Exoplanet imaging and discovery project – version 2

Originated 2019 October 2

My thanks to Mark Trapnell who has pilot tested this project which incorporates his suggested changes.

Note. Section 6, 'What to do if you discover a new exoplanet' is not yet complete as there is not yet a confirmed mechanism for amateurs to report such discoveries. One possibility is to use The Astronomer's Telegram website at <u>http://www.astronomerstelegram.org/</u> The editors have been contacted with a view to understanding how we might use this facility.

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1.0 Introduction

The nature of this project makes it suitable for those new to exoplanet imaging and the more experienced imager.

In Chapter 3 of his book 'Exoplanet Observing for Amateurs', Bruce Gary describes a project – monitoring known Bright Transiting Exoplanets (BTEs) out-of-transit. Known exoplanets may well have additional companions orbiting in the same plane so observing at times other than those for known transits may yield a discovery. To maximise the chances of such a discovery the impact parameter, closeness of the known transit to the centre of the star, needs to be much less than 1.0 which indicates a grazing transit. This is explained below.

A list of targets is included in section 3.1. The purpose of this project is to have observers concentrate on these to maximise the chances of discovering an exoplanet

2.0 Target selection

This section explains how to select stars specific to this project. For this exercise I selected the brighter host stars with the greatest transit depths. For another specific star enter its name in the Name box being careful to include dashes, spaces, etc. These will be helpful for beginners to exoplanet imaging and those who wish to confirm their expertise. It may be a good idea to image the transit of the known exoplanet before searching for additional ones. Such an exercise will confirm that all is well with your equipment and method.

First one needs to find suitable exoplanet transits. Gary's book refers the reader to the Exoplanet Transit Database (ETD) but I would like to introduce an alternative source – Find Exoplanet Transits – Figure 2.1.

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Find Exoplanet Transits						
This form calculates which transits of the 2500 known transiting exoplanets are observable from a given						
location at a given time. Specify a time window, an observing location (either an observatory from the list or choose "Enter latitude/longitude" at the end of the list), and optionally any filters (e.g. minimum						
transit depth or elevation). The output includes transit time and elevation, and links to further						
information about each object, including finding charts and airmass plots. (There are also stand-alone						
pages for generating finding charts and airmass plots for any target.)						- 1
Observatory:						
Choose an observatory, or choose "manual coordinate entry" at end of list:						
Enter specific latitude/longitude/timezone 🔹 💿 Use UTC / 🔍 Use observatory's local time.						
Observatory latitude (degrees): 51 (North is positive.)						
Observatory longitude (degrees): -1 (East is positive.)						
Observatory timezone: UTC 🔹						
Date window:						
Base date for transit list (mm-dd-yyyy or 'today'): 10-01-2019						
From that date, show transits for the next 90 days.						
(Also include transits from the previous days.)						
Constraints:						
Elevation:						
Only show transits with an elevation (in degrees) of at least:						
at ingress: 30						
Combine constraints with O AND OR.						•

Figure 2.1. Find Exoplanet Transits homepage

Location – Latitude 51 degrees North, Longitude -1 Base data for transit list – 10-01-2019 (2019 October 1 in English) Show transits for next 90 days Elevation – ingress and egress of at least 30 degrees Out-of-transit baseline – 1 hours to show whether out-of-transit baseline can be observed. Depth – at least 20 millimag V magnitude – brighter than 13

Clicking on submit displays the 'Upcoming events' page – Figure 2.2.

Upcoming t		+							0
← → C Apps G	https://astro.swart Google	hmore.edu/pri	nt_transits.cgi	observatory_stri	ng=Specified_La	at_Long&us	e_utc=1&obs		🚈 🛛 🝝 Other bookma
earch:		Show if vis	ible transit %	+ baseline % >	0		V _{max} :		
Local evening date	Name 🗍	V or Kepler ∳ mag	Start— Mid —End	Duration 🔶	BJD _{TDB} start- mid-end	Elev. at start, mid, end ±1.2 hrs	% of transit (baseline) observable, ∲ Suggested obs. start, end	RA & Dec (J2000)	Depth (ppt) ≑
 Wed. 2019- 10-02 (local date) Nautical twilight 18:51 – 04:55 (UTC) 	HAT-P-19 b Finding charts: Annotated. SkyMap: Info: Exoplanets.org, Simbad, Gaia DR2, TIC, VSX, Vizier phot.: Airmass.plot, ACP plan	12.90 Moon 24% @128°	22:57 00:09- 01:35 03:00 04:12 ±0:08	2:50	8759.507 8759.566 8759.625	71° 74°, 66°, 53° 42°	100% (100%) 22:49—04:20	00:38:04.01 +34:42:41.5	20.1
Thu. 2019-10 Thu. 2019-	-03: Nautical twiligh <u>Qatar-1 b</u> Finding charts:	t 2019-10-03	3 18:49 — 20	19-10-04 04:57	local time /	2019-10-0	03 18:49 — 2019-	10-04 04:57 U	тс
10-03 (local date) Nautical	Annotated, <u>SkyMap;</u> Info: <u>Exoplanets.org</u> , Simbad, Gaia DR2.	12.84 Moon 31%	18:17 19:29— 20:17 —21:05	1:36	8760.312 8760.346 8760.379	73° 76°, 74°, 71°	100% (66%)	20:13:31.61 +65:09:43.5	21.2

Figure 2.2. Find Exoplanet Transits, Upcoming events

3.0 Project targets

3.1 Selected targets

In addition, high declination targets, for the given location, were chosen so that these can be observed for longer periods and improve chances of detecting additional exoplanets. Data in Table 3.1 is from <u>Find Exoplanet Transits</u> except for the Impact parameter and Orbital inclination which is from <u>http://exoplanets.org/</u>. The Impact parameter and Orbital inclination are important as they indicate the chances of discovering additional planets in the system.

Star and planet (1)	ETD (2)	V mag	Transit duration (hrs)	Transit Depth (ppt/ millimag)	RA	Dec	Observing period
HAT-P-19 b	Link	12.9	2.50	20.1	00:38:04.10	+34:42:41.5	Jul - Dec
WASP-11 b		11.9	2.33	16.2	03:09:28.54	+30:40:24.7	Aug - Feb
HAT-P-12 b	Link	12.8	2.20	19.8	13:57:33.48	+43:29:36.7	Jan - Jul
XO-1 b	Link	11.2	2.56	17.6	16:02:11.84	+28:02:10.4	Feb - Aug
HAT-P-18 b	Link	12.8	2.42	18.6	17:05:23.15	+33:00:44.9	Mar - Aug
WASP-10 b	Link	12.7	2.13	25.2	23:15:58.30	+31:27:46.2	Jun - Dec

Table 3.1. Selected targets

Notes

(1) Link to NASA Exoplanet Archive – enter star name (without 'b') in search box to obtain data

(2) Exoplanet Transit Database links

Observability of the selected targets can be ascertained using the Object Visibility facility at <u>http://catserver.ing.iac.es/staralt/</u> Figure 3.1 is a screen shot of the inputs for the given location and stars listed in Table 3.1.

Inputs;

- Mode; Starobs
- Night; first night of required observing period. 01 September 2019 in this example
- Observatory; -1.00 (Longitude), 51.00 (Latitude), 39 (Altitude), 0 (UT offset)
- Coordinates; Enter a name and RA and Dec for each star
- Moon distance; as is
- Options; Min elevation = 20, Output = GIF (attachment)
- Submit

The output chart is shown in Figure 3.2.

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Apps Ġ Google	2013					Other I	bookm	18
	Mode	Starobs •						
	Night	01 \checkmark September \checkmark 2019 \checkmark or date when the local night starts. Staralt, Startrack only.						
	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-offset(hours) Ex.: 289.2767 -30.2283 2725 -4 -1.00 51.00 39 0						
	Coordinates	Formats can be any of these: name hh mm ss tdd mm ss name ddd.ddd dd.ddd name ddd.ddd dd.ddd name must be a single word with no dots, avoid using single numbers. Every entry must be in the same format, do not use different formats with different entries. We recommend a maximum of 100 targets per submission. H12 13 57 33 +43 29 37 X1 16 02 12 +28 02 10 H18 17 05 23 +33 00 45 W10 23 15 38 +31 27 46 Alternatively, you can upload a file with coordinates. You can use the same format as in the TCS catalog. Target names must be single words with no dots. Choose File No file chosen						
	Options	Moon distance Included on plot. Moon coordinates at ~02:00 UT. Staralt only. 20°, X=2.9 ▼ Min. elevation (or max. airmass X). Starobs, Starmult only. GIF [inline] ▼						
	Submit	Retrieve Help						
		WHT: 89.8° < Altitude < 12° (plot). Targets with +28:57:40>Dec>+28:33:40 won't be						

Figure 3.1. Object visibility inputs

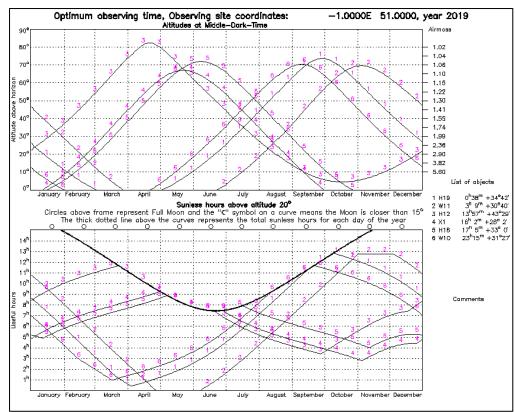


Figure 3.2. Object visibility output

From Figure 3.2 one can see that, for example, item 1, HAT-P-19 is observable from mid-June to mid-January (above a minimum of 20 degrees altitude).

3.2 Additional data on selected targets

Additional data on the targets listed in Table 3.1 is available using HAT-P-19 b as an example.

There are two ways of bringing up a chart. In the Name column;

- selecting Annotated Figure 3.3
- selecting SkyMap Figure 3.4

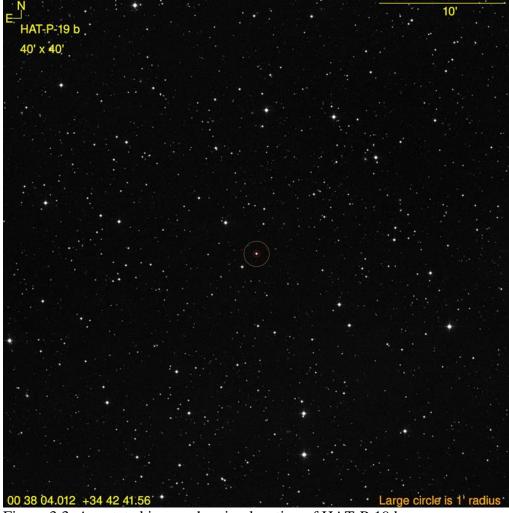


Figure 3.3. Annotated image showing location of HAT-P-19 b

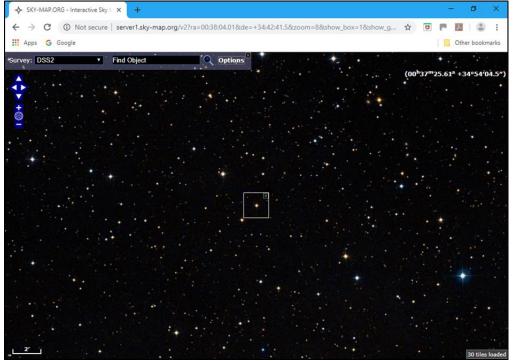


Figure 3.4. Skymap chart showing location of HAT-P-19 b

Data for the HAT-P-32 system, Figure 3.5, is displayed by selecting Exoplanets.org in the Name column, Figure 2.2.

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ightarrow C (i) Not secure e	xoplanets.org/detail/H	HAT-P-19_b		Q	4		٢
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oplanets Data Explorer Table	Plots Send data reports to:	datamaster@exoplanets.org and bu	ig reports to: webmaster@exoplani	ets.org		F	lelp
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		HAT-P-	19 b				
	0	Orbital P	arameters	Stella	ar Properties		
		Msin(i) [mjupiter]	0.292 ± 0.0176	Star Name		HAT-P-19	
		Planet Mass [mjupiter]	0.292 ± 0.0176	Binary Flag		Х	
		Semi-Major Axis [au]	0.04664 ± 0.00078	Mass of Star	[msun]	0.842 ± 0.042	2
		Separation [au]	0.04664 ± 0.00078	Radius of Star	[rsun]	0.820 ± 0.04	в
		Orbital Period [day]	4.0087780 ± 6×10 ⁻⁶	[Fe/H]		0.230 ± 0.08	
Velocity Profile Curren	tly Unavailable	Velocity Semiamplitude [m/s]	42.0 + 2.1	T _{eff}	[k]	4990 ± 130	
		[m/s]	42.0 = 2.1	Density of star	[g/cm^3]	Unavailable	
		Orbital Eccentricity	0.067 ± 0.042	log10(g)		4.540 ± 0.05	
			88.20 ± 0.4	Vsin(i)	[km/s]	0.70 ± 0.5	
		Argument of Periastron	256 ± 77	Gamma	C. Contraction	Unavailable	
			Unavailable				
			2454798.98800 ± 0.00034	Stella	r Magnitudes	;	
		Velocity Slope [m/s/day]		V mag		12.9	
Discovery and Ref	ferences	Spin-Orbit Misalignment	Henunilahla	B-V		Unavailable	
Other Name	2MASS	[deg]	Unavallable	2MASS J		11.1	
	J00380401+3442416	Transit	1	2MASS H		10.6	
First Publication Date	2011			2MASS K _S		10.5	
Method of discovery for the planet	Transit	Transit P	arameters	S _{HK}		Unavailable	
Method of discovery of first planet in system	Transit	Planetary Radius [rjupiter]	1.132 ± 0.072	log R _{HK}		Unavailable	
Orbit Reference	Hartman 2011	and the second se	2455091.53417 ± 0.00034	KP		Unavailable	1
First Reference	Hartman 2011	Duration of Transit [day]	and the second sec			onavanable	
EPE Link	HAT-P-19	Impact Parameter	0.404 +0.061/-0.088	Coordina	tes and Catal	loas	
ETD Link	HAT-P-19 b	a/R*	12.26 ± 0.75	RA (h:m:s)		0:38:04.012	
Exoplanet Archive Link	HAT-P-19 b	Transit Depth	0.02011 ± 0.00057	DEC (d:m:s)		+34:42:41.5	
SIMBAD Link	GSC 02283-00589	Planetary Density [g/cm^3]	0.250 ± 0.04	Parallax		+34:42:41.5	
		Surface Gravity	2.755 ± 0.058	FaialldX	[marcsec] 4	1.05 ± 0.55	

Figure 3.5. Exoplanet.org data for the HAT-P-19 exoplanetary system.

3.3 Aids to target identification

(a) Exoplanet.org data, linked to from the relevant entry in the Find Exoplanet Transit listing includes alternative names in the Discovery and References column on the left of the page.

(b) The Exoplanet.eu catalog can be searched for the target star - Figure 3.6.

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Showing 1 planets / 1 plane Show 100 • entries	etary systems / 0 mu	ultiple planet sys	stems	Ρ	lanet Searc	h <mark>hat-p-1</mark> 9		× Show	All fields / hide columns]
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Show 100 • entries	Mass (MJup)	Radius (R _{Jup})	Period (day)	a (AU)	е	<i>i</i> (deg)	Ang. dist. (arcsec)	Discovery	Vpdate]

Figure 3.6. Exoplanet.eu entry for HAT-P-19

Clicking on HAT-P-19 b in the Planet column links to more data for the system including alternative names, or aliases, at the bottom of the Star column under remarks – Figure 3.7.

The Extrasolar	r Planet Encyclopae: × +								_	٥	\rightarrow
→ C	Not secure exoplan	et.eu/catalog/hat-p-19_b/			e	1 1	۵		r	Θ	
Apps Ġ Go	oogle								Othe	er bookr	mark
	Name	НАТ-Р-19 Ь		Star							
	Planet Status	Confirmed		HAT-P-19				- 1			
	Discovered in	2010		Name	HAT-P-19						
	Mass	0.292 (_{-0.018} ^{+0.018}) M _J		Distance	215.0 (± 15.0) pc			- 1			
	Mass*sin(i)	-		Spectral type	к			- 1			
	Semi-Major Axis	0.0466 (± 0.0008) AU		Apparent magnitud V	e 12.9						
	Orbital Period	4.008784 (± 7e-07) day	+	Mass	0.842 (± 0.042) M _{Sun}						
	Eccentricity	0.067 (± 0.042)		1				- 1			
	ω	256.0 (± 77.0) deg		Age	8.8 (± 5.2) Gyr			- 1			
	Tperi	-		Effective temperatu	re4990.0 (± 130.0)	_		- 1			
	Radius	1.132 (_{-0.072} ^{+0.072}) R _J		Radius	0.82 (± 0.048) Rg	_					
	Inclination	88.51 (± 0.22) deg	+	Metallicity [Fe/H]	0.23 (± 0.08)			- 1			
	Update	2015-08-26		Detected Disc	-			- 1			
	Detection Method	Primary Transit		Magnetic Field	-			- 1			
	Mass Detection Method	_		RA2000	00:38:04.0						
	Radius Detection Method	-		Dec ₂₀₀₀	+34:42:42			- 1			
	Primary transit	2455091.535 (± 0.00015) JD	⊨ +	Alternate Names							
	Secondary transit	_		Planetary system	1 planet			- 1			
	λ	_		Remarks Alias GSC 2283-009	589						
				Alias 2MA55 00380							
	Impact Parameter b	-		More data							

Figure 3.7. More Exoplanet.eu catalog data

(c) The free planetarium program <u>Stellarium</u> has an exoplanet feature which allows one to search for and display the position of a specific exoplanet. Figure 3.8 is a screen shot showing HAT-P-19.



Fig 3.8. Stellarium screenshot showing HAT-P-19

4.0 Searching for exoplanets out-of-transit

4.1 When to search

In order to determine when known exoplanets are in and out of transit (based on the input parameters listed in section 2) click on the exoplanets name in the Name column of the Find Exoplanet Transits listing which produces a list of transits for the next 90 days. This will enable observers to search for additional exoplanets between known transits.

4.2 Targets

Targets were selected by;

- a) Their inclusion in the Exoplanet Transit Database to allow observers to compare results for existing exoplanets
- b) Existence of multiple exoplanets as listed in the NASA Exoplanet Archive

Table 4.1 lists targets, based on the criteria mentioned above, which may have additional planets. See Appendix B for further data.

Star (1)	ETD (2)	RA	Dec	Known planets	Potential planets (3)
Kepler-9	<u>b</u>	19 02 17.756	+38 24 03.1	3	2
Kepler-11	<u>d</u>	19 48 27.622	+41 54 32.8	6	1
	<u>e</u>				
	<u>f</u>				
	g				

Kepler-19	<u>b</u>	19 21 41.002	+37 51 06.4	3	3
WASP-47	<u>b</u>	22 04 48.731	-12 01 07.9	4	5

Table 4.1. Target data

Notes

(1) Link to NASA Exoplanet Archive – enter star name (without 'b') in search box to obtain data

(2) Exoplanet Transit Database links

(3) These are planets that might exist between the known planets using the Titius-Bode law as explained in Appendix B

As mentioned in section 3.1 observability of the selected targets can be ascertained using the Object Visibility facility at <u>http://catserver.ing.iac.es/staralt/</u> Figure 4.1 is a screen shot of the inputs for the given location and stars listed in Table 4.1.

Inputs;

- Mode; Starobs
- Night; first night of required observing period. 01 September 2019 in this example
- Observatory; -1.00 (Longitude), 51.00 (Latitude), 39 (Altitude), 0 (UT offset)
- Coordinates; Enter a name and RA and Dec for each star
- Moon distance; as is
- Options; Min elevation = 20, Output = GIF (attachment)
- Submit

The output chart is shown in Figure 4.2.

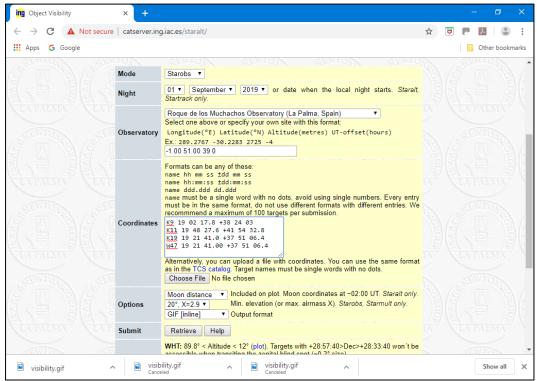


Figure 4.1. Object visibility inputs

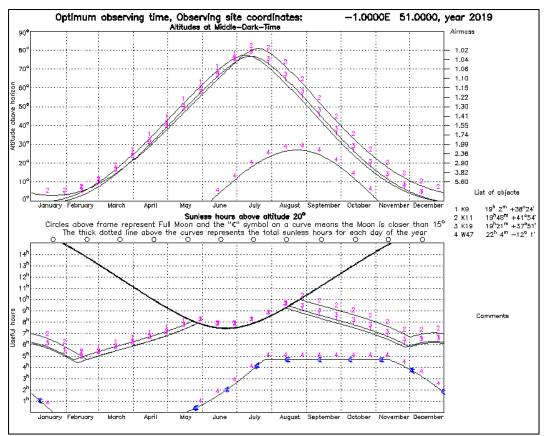


Figure 4.2. Object visibility output

From Figure 4.2 it can be seen that WASP-47 is not an ideal target for UK observers but is better placed for observers further south.

5.0 Imaging, analysis and reporting

5.1 Verification

A useful check on one's equipment and expertise is to first monitor the selected star during a transit. I would strongly recommend doing this particularly if you are new to this activity, to verify one's observations.

Using HAT-P-19b as an example a transit light curve can be obtained;

- access the Exoplanet Transit Database
- select HAT-P-19b from the list on the left of the page
- scroll down and select <u>TRESCA</u> against one of the light curves listed, 2017-01-12 by Marc Breton in this example, and the transit light curve will be displayed – Figure 5.1.

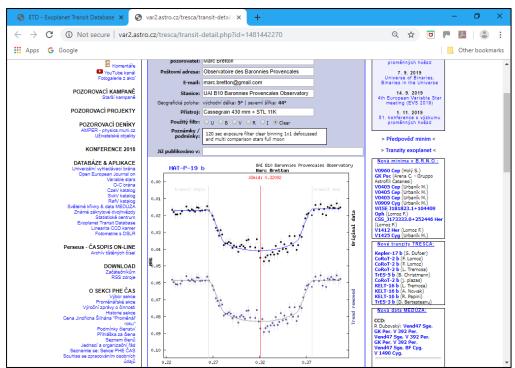


Figure 5.1. Transit light curve for HAT-P-19b Credit Marc Breton/TRESCA

So now you know about one exoplanet orbiting HAT-P-32 the time has come to try and discover another in that system.

5.2 Imaging and reporting

At this point, to avoid duplication on the website, one should refer to the 'Exoplanet Transit Imaging and analysis Process' by Mark Salisbury starting at paragraph 5.0 (or from the beginning for an introduction and additional information on target selection). To produce a light curve from your observations, AstroImageJ is recommended and there are guides to this on the Guides/Tutorials. It is good practice to make ones results available to the wider astronomical world. Submitting observations to the BAA Photometry Database and the Exoplanet Transit Database (ETD) is covered in section 7.0 of Mark's process. Links to the BAA Photometry Database and relevant guides are listed on the Guides/Tutorials page in the section Other guides and tutorials.

5.3 Imaging guidelines

The following guidelines, my thanks to ETAG, are suggested to increase the chances of a successful imaging run. Even if not all the conditions are ideal please do give this project a try. The more you try the better you will get.

- clear dark skies even hazy cloud will affect magnitude measurements
- not too windy (< 30 mph)
- not around time of full moon
- altitude 30° above horizon throughout whole transit
- not close to moon > 60 arcmin
- use an exposure time / binning to get a good signal to noise ratio (SNR) > 600 at least half well depth
- define your filter. Red preferred but try unfiltered for small telescopes and/or improve SNR

I thought it worthwhile including these comments by Paul Leyland, an ETAG member, to supplement the above.

Above all: carry out a dry run on the star to be observed well in advance of the predicted time of transit. Use this to determine the exposure time to reach a desirable SNR. A photometric accuracy of x millimags requires a SNR of 1000/x (an approximation but a very good one). Ideally one should aim for an accuracy of around a tenth of the transit depth but even an accuracy of, say, a half, can give useful measurements, especially when pooled with those of other observers.

If you do this, the other conditions on altitude, moonlight and twilight become moot.

From the exposure time, compute the cadence. If you need a ten-minute exposure, you are not going to measure the ingress, mid-transit and egress times to much better than that. Nonetheless, if your observations are pooled with those made by others, the joint data set may give better timings than those obtainable from any one contribution.

It's not strictly necessary to see the whole transit. If the star isn't visible (whether below the horizon or behind clouds) at your site until after first contact, you can't measure ingress and mid-transit times. Another observer elsewhere may not be able to measure the egress and mid-transit times for similar reasons; the two data sets combined allow for recovery of all three times. Please don't put people off observing! Remember "the perfect is the enemy of the good".

You may have noticed an underlying theme, summarized as "Many hands make light work", as in make the collected starlight work for you and the astronomical community. Submit your data, even though it may not be as pretty as you would wish. That's why the first exoplanet photometry data set is in the BAA-VSS database despite the entirely spurious spike in brightness part way through the session.

6.0 What to do if you discover a new exoplanet

Note; A good question to which, as yet, I don't have what I consider to be a satisfactory answer.

6.1 Discovery confirmation

As with all potential discoveries one should seek confirmation before reporting it as such.

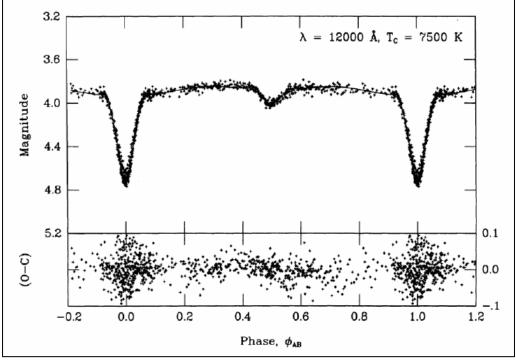
Data on the known exoplanet(s) in an exoplanetary system can be obtained from the <u>NASA</u> <u>Exoplanet archive</u>. For example, entering HAT-P-19 in the search box on the home page confirms that there is only one know planet in that system, Figure 6.1.

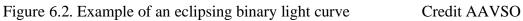
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Confirmed Hoat Overview This page contains all available information in th archive about a specific planet host. All planetars stellar and statistical information displays by default, and views can be customized by selectir and de-selecting fields in the bottom-left pane. Denotment el Planets table, are indicated by an orange background for the row. See the <u>APIC planet</u> <u>Calumps</u> documentation for column definitions a the <u>user's guide</u> for a defailed explanation of this page.	r, ng a nd	PLAN	ETI	HOST PAG		RVIE	W	Finde		2MASS
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ections Update Select All Reset	~	HAT-P-19		2MASS	5 J00380401·	+3442416		WIS	E J00380	3.98+344241.2
Overview	-			NASA	Exoplane	Archive Li	nks			
Planet Orbital Properties		Planet			d Overviews			Tra	nsit Servi	ce
Planet Parameters		HAT-P-19 b		Confirmed lanet Ho		pler Pipeline			наті	P-19 b Transits
Planet Transit Properties		1011-100		<u>iuner</u> <u>no</u>	<u>sc</u>				1101-1	-13 b Hullaita
Notes	-				Planet Orb	ital Propert	ies			
 ✓ General Information ✓ Summary of Stellar Information 		Planet Period (days	Se	emi-Major Axis (AU)	Inclination (deg)	Eccentricity	Time of Periastron Passage (days)	Longitude of Periastron (deg)	Date of Orbital Solution	Reference
Stellar Information		b 4.0087780±0.000	0060 0.0	04664 +0.00076	88.20±0.40	<0.024	null	(ueg) null	null	Bonomo et al. 201
		b 4.0087842±0.000			88.51±0.22	null	null	null	null	Seeliger et al. 201
Stollar Proportion										
Stellar Properties	-	b 4.008778±0.00	0006	0.0466±0.0008	88.2±0.4	0.067±0.042	nuli	256±77	null	Hartman et al. 201

Figure 6.1. Data on HAT-P-19 exoplanetary system

It could, for example, be an eclipsing binary, example in Figure 6.2 showing primary (deeper) and secondary (Shallower) eclipses. Data on these can be found at;

- http://www.as.up.krakow.pl/o-c/index.php3
- http://var2.astro.cz/EN/brno/eclipsing_binaries.php





A typical exoplanet transit light curve is shown in Figure 5.1 above.

Notifying other exoplanet observers can be done via the <u>BAA Exoplanet forum</u> plus an email to the Assistant Director (Exoplanets). Further observations by others may, or may not, confirm the discovery.

6.2 Discovery reporting

One can report newly discovered asteroids, variable stars, novae and supernovae to various websites e.g. <u>NEO Confirmation Page</u>, <u>AAVSO VSX</u>, <u>CBAT</u> but the equivalent does not appear to exist for exoplanets.

There are various databases to which exoplanet data can be uploaded e.g.;

- The BAA Photometry Database
- AAVSO Exoplanet Database
- Exoplanet Transit Database
- TRESCA

However, there is no facility in these for identifying potential/confirmed exoplanet discoveries. Therefore, it seems to me that we do need a vehicle for flagging up potential exoplanets so that others can confirm, or not as the case may be, that the discovery is real and not, for example, an eclipsing binary.

One possibility is to use The Astronomer's Telegram website at <u>http://www.astronomerstelegram.org/</u> The editors have been contacted with a view to understanding how we might use this facility.

What needs to be reported also needs definition but a minimum might be;

- host star name
- newly discovered planet name which would be host star plus next letter after existing planets e.g. Kepler-9 e as b, c and d are known
- transit data; mid-time and duration

Appendix A Impact parameter and orbit inclination

Table A1 lists hypothetical planets for various values of impact parameter, b. For a grazing transit, b=1, the orbital period is 16.8559 days and the orbital radius is 8176488 km/0.12150 au. Therefore, if a potential planet has values greater than these it is not likely to be real unless, of course, it is orbiting in a different plane.

Data from Exoplanets.org for HAT-P-19 b;

- impact parameter (b) = 0.404
- semi-major axis (a) = 0.04664 au = 6977245 km
- stellar radius (R^*) = 696265 km
- orbital inclination (i) = 88.9 degrees

Planet	b	a=bxR*/cosi	a (km)	a (au)	Orbital period (days)
HAT-P-19 b	0.404	0.04664	6977245	0.04664	4.0088
Planet 1	0.200	0.02430	3635298	0.02430	1.5076
Planet 2	0.300	0.03645	5452947	0.03645	2.7697
Planet 3	0.400	0.04860	7270595	0.04860	4.2642
Planet 4	0.500	0.06075	9088244	0.06075	5.9594
Planet 5	0.600	0.07290	10905893	0.07290	7.8339

Planet 6	0.700	0.08505	12723542	0.08505	9.8718
Planet 7	0.800	0.09720	14541191	0.09720	12.0611
Planet 8	0.900	0.10935	16358840	0.10935	14.3918
Planet 9	1.000	0.12150	18176488	0.12150	16.8559

Table A1. Hypothetical additional planets in HAT-P-19 system

Paul Anthony Wilson explains how the impact parameter is calculated on his webpage at <u>https://www.paulanthonywilson.com/exoplanets/exoplanet-detection-techniques/the-</u>exoplanet-transit-method/ and the relevant section is shown in Figure A1.

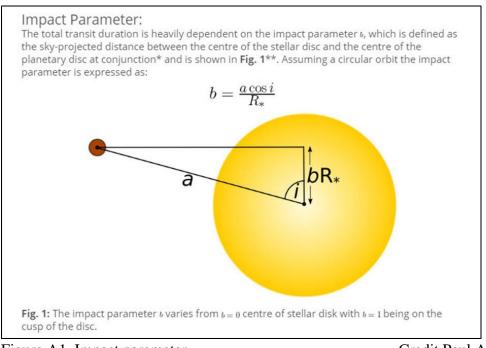


Figure A1. Impact parameter

Credit Paul Anthony Wilson

Figure A2 shows a diagram similar to Figure A2 for the hypothetical Planet 9 in the HAT-P-19 system.

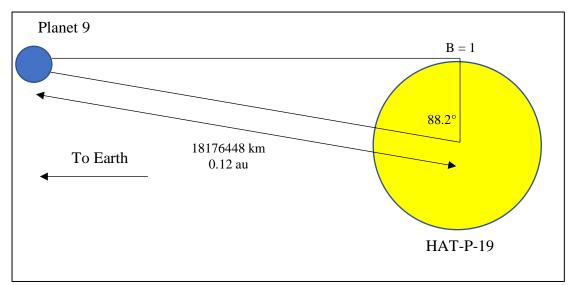


Figure A2. Limits to planet discovery using HAT-P-19 data

Appendix BTitius-Bode law – its application to exoplanetary systemsB1Introduction

The Titius-Bode law may help determine possible orbits of yet undiscovered planets. The law describes the semi-major axis of each planet outward from the Sun by the equation, a = (4 + x)/10 au where x = 0, 3, 6, 12, 24, etc with each number being double the previous one (with the exception of the 2nd).

Table B1 (from the paper 'Applying Titius-Bode's law on Exoplanetary Systems' by Mohammed Basil Altaie and A.I.Al-sharif), -

https://www.researchgate.net/publication/301848233_Applying_Titius-

Bode's Law on Exoplanetry Systems shows the relationship between the planets in the Kepler 215 system.

	Kepler 215								
Titius-Bode									
n	Value	Calculated semi-major axis (Ac)	Scale factor applied to Ac	Actual semi- major axis (Aa)	Log Ac	r	P(days)	Log(P)	
1	0	0.40	0.0452		-1.3449		4.0434	0.6067	
2	3	0.70	0.0791	0.0840	-1.1018	1.7500	9.3607	0.9713	
3	6	1.00	0.1130	0.1130	-0.9469	1.4286	14.6671	1.1663	
4	12	1.60	0.1808	0.1850	-0.7428	1.6000	30.8644	1.4895	
5	24	2.80	0.3164	0.3140	-0.4998	1.7500	68.1610	1.8335	

Table B1. Titius-Bode law applied to the Kepler 215 system

Planets for which n=2 to 5 are confirmed planets.

The authors chose the planet at 0.1130 as that for which n=3.

They multiplied the calculated semi-major axis, Ac, by the scaling factor of 0.1130.

If the ratios, r, of planet (n+1)/planet n are not similar this would indicate that there are gaps in the planetary system.

A plot of log Ac against the planet number, Figure B1, will be a straight line if the planets fit the Titius-Bode law. Similarly, A plot of log P against the planet number, Figure B2, will also be a straight line if the planets fit the Titius-Bode law. Period data was taken from the NASA Exoplanet Archive.

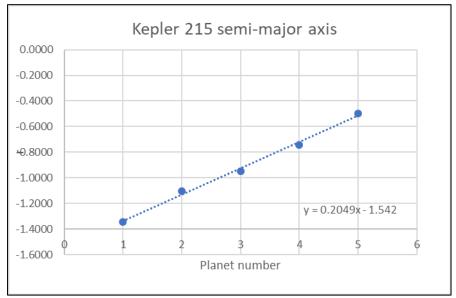


Figure B1. Log of semi-major axis vs planet number

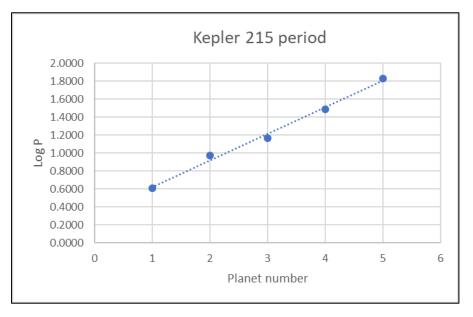


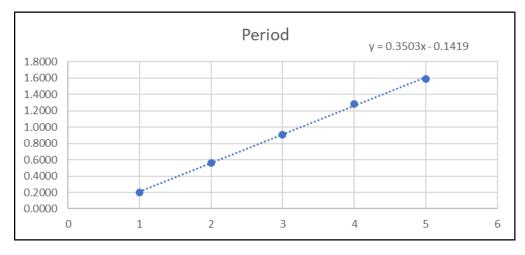
Figure B2. Log of period vs planet number

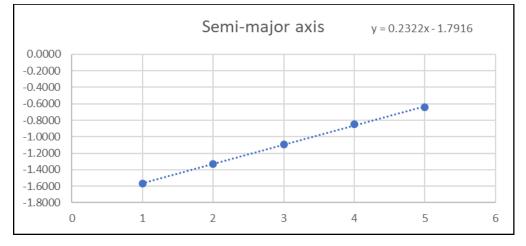
B2 Data for targets listed in 4.2, Table 4.1

For each star a table of data shows actual and predicted planets. Predictions are based on data obtained from plots of semi-major axis and periods of known planets shown below each table.

Kepler-9

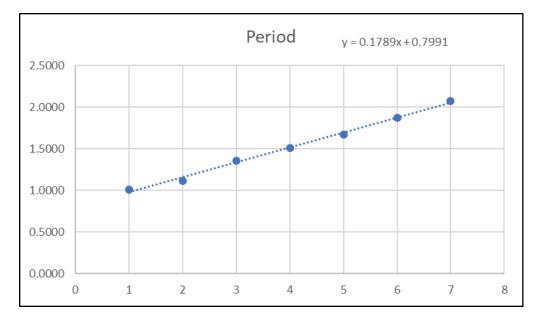
Kepler-9							
RA 19 02 17.756, Dec +38 24 03.1							
TB number Planet ID SMA (au) Log SMA Period (days) Log Period							
1	d	0.0273	-1.5638	1.5929	0.2022		
2	у	0.0471	-1.3272	3.6199	0.5587		
3	Z	0.0804	-1.0950	8.1096	0.9090		
4	b	0.1430	-0.8447	19.2389	1.2842		
5	С	0.2270	-0.6440	38.9853	1.5909		

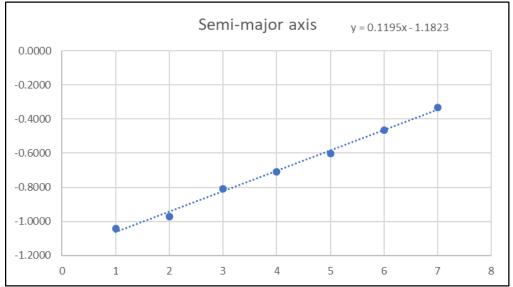




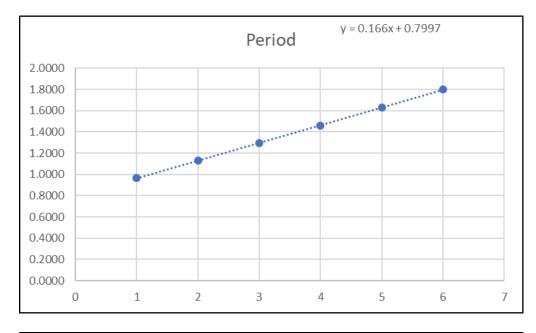
Kepler-11

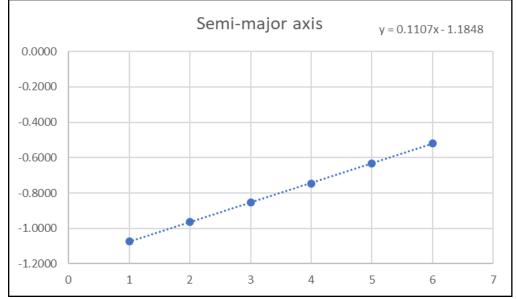
Kepler-11							
RA 19 48 27.622, Dec +41 54 32.8							
TB number Planet ID SMA (au) Log SMA Period (days) Log Period							
1	b	0.0910	-1.0410	10.3039	1.0130		
2	с	0.1070	-0.9706	13.0241	1.1147		
3	d	0.1550	-0.8097	22.6845	1.3557		
4	е	0.1950	-0.7100	31.9996	1.5051		
5	f	0.2500	-0.6021	46.6888	1.6692		
6	x	0.3425	-0.4654	74.5590	1.8725		
7	g	0.4660	-0.3316	118.3807	2.0733		





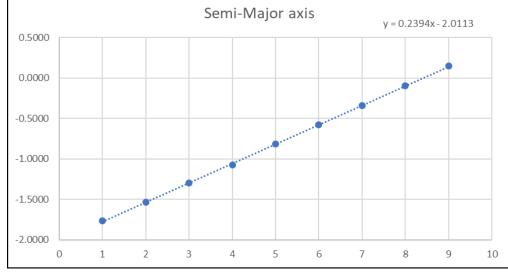
Kepler-19							
RA 19 21 41.002, Dec +37 51 06.4							
TB number	TB number Planet ID SMA (au) Log SMA Period (days) Log Period						
1	b	0.0846	-1.0726	9.2872	0.9679		
2	x	0.1088	-0.9634	13.5425	1.1317		
3	у	0.1404	-0.8528	19.8472	1.2977		
4	с	0.1796	-0.7457	28.7310	1.4584		
5	Z	0.2337	-0.6314	42.6285	1.6297		
6	d	0.3030	-0.5186	62.9500	1.7990		

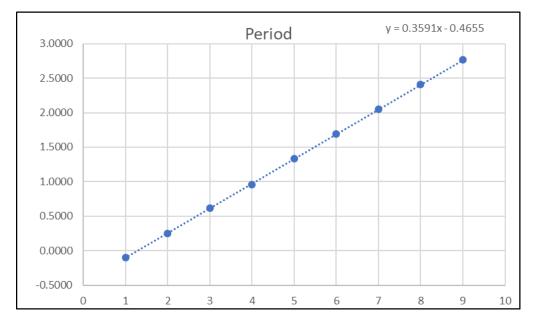




WASP-47

WASP-47							
RA 22 04 48.731, Dec -12 01 07.9							
TB number	Planet ID	SMA (au)	Log SMA	Period (days)	Log Period		
1	е	0.0173	-1.7620	0.7896	-0.1026		
2	v	0.0293	-1.5325	1.7894	0.2527		
3	b	0.0510	-1.2924	4.1591	0.6190		
4	d	0.0850	-1.0706	9.0308	0.9557		
5	w	0.1534	-0.8143	21.3796	1.3300		
6	x	0.2661	-0.5749	48.8765	1.6891		
7	у	0.4618	-0.3355	111.7378	2.0482		
8	Z	0.8015	-0.0961	255.4465	2.4073		
9	с	1.4100	0.1492	588.5000	2.7697		





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