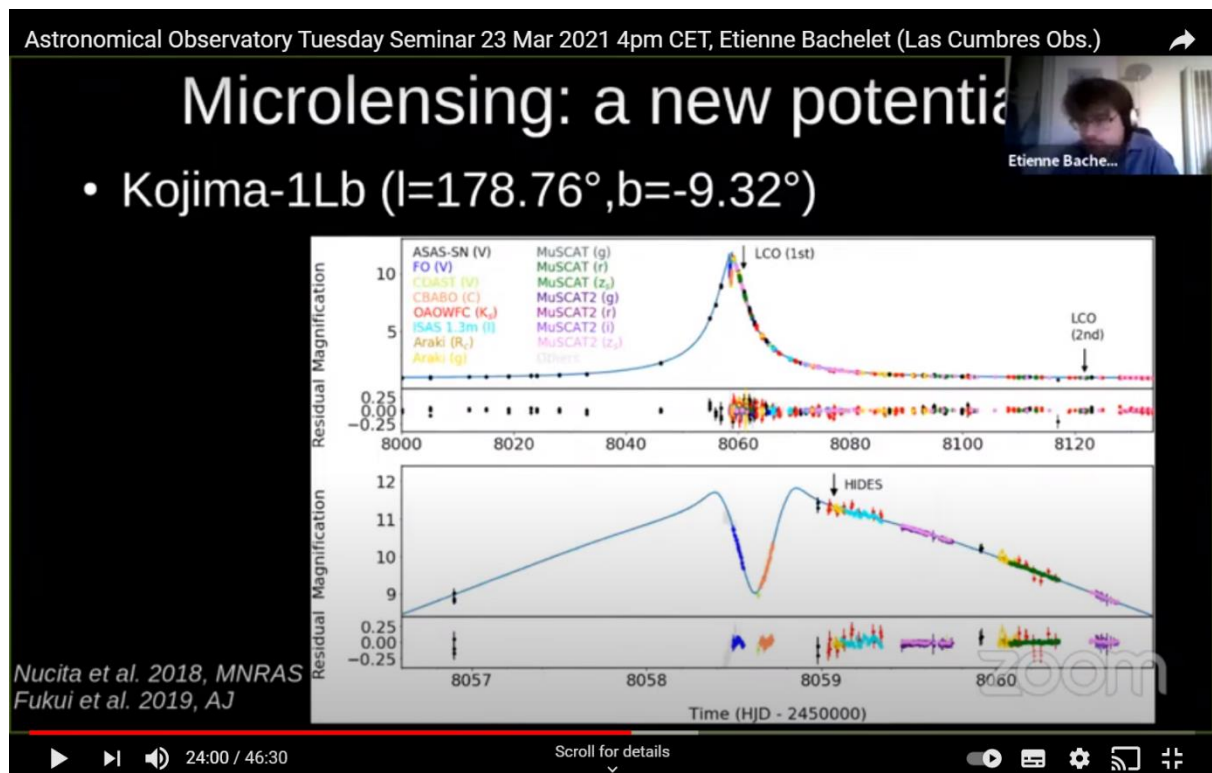Figure 4.1. Detection of exoplanet MOA-2016-BLG-227b

Figure 4.2. Detection of Neptune size planet

The event shown in Figure 4.2 was first detected by Kojima, a Japanese amateur astronomer. The anomaly at the peak is due to a Neptune size planet.

Appendix 4   The theory and maths of microlensing
Microlensing Source for all you need to know about microlensing.

Microlensing exoplanets (extracted from the Scholarpedia website)
Prof. Penny D Sackett, Research School of Astronomy and Astrophysics, Mount Stromlo, The Australian National University.

A microlensing exoplanet is a planet orbiting a star other than our own Sun that is detectable due to the effects that the gravitational field of its planetary system has on the passing light of a distant background star. The microlensing technique is particularly well-suited to finding low-mass planets and planets around distant or very dim stars. Astronomers have published findings on several different microlensing exoplanets, with masses ranging from more than Jupiter to only a few times more massive than our own Earth

Microlensing
Microlensing is a form of gravitational lensing in which the light from a background source is bent by the gravitational field of a foreground lens to create distorted, multiple and/or brightened images. In microlensing, the separation of order a milli-arcsecond between multiple images is generally too small to be resolved by modern telescopes. The combined light of all images is instead observed as a single image of the source, blended with any light that may be emanating from the lens itself. The brightness of the combined image is a function of the projected separation of the source and lens on the observer's sky, and thus can change as the source, lens and observer move relative to one another. The time variability of the combined image - namely an apparent change in source brightness as a function of time recorded as a microlensing light curve - is the usual observational signature of microlensing.
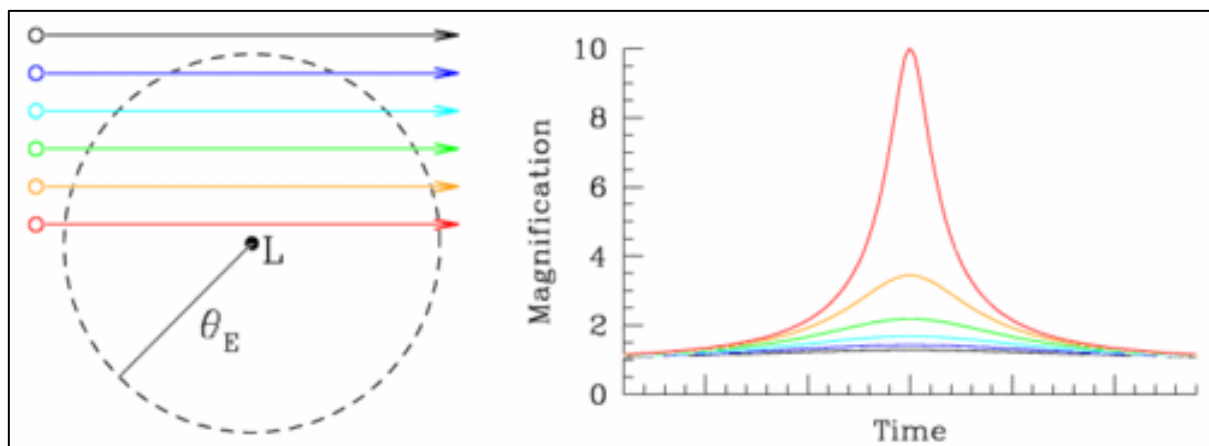
Figure 1: *Left:* Possible source trajectories are shown in different colours with respect to a single microlens **L** with an Einstein radius of *θE* . *Right:* Lightcurves of the background source star are shown, colour-coded to match their corresponding trajectories at left.

A single microlens
If the lens is a single, isolated, compact object and relative motions are rectilinear, the light curve of the background source is simple, smooth and symmetric (see Figure 1). The background star appears to brighten and then dim as the projected separation between the source and lens first decreases and then increases. For sources and microlenses in our own

Galaxy, a typical timescale for the detectable rise and fall of the apparent brightness of the source star is on the order of weeks to months. The basic shape is the same (see Fig. 1) regardless of the relative path the source takes on the sky; the amplitude of the light curve is determined by the minimum angular separation between the lens and source in units of the Einstein radius, i.e. θ_{LS}/θ_E .

Gravitational lensing was predicted by Albert Einstein's theory of general relativity. Instead of light from a source traveling in a straight line (in three dimensions), it is bent by the presence of a massive body, which distorts spacetime. An Einstein Ring is a special case of gravitational lensing, caused by the exact alignment of the source, lens, and observer. This results in symmetry around the lens, causing a ring-like structure – Figure 2.

Figure 2. An Einstein ring

Beginning in the 1990s and proceeding to this day, millions of stars have been monitored every night in search of the few that are microlensed by an observable amount at that time. These surveys were motivated by the desire to measure the contribution of dim stars, stellar remnants, black holes, and brown dwarfs to the unseen dark matter in the Milky Way. Soon thereafter, however, they became important to the search for exoplanets orbiting faint stars and brown dwarfs, which would be difficult to detect by any means other than microlensing.

Microlens with multiple components
If the lens is multiple, as is the case when the lens is a binary star or a star with planets, the magnification pattern experienced by a background source is no longer circularly symmetric on the sky. In this case, the shape and maximum amplitude of the light curve depends on relative path the background source takes through the lens magnification pattern. The resulting light curve can exhibit large changes in shape over rather short periods of time if the background star passes near what is known as a caustic in the lensing pattern.
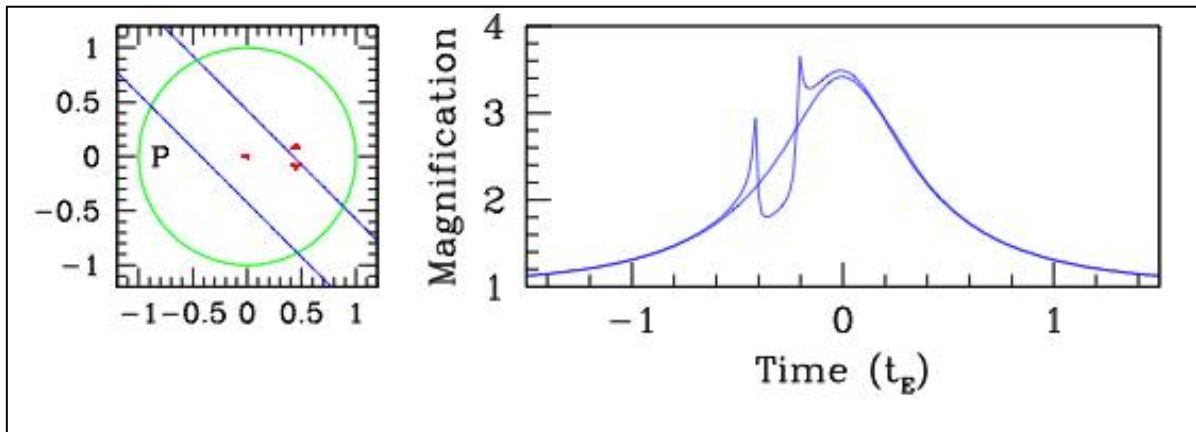
Detecting planets with microlensing

Figure 3: Microlensing exoplanets can cause sharp deviations in the otherwise smooth light curve of a background star during a microlensing event, but only if the path of the background star passes near one of the caustics (shown as red zones) caused by the combined gravitational potential of the planet and its host lensing star. Two possible background star trajectories are shown at left, and the resulting light curves are displayed on the right. The green circle is the Einstein ring, and the position of the planet is marked with a **P**. The Einstein time depends on the relative proper motion μ of the lens with respect to the source through $tE=\theta E/\mu$, and thus is different for different microlensing events.

Because the planet has a gravitational mass that is much smaller than that of the lensing star, the percentage of the lensing pattern area influenced by the planet will be relatively small. This means that the probability that the source trajectory will cross the planet-affected area is low, and thus the chance of detecting a planet by microlensing is also low, even if the planet is present. On the other hand, the combined gravitational field of the star and planet can create strong deviations in the lensing pattern (caustics) over this small area. This means that the changes in the light curve of the background source can be quite dramatic if it does happen to cross the planet-affected area. This is true even for planets with masses as low as that of Earth, as long as the size of the background source star is not more than about 5 times larger than the area of anomalous lensing pattern created by the planet.

What can be learned
The parameters that are easiest to measure from microlensing light curves that exhibit the presence of the planet are the mass ratio between the planet and its parent star, $q=Mp/M*$, and the angular separation between the planet and star on the sky at the time of the lensing event, $d=\theta*,p/\theta E$, in units of the Einstein ring radius. Both denominators depend on the mass of the lensing star (not the source star), while the Einstein radius depends on the relative distance of the lensing star along the sight line of the observer. The quantity q indicates how massive the planet is compared to its host star. If the size of θE can be measured (which is usually possible for planetary microlensing events), then d places a lower limit on the size of the orbit. In about 1/2 of all microlensing planets discovered to date, the mass and distance of the planet have been determined by a variety of auxiliary techniques.

Roger Dymock
ARPS Assistant Director Exoplanets