MICROlensing Search for EXoplanets

A Gravitational Microlensing Pro-Am Project - Version 4

Updated 2021 July 26

Introduction

This is very much an evolving document which will be updated as it is reviewed and comments acted upon.

We at the very early stages in this project so your involvement would be most welcome. You will notice that the required frequency of observations is, typically, daily 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

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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.

157 planets have been discovered from the ground using this technique (2021 July 26). For updates go to the <u>Exoplanet.eu catalog</u> 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 <u>https://svs.gsfc.nasa.gov/20242</u> from which the above text was taken.

See also;

https://en.wikipedia.org/wiki/Gravitational_microlensing#:~:text=Gravitational%20microlen sing%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 <u>Microlensing</u> <u>Searches for Exoplanets</u> and at <u>The Use of High-Magnification Microlensing Events in</u> <u>Discovering Extrasolar Planets</u>

Of more relevance to amateur observers is the paper <u>'Detecting Exoplanets by Gravitational</u> <u>Microlensing using a Small Telescope</u>' 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. The project has a webpage here which is still in development: <u>https://bh-tom.astrolabs.pl/)</u>. 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 weekly 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 <u>Gaia Alerts app</u> for; <u>iOS</u> and <u>Android</u> 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.

BHTOM Target Gaia21bfr	× +			○ - 0
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Update Delete F	etch target names	Photometry		
Names	Gaia21bfr	Photometry	Check for new data	Interactive photometry plot
Target Type	SIDEREAL			
Right Ascension	281.53458			• G_Gaia
	18:46:8.299	15.8 -		
Declination	-10.20734			
	-10:12:26.424	16.0 -		
Epoch	2000.0			
Galactic Longitude	23.23707296746134	16.2 -		
Galactic Latitude	-3.4715469141668587			
		16.4 -		
gaia_alert_name	Gaia21bfr			
calib_server_name	ivo://Gaia21bfr	16.6 -		
ztf_alert_name		10.0		
aavso_name				
gaiadr2_id TNS_ID	AT2021fbo	16.8 -		
classification	Bright microlensing event			
tweet	False	17.0 -	14 DO 44 9 15 17	
jdlastobs	2459279.214			
maglast	15.77	2015 2016 2017	2018 2019 2020 202	>
priority	8.0		UTC time	
dicovery_date				
cadence	1.0	Download photometry data		
- ···				

Figure 3.3.1. Example of a high magnification microlensing event

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

a) On the **<u>BHTOM</u>** website select Targets and then under Filter Targets input;

- Dec min; -15 (ensures targets are at least 20° above the horizon at culmination)
- Dec max; +90
- Classification; microlensing event
- Maglast max; 17.9

A list of filtered targets is produced, Figure 3.2.5

BHTOM Black Hole list	🗙 🔕 Gaia Alerts II	ndex ×	ing Object Visibility	:	× 😔 index.php	(850×680)	× +		•	- 0 ×
← → C 🔒 bh-tom.	.astrolabs.pl/bhlist/?type=	=&name=&key=&value	=&cone_search=&tar	getlistname	=&ra_min=+&r	a_max=&dec_min=-1	5&dec_max=90&tar	get_con Q	☆ 🖻 📕	🙂 🗯 😩 🗄
🗰 Apps 🕒 Google 🔇										Other bookmarks
BHTOM Targets Targ	get Grouping Observator	ies About							Roger Dj	ymock Logout
		H		Ada	d/Remove from g	rouping BAA Exopla	nets North	~ 7	Ndd Remove	
Even Nam	it ie/Aliases RA	Dec	Number of Observations	Last Gaia [mag]	Target Importance	Time from last obs [days]	Required Cadence [days]	Observing Priority	Sun distance [deg]	
Gaia	20erh 82.45271	15.42842	749	17.85	8.0	24.3	1.0	194.1	74	
Gaia	19dke 291.49451	28.40686	5285	15.18	10.0	17.2	1.0	172.5	86	
Gaia	20cwd 291.63793	19.17868	2099	16.58	7.0	29.9	2.0	104.7	76	
Gaia	21bfr 281.53458	-10.20734	90	15.14	8.0	13.0	1.0	104.3	107	
Gaia	21brx 77.76495	24.42879	72	17.59	6.0	15.1	2.0	45.2	56	
Gaia	21asq 293.34164	20.439	226	17.89	5.0	15.5	2.0	38.7	85	
Gaia	21atr 287.83576	13.71737	262	17.34	5.0	11.3	2.0	28.2	97	
Galai	20fup 306.2179	38.16914	701	14.01	5.0	3.0	2.0	7.4	76	
Gaia	20efl 290.86091	8.61713	1126	14.44	0.0	24.9	100.0	0.0	77	
Gaia	18akt 96.325375	12.536261111111111	257	13.56	0.0	63.8	100.0	0.0	88	
« 1 ×	30									

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 > 0 (indicated in red)

c) Review each candidate on BHTOM

d) On the <u>Gaia Alerts page</u> 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

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

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Gaia21bfr										
Details Follow-up										
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	Alerting date 2021-03-05 15:21:40	UP 18.	00							
	Julian date 2459279.14	Jer 19.	00							
	Alerting magnitude	20.	00							
	15.80 Historic magnitude	21.	00							
Fov: 5.98	17.01 Historic StdDev	22	- E 11 H							
Other surveys detections	0.04 Class	22.	2014 2015	2016	2017		2020	2021	2022	
None Comments	unknown Publication date				Obser	rvation date (TCB)				
Galactic plane source rises by 1.2 mag, candidate microlensing event	March 7, 2021, 10:33 a.m.	o Dete	ctions o Alert	Scans	Ontrusted					
ATels					See here fo	or an explanation	of lightcurves.	Get lightcu	rve data	
AstroNotes										
None										

Figure 3.3.3. Gaia Alerts page for Gaia21bfr

g) An aid to determining visibility is Object Visibility – STARALT at <u>http://catserver.ing.iac.es/staralt/</u> using the Starobs feature as shown in Figure 3.3.4, input, and Figure 3.3.5, output. What we are looking for here is those targets which are currently observable. Copy and paste RA, Dec decimal data from BHTOM target list – format correctly

BHTOM Black Hole list	🗙 📔 🧕 Gaia Alerts Index	× 🧶 Ga	aia21bfr × ing Object Visibility	× 👩 index.php (850×680)	× +	•	- 0	×
← → C ▲ Not secu	ire catserver.ing.iac.es/staralt/				Q 🕁		• * .	:
🛄 Apps Ġ Google 🔇							Other book	marks
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AND AND AND		Mode	Starobs V					20
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Comme Com		Observatory	Roque de los Muchachos Observatory (La Palma, Spain) Select one above or specify your own site with this format: Longitude(?E) Latitude(?N) Altitude(metres) UT-off EX: 289.2767 - 30.2283 2725 - 4 54.00 +00 00 100 0	-set(hours)				EV AP
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LITTLE LITTLE			Alternatively, you can upload a file with coordinates. You can as in the TCS catalog. Target names must be single words with Choose file No file chosen					11
		Options	Moon distance Included on plot. Moon coordinates at ~only. 10°, X=5.8 v Min. elevation (or max. airmass X). Stan. GIF (inline) Output format					
LA PALMA LA PA		Submit	Retrieve Help					•

Figure 3.3.4. Starobs input



Figure 3.3.5. Starobs output

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

i) Check all data.

j) Review previous alerts – continuing and those that can be cancelled

An example of the final filtered list of observable Northern hemisphere targets is shown in Table 3.2.1.

				Cadence
Target	RA	Dec	Last Gaia mag	Days
Gaia20cwd	19 26 33.1	+19 10 43	16.58	2.0
Gaia21bfr	18 46 08.3	-10 12 26	15.14	1.0
Gaia21asq	19 33 22.0	+20 26 20	17.89	2.0
Gaia21asq			17.89	2.0

Table 3.3.1. Northern hemisphere targets

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

1) 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 <u>https://archive.stsci.edu/cgi-bin/dss_form</u>, example shown in Figure 3.3.7 and/or the Gaia Alerts index for the particular target.

BHTOM Target Gaia21asq 🛛 🗙 🧕	Gaia Alerts Index 🛛 🗙 🛛 🧕	Gaia21bfr	× ing Object Vis	ibility 3	< 🏠 index.php (850×68)	» × +	•		٥	>
→ C	ohlist/82/					@ ☆	P .	U	* 1	5
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3HTOM Targets Target Grouping	Observatories About						Porer	Dymock	Logou	
	Observatories About						Noger	Dyfflock	Logod	-
Colollog										
Gaia21asq		Photometry	pectroscopy Upload	Manage Groups	Data					
Update Delete F	etch target names	Photomet			A 11 1.					
Names	Gaia21asq	Flotomet	y		Check for new data	Interactive photomet	ry plot			
Target Type	SIDEREAL						V)			
Right Ascension	293.34164	17.8 -				• G_Gai	a			
	19:33:21.994						-			
Declination	20.439					1.				
	+20:26:20.400	17.9 -								
Epoch	2000.0									
Galactic Longitude	55.795480832610245	18.0 -								
Galactic Latitude	0.43044030164384195	10.0 -								
gaia_alert_name	Gaia21asq	18.1 -								
calib_server_name	ivo://Gaia21asq	10.1								
ztf_alert_name						2				
aavso_name gaiadr2_id		18.2 -			:					
TNS_ID	AT2021cps		1.4	·	aa ah ah 20					
classification	microlensing event candidate	18.3 -	有效的	1.11.21	i filita de la compañía de la					
tweet	False	•			•					
idlastobs	2459310.423	2015	2016 2017	2018 20	19 2020 203	2				
maglast	17.89			UTC time						
priority	5.0									
dicovery_date		Download photor	netry data							
cadence	2.0	- Southeas priotor								
Sun_separation	84.5	Comments								

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 **<u>BHTOM</u>** website select Targets and then under Filter Targets input;

- 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.

Filtered targets are shown in Table 3.3.2.

				Cadence
Target	RA	Dec	Last Gaia mag	Days
Gaia20dwf	18 26 29.4	-20 03 52	16.00	0.5
Gaia21bol	11 26 21.7	-69 21 31	18.15	3.0

Table 3.3.2. Southern hemisphere targets

3.3.4 Microlensing email alert format

Method of publication is via email. Example text is shown below.

Microlensing Search for Exoplanets

New alerts

Gaia21bvg Region; Southern hemisphere RA 18 31 24.1 Dec -34 12 05 Last Gaia magnitude; 15.47 Time between observations; 1.0 day Gaia alerts link (includes data and finder chart) http://gsaweb.ast.cam.ac.uk/alerts/alert/Gaia21bvg/

Gaia21btu

Region; Southern hemisphere RA 18 12 10.8 Dec -21 18 13 Last Gaia magnitude; 17.51 Time between observations; 3.0 days Gaia alerts link (includes data and finder chart) http://gsaweb.ast.cam.ac.uk/alerts/alert/Gaia21btu/

Previously notified alerts for which observations are still required Gaia21auw

Region; Southern Hemisphere RA 17 29 18.2, Dec -21 52 31 Last Gaia magnitude; 15.50 Time between observations; 1.0 day Gaia alerts link (includes data and finder chart) http://gsaweb.ast.cam.ac.uk/alerts/alert/Gaia21auw/

Gaia21bfr

Region; Northern hemisphere, Southern hemisphere RA 18:46:08.3, Dec -10:12:26 Last Gaia magnitude; 15.14 Time between observations; 1.0 day Gaia alerts link (includes data and finder chart); http://gsaweb.ast.cam.ac.uk/alerts/alert/Gaia21bfr/

Gaia21ckj

Region; Northern hemisphere, Southern Hemisphere RA 18 53 23.0, Dec; -01 14 06 Last Gaia magnitude; 17.37 Time between observations; 1.0 day Gaia alerts link (includes data and finder chart); http://gsaweb.ast.cam.ac.uk/alerts/alert/Gaia21ckj/

Gaia21dwf

Region; Southern hemisphere RA 18:26:29.4, Dec -20:04:52 Last Gaia magnitude; 16.00 Time between observations; 1.0 day Gaia alerts link (includes data and finder chart); http://gsaweb.ast.cam.ac.uk/alerts/alert/Gaia20dwf/

Observations are no longer required for; Gaia21azb Gaia21bzr

Please send observations to Roger Dymock. Data required;

Observing site Observer, name Photometric software Date and time (JD) Filter used Magnitude Error

Data from **<u>BHTOM</u>** and <u>Gaia Photometric Alerts</u> websites

3.5 Imaging

The required cadence (frequency of observations) is typically 1 day. This means that observations could fit in with exoplanet transit runs by taking a few images before or after those sessions. During high-magnification events, which are extremely sensitive to the presence of exoplanets, imaging sampling/cadence every 2-5 mins is recommended. Such events typically last 1-5 days

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 <u>MicroFUN</u> project range from 10 to 16 ins, 25 to 41 cms

Please note this new advice

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 2459249.03359	12.912 (12.916 (26.136 Gaia 26.140 Gaia		g20fnr g20fnr
2459249.03487	12.907 0	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

During high-magnification events, which are extremely sensitive to the presence of exoplanets, imaging sampling/cadence every 2-5 mins is recommended. Such events typically last 1-5 days

Calibrate images prior to uploading to the <u>BHTOM website</u>. Figure 3.5.2 is an image, being 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 Date and time (JD) Filter used Magnitude Error

4.0 Links

ASASSN – All-Sky Automated Survey for Supernovae

BlackHole TOM - <u>https://bh-tom.astrolabs.pl/</u> 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 <u>bhtom@astrouw.edu.pl</u>

BlackHole Help; <u>bhtom@astrouw.edu.pl</u> 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/BpNbksegUBI 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 31 hrs 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

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

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

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

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

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

<u>Microlensing Source</u> – 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 <u>Optical Gravitational Lensing Experiment (OGLE)</u> 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.

Warrumbungle Observatory

Select Astrophotography Online to schedule and pay for observations

Zwicky Transient Facility (ZTF) - https://www.ztf.caltech.edu/

5.0 Acknowledgements

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In addition to the above named I would also like to acknowledge the help given by; Etienne Bachelet, Postdoctoral Fellow at Las Cumbres Observatory

Jennifer Yee (MicroFUN project), Astrophysicist at the Center for Astrophysics | Harvard & Smithsonian

Pawel Zielinski PhD, Astronomical Observatory, University of Warsaw Siegfried Vanaverbeke, Belgian VVS, astrolab IRIS and University of Concepcion (Chile)

Appendix 1Example of image processing using AstrometricaA1.1Target – Gaia21bfr

Finder chart from BHTOM is shown in Figure A1.1



A1.1. Finder chart for Gaia21bfr

A1.2 Program Settings

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

Program Settings - Warrumbungle UCAC4_RM.	cfg	×
Observing Site CCD Program Environment Scale and Orientation Focal Length 3409.0 mm ± 1.0 % Position Angle 8.2 * ± 10.0 * Pointing ± 5.0 * Flip Horizontal Flip Vertical Auto-Rotate on PIERSIDE keyword ✓ Auto-Save FITS with WCS Time in File Header • Start of Exposure Middle of Exposure Offset 11.00 h from UT Precision 1.00 Seconds ✓ Skip checking of Time after Loading * *	Catalogs Internet CCD Chip Pixel Width 9.0 µm Pixel Height 9.0 µm Saturation 32000 Color Band C Blue (B) C Visual (V) Red (R) C Infrared (I) C Gaia Broadband (G) Filter R (Cousins) ▼ Exposure from FITS Minutes Seconds C Milliseconds	
<u>O</u> pen <u>Save</u> Save <u>A</u> s	OK Cance	

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.

Program Settings - Warrumbungle UCAC	C4_RM.cfg X
Observing Site CCD Program Enviro	onment Catalogs Internet
Object Detection Aperture Radius 6 Pixels Detection Limit 6.0 σ Minimum FWHM 1.50 Pixels PSF-Fit RMS 0.20 Search Radius 0.75 Search Radius 0.75 Pixels Background from ♥ PSF Output Output Output Plate Constants ♥ Linear Fit © Quadratic Fit ♥ Cubic Fit ♥ Output	Star Catalog UDCAC 4 Upper Limit Lower Limit 14.5 Reference Star Matching Number of Stars 100 Search Radius Image Alignment Number of Stars 50
Besiduals Astrometric Limit 0.50 " Photometric Limit 0.40 mag	MPC Report Include Magnitude Position to 0.001s/0.01'' Magnitude to 0.01mag

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 = 0.13mag

The Centroid feature was used to position the measuring aperture and size it so that it did not overlap the adjacent star – Figure A1.5.



Figure A1.5. Centroid size and position

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. 2459347.17508 15.685 R R 17.32 24.401 UCAC4 g21bfr ----- end -----

A1.4 Error calculation

Error = $\sqrt{(4/\text{SNR}^2 + \text{dmag}^2)}$ = $\sqrt{(4/17.32^2 + 0.13^2)}$ = $\sqrt{(0.013^2 + 0.13^2)}$ = 0.17

Reported R magnitude would therefore be 15.69 +/- 0.17

Note 1

In the settings for this example the Upper and Lower Mag Limits were set to 12 and 14.5 respectively. Changing these to 12 and 18 increased the number of Ref. stars and Ref/Ast stars from 504 and 416 to 640 and 517 but the end results were unchanged.

Appendix 2 BHTOM website

A2.1 Overview

A manual is available at <u>http://visata.astrouw.edu.pl/~wyrzykow/2021.01-BHTOM-manual-v.1.1.pdf</u> A few notes from my experience follows to help you navigate the <u>Black Hole TOM</u> website.

A2.2 Registering – add observatory

Not so straight forward as yet. The template for the OBSINFO file is somewhat of a nightmare. Mine for the Warrumbungle Observatory robotic telescope in Australia is shown in section A2.3.4 below. An alternative is to use a text version of your FITS header but mention this in the Comment box. You will also be asked to provide the limiting magnitude for your observatory plus all the filters available to you. The group is very helpful and will advise you of any further info required. A more user-friendly version of the OBSINFO file should be available soon.

If you are a BAA member, please, in addition to your name, mention this affiliation. This is required should any of your data be used in a future publication.

After your observatory is set up you have to log in, quite straight forward, and add it from the list, Figures A2.2.1 and A2.2.2.



Figure A2.2.1.1ist of observatories

BHTOM Target Gaia20	fnr 🗙 🔢 BHTOM Target		× +					- ø ×
\leftrightarrow \rightarrow C $$ bh	-tom.astrolabs.pl/observatory/list/					Q ☆	P 🖪 (• * 0 :
Apps G Google	0							Other bookmarks
BHTOM Targets	Target Grouping Observatories							
	List of observatories							
	with your name.			or uploading the data for processing. You should register an observatory in your account if you wa				
				ning to upload images or instrumental photometry for it. You can choose one from the list of alrea n the same telescope counts as a different observatory.	dy registered	observatories		
				hich can be used in the Cambridge Photometric Calibration Server. However, you can also upload	your data to	the CPCS direct	tly	
	My Observatories							
	Add new observatory							
	Observatory Name	Lon	Lat	CPCS Hashtag	Activation	Comment	Update	Delete
	Observatory Name Warrumbungle0.51_SBIG6303E			CPCS Hashtag bhtom, Warrumbungle0.51_SBIG6303E_Roger_Dymock_965fc40d466d24ce28ed875377341635		Comment	Update Edit	Delete
						Comment		
						Comment		
						Comment		
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						Comment		
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						Comment		
						Comment		
						Comment		
						Comment		

Figure A2.2.2. Observer specific observatories

A2.3 Uploading images and data to the BHTOM website

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

A2.3.1 Uploading FITS images

Once you have set up your observatory you can upload images without having to measure the magnitude of the object concerned. The magnitude of the target is calculated by CCDPhot on the BHTOM website.

This example uses an image if Gaia20fnr obtained with the Warrumbungle robotic telescope.

IMPORTANT NOTE. THE FITS HEADER MUST EXACTLY MATCH THAT IN THE OBSINFO FILE INPUT WHEN YOUR OBSERVATORY IS SET UP. IF NOT, YOU WILL GET PHOTOMETRY ERRORS WHEN YOUR UPLOADED IMAGES ARE ANALYSED BY CCDPHOT

FITS headers can be edited with, for example, AIP4WIN or the FITS4Win2 utility

- for Gaia objects the value of the OBJECT key in the FITS header must be e.g., Gaia20fnr
- ensure OBSERVER in the FITS header is your name e.g., Roger Dymock
- check DATE-OBS includes date and time
- delete TIME-OBS if present
- select target from the Targets screen Figure A2.3.1
- select Upload
- choose file (Gaia20fnr clear1.fit)
- click on Data product type (Fits image for photometric processing)
- select Dry Run if a test
- select Observatory Warrumbungle $0.51_SBIG6303E$
- Figure A2.3.2 shows the completed Upload screen
- click on the Upload button resulting screen Figure A2.3.3

BHTOM Target Gaia	a20fnr 🗙 🥮 2	2021.01-BHTOM-manual-v.1.1 × +		
\leftrightarrow \rightarrow C $\hat{\mathbf{n}}$	bh-tom.astrolabs.pl/bhl	ist/56/	Q & 1	P 🖪 🖻 🛪 😁 E
Apps G Google	3			Other bookmarks
BHTOM Targe	ets Target Grouping O	bservatories About		Roger Dymock Logout
	Successfully uploaded	d: Gala20fnr_clear_1_HNkf6dt.fit. Your file l	s processing. This might take several minutes	×
	Gaia20fnr		Photometry Spectroscopy Upload Manage Groups Data	
	Update Delete	Fetch target names		-
	Names	Gaia20fnr	Photometry Check for new data Interactive photometry plot	
	Target Type	SIDEREAL		
	Right Ascension	90.267		
	Declination	06:01:4.080 -18.9677 -18:58:3.720	12.0 -	
	Epoch	2000.0	I (APASS)	
	Galactic Longitude Galactic Latitude	224.87750824442153 -19.372360970063426	13.0 -	
	gaia_alert_name	Gaia20fnr	13.5 -	
	calib_server_name ztf_alert_name	ivo://Gaia20fnr		
	aavso_name gaiadr2_id	2990431491637998848	14.0 -	
	TNS_ID classification	AT2020ably Bright microlensing event	14.5 -	
	tweet	False		
	jdlastobs	2459234.9891535	15.0 -	
	maglast	12.87	2015 2016 2017 2018 2019 2020 2021	
	priority	10.0	* * * * * * * *	
	dicovery_date cadence	0.1	Download photometry data	Ŧ

Figure A2.3.1. Gaia20fnr details

🔢 BHTOM Target Gaia20fnr 🛛 🗙 🕂	÷	0 - 0
\leftrightarrow \rightarrow C \triangleq bh-tom.astrolabs.pl/b	ohlist/56/	Q 🕁 🗖 🛃 🖬
Apps Ġ Google 🔇		Other bookma
BHTOM Targets Target Grouping	Observatories About	Roger Dymock Logout
Gaia20fnr Update Delete F	etch target names	Photometry Spectroscopy Upload Manage Groups Data
Names	Gaia20fnr	Upload a data product
Target Type	SIDEREAL	Here you can upload your photometric and spectroscopic observations for this target. Please refer to the BHTOM manual for details.
Right Ascension	90.267	Example CSV formats for photometry and spectroscopy. SExtractor format is required for instrumental photometry. FITS is
	06:01:4.080	supported for spectra. For photometric FITS processing choose the observatory from the list. You can add a new instrument here.
Declination	-18.9677	Files
	-18:58:3.720	Choose files Gala20fnr clear 1.fit
Epoch	2000.0	
Galactic Longitude	224.87750824442153	Data product type
Galactic Latitude	-19.372360970063426	Instrumental photometry file (SExtractor format) Fits image for photometric processing Spectrum as ASCII
gaia_alert_name	Gaia20fnr	Photometric time-series (CSV)
calib_server_name	ivo://Gaia20fnr	Photometric time-series (ASAS-SN format)
ztf_alert_name		Matching radius
aavso_name gaiadr2 id	2990431491637998848	Default for the Observatory
TNS_ID	AT2020ably	✓ Dry Run (no data will be stored in the database)
classification	Bright microlensing event	
tweet	False	Observatory
jdlastobs	2459298.5648081	Warrumbungle0.51_SBIG6303E
maglast	12.95	Force filter
priority	10.0	Auto
dicovery_date cadence	0.1	71800
Sun_separation	86.6	Comment
dont_update_me	False	Comment
Survey View		

Figure A2.3.2. Completed Upload screen



Figure A2.3.3 Uploaded image being processed

A2.3.2 Uploading photometric data

Photometric data can be uploaded as a CSV table - Figure A2.3.4.

	× +	w.edu.pl/~wyrzykow/2021.01-BHTOM	-manual-	v.1.1.pdf				Q 🕁	0 P 1		0 * (1 :
ps G Google 🔇 2021.01-BHTOM-manu	Jal-v.1.1		28 /	31 -	50% +	I 🔊 _				ŧ	Other b	ookmark
		Photomet	ric o	data u	upload	ing - CS	SV table		🧏 Ope	en in Acr	obat	
	Caial9dke Update Delen Names Target Type Right Ascension Declination Epoch Galactic Longitude Galactic Latitude gala_alert_name	Fetch target names Gala 19dke SIDEREAL 291.49451 19:25:58.682 28.40886 +28:24:24.696 200.0 62.011128810184644 5.704135187425682 Gala19dke	Here you co details. Example Co supported For photom Files Choosee Data produ • Instrum • Fits imag • Spectrur	a data pr an upload your SV formats for p for spectra. hetric FITS proce Files No fil ict type ental photometi ge for photometi	roduct photometric and spec- hotometry and spec- essing choose e chosen ry file (SExtractor for rric processing	valory from the list.	uploading CSV file wi photometric data	th for HTS is		ki Logo.		
example CSV	calib_server_name ne on table	* hov/cels193ke # FACILITY: LCO # OBS-NAME: Observer's Name time 55959.06999999983 55959.06999999983 55959.0699999983	filter r g	magnitude 15.582 15.676 15.591	error 0.005 0.007 0.008		database	AAVSO				

Figure A2.3.4. 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 A2.3.1, and then saved as a .csv file, Figure A2.3.5. 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: Wari						
# OBS-NAME: Ro						
time	time filter magnitude					
59329.85846	R	12.545	0.003			
59329.86115	В	14.033	0.007			
59329.86672	В	14.014	0.007			
59329.86959	R	12.515	0.003			
59329.87226	В	14.031	0.006			
59329.88066	0.003					
59329.88336	В	13.992	0.006			

Table A2.3.1. Photometry input in Excel format

Photodata.csv	- Notepad			<
<u>File Edit Form</u>	at <u>V</u> iew <u>H</u> elp			
<pre># OBS-NAME: time,filter, 59329.85846, 59329.86115, 59329.86672, 59329.86959, 59329.87226,</pre>	Narrumbungle C Roger Dymock,, magnitude,erro R,12.545,0.003 B,14.033,0.007 B,14.014,0.007 R,12.515,0.003 B,14.031,0.006 R,12.511,0.003		ory,,,	^
	8,13.992,0.006			~
Ln 11, Cc 100%	Windows (CRLF)	UTF-8		a Vite

Figure A2.3.5. Photometry input in csv format

A2.3.3 Checking input

Input can be reviewed by selecting;

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

A2.3.4 Example obsinfo file

# DESCRIPTION	KEY	WORD as	strolabe	
FORMAT VALUE (s	3)	CON	IMENT	CONF FLAG
#	(in FITS)	(standard	.)	
([T]rue/[F]alse)				
#				
# OBSERVATORY				
	: -	• <u>ODCEDUA</u> T	· ctr	
				•
Warrumbungle_Observatory : - Observer	• OBSERVER	• OBSERVER	• str	
Roger Dymock : -		: F		•
Obserwatory longitude [deg]			: float	:
210.806728 : dec				
Observatory latitude [deg]			: float	: -
31.276249 : deg		: F		
Observatory altitude [m]	: -	: ALTITUDE	: float	: 552
: m : F				
±	: TELESCOP	: TELESCOP	: str	:
<pre>F_6.8_PlaneWave_CDK_0.51m : -</pre>		: F		
5	: -		: str	:
Warrumbungle_Telescope : ne	ear SSO	: F		
# TTME (stant of ownerition)				
<pre># TIME (start of exposition) Time system</pre>	• _	: TIMESYS	· ctr	: UTC
: - : F	• -	. IIMESIS	. SUI	. 010
Date	• DATE-OBS	: DATE-OBS	• 37373777-r	mm-dd•-
: "-" : F	. Ditte 000	• 01111 000	• ४४४४ 1	iun da .
· · · · · ·	: TIME-OBS	: TIME-OBS	: hh:mm:	:ss : -
: ":" : F				-

Julian date	: JD	: JD	: float	: -
: middle of exp. : F Exposition time	: EXPTIME	: EXPTIME	: float	: -
: seconds : F				
<pre># INSTRUMENT Instrument name</pre>	: INSTRUME	E : INSTRUME	E : str	:
SBIG_STL-6303-3-CCD : - Detector X size [pix]	-	: F : NAXIS1	: int	: -
: - : F Detector Y size [pix]	: NAXIS2	: NAXIS2	• int	· _
: - : F Binning		G : BIN		• : 1
2 : -	: F			
Instr. mode, readout speed 2380 1190 : ns/pix		: READTIME : F		:
Gain 2.45 : e/ADU	: EGAIN : F	: GAIN	: float	: 1.4
Read-out noise 5.6 : ADU (13.5e RMS	: -) : F	: RDNOISE	: float	: 9.7
Saturation limit 64000 40000 : ADU	: -	: SATURATE : F	I : int	:
Pixel scale along x-axis 0.0001494 0.0002987 : deg/p.	: -	: CDELT1 : F	: float	:
Pixel scale along y-axis	: -	: CDELT2	: float	:
0.0001494 0.0002987 : deg/p. X reference pixel (center)	: -	: F : CRPIX1	: int	:
1536 768 : pix po Y reference pixel (center)		: F : CRPIX2	: int	:
1024 512 : pix po Pixel size along x-axis		: F : PIXSIZE1	L : float	: 9.0
18.0 : microm Pixel size along y-axis	: F			: 9.0
18.0 : microm Position angle	: F	: ORIENTAT		: 0.0
: deg : F	: -			
Image type Light Frame OBJECT : -		P : OBSTYPE : F	: str	:
Filters V, R, I, Clear B, V, R, I, 1		: FILTER and ID : F	: str	: В,
Tel. limiting magnitude (V) : mag (in V passband) : F	: -	: MAGLIMIT	[: float	: 20.5
# OBJECT & WCS				
Object name : - : F	: OBJECT	: OBJECT	: str	: -
Epoch of coord. system			: float	:
2000.0 : year Coord. system		: F 5 : RADESYS	: str	:
FK5 : - Coord. type projection RA	: CTYPE1	: F : CTYPE1	: str	:
RATAN : - Coord. type projection DEC	: CTYPE2	: F : CTYPE2	: str	:
DECTAN : - Coord. unit RA	: -	: F : CUNIT1		:
deg : - Coord. unit DEC	• _	: F : CUNIT2		•
deg : -		: EONI12 : F		

	Right Ascension	: F	:	OB	JCTRA	:	RA	:	float	:	-
•	Declination	• -	:	OB	JCTDEC	:	DEC	:	float	:	-
:	deg	: F									
	Right Ascension	WCS	:	-		:	CRVAL1	:	float	:	-
:	deg	: F									
	Declination WCS		:	-		:	CRVAL2	:	float	:	-
:	deg	: F									
#	OTHER & CALIBRA	FION									
	Original filenar	ne	:	-		:	FILENAME	:	a32	:	-
:	original filenar	ne		:	F						
	Overscan		:	-		:	OVERSCAN	:	str	:	No
:	does overscan ex	kist		:	F						
	Trim section		:	-		:	TRIMSEC	:	str	:	-
:	specifies initia	al trim	section	n :	F						
	Low good flat le	evel	:	-		:	FLATLOW	:	float	:	-
:	ADU low thresho	ld		:	F						
	High good flat	level	:	-		:	FLATHIGH	:	float	:	-
:	ADU highthresho	ld		:	F						

Additional information & comments:

FITS extention : *.fit

http://new.sierrastars.com/Telescopes/Warrumbungle

https://www.virtualtelescope.eu/wordpress/wp-

content/uploads/2012/10/STL6303_specs_7.12.11.pdf

field of view of 27.6 x 18.4 arc minutes

The CCD chip has a high quantum efficiency (68% peak).

Kodak KAF 6303E 3060 x 2040 pixel CCD chip with 9-micron

pixels giving an image scale of 0.54 arc seconds/pixel

un-binned and 1.1 arc seconds/pixel binned 2 x 2.

The Warrumbungle telescope is housed in a Sirius 3.5-meter dome



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. $\theta LS/\theta E$.

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 <u>caustic</u> 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.

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