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 http://www.astronomerstelegram.org/ The editors have been contacted with a view to understanding how we might use this facility.

Contents

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.

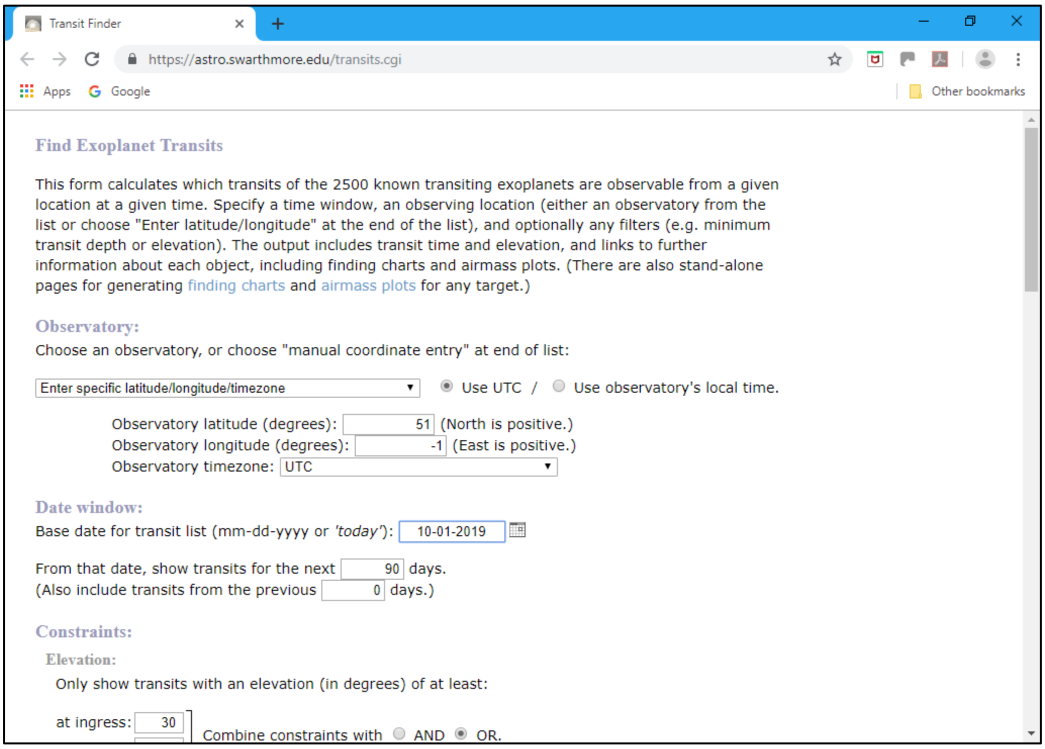


Figure 2.1. Find Exoplanet Transits homepage

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.

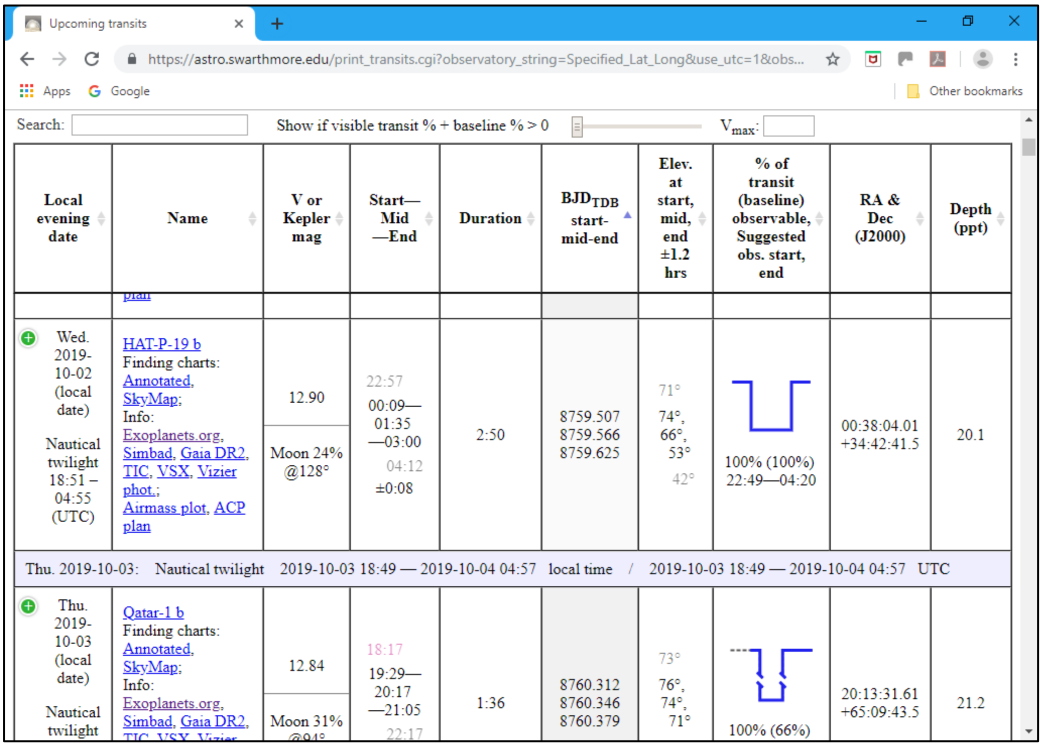


Figure 2.2. Find Exoplanet Transits, Upcoming events

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 Find Exoplanet Transits except for the Impact parameter and Orbital inclination which is from http://exoplanets.org/. 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 http://catserver.ing.iac.es/staralt/ 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.

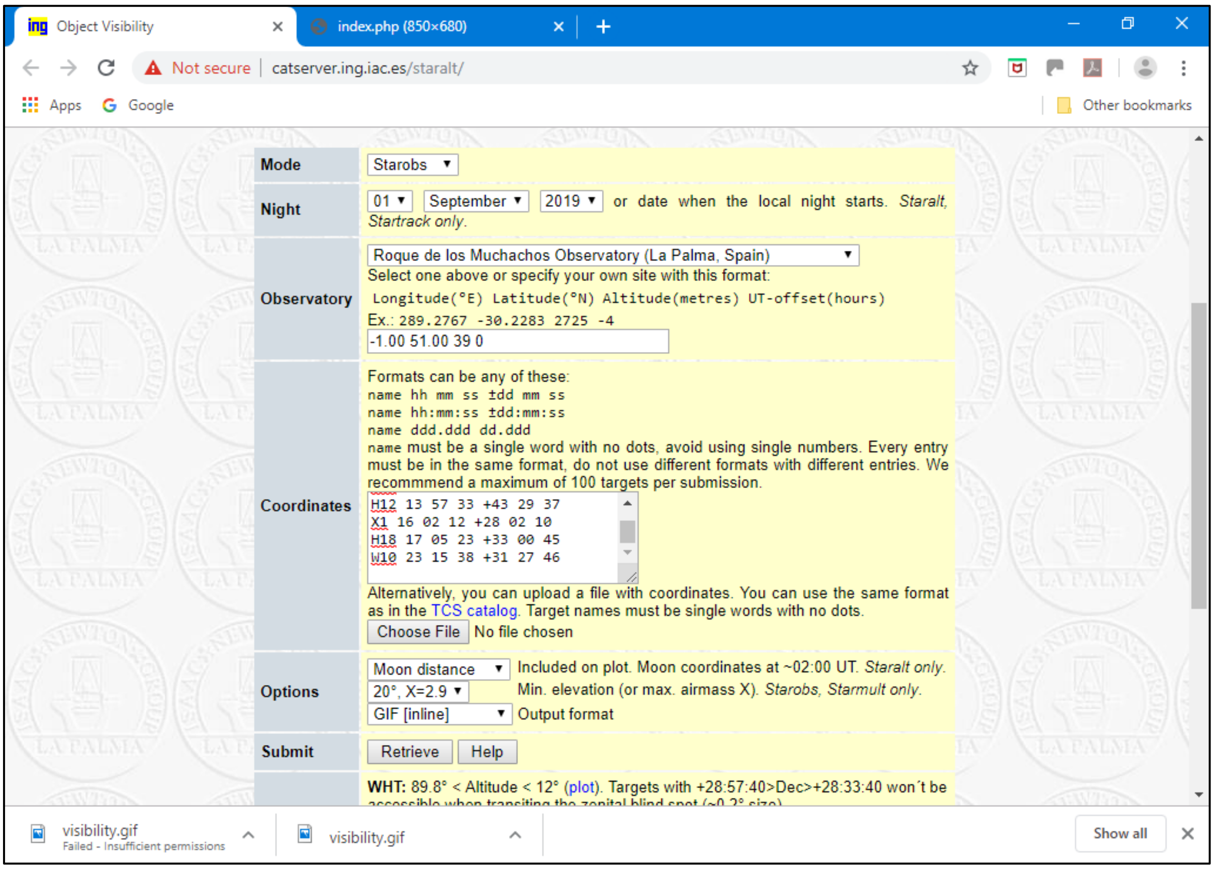


Figure 3.1. Object visibility inputs

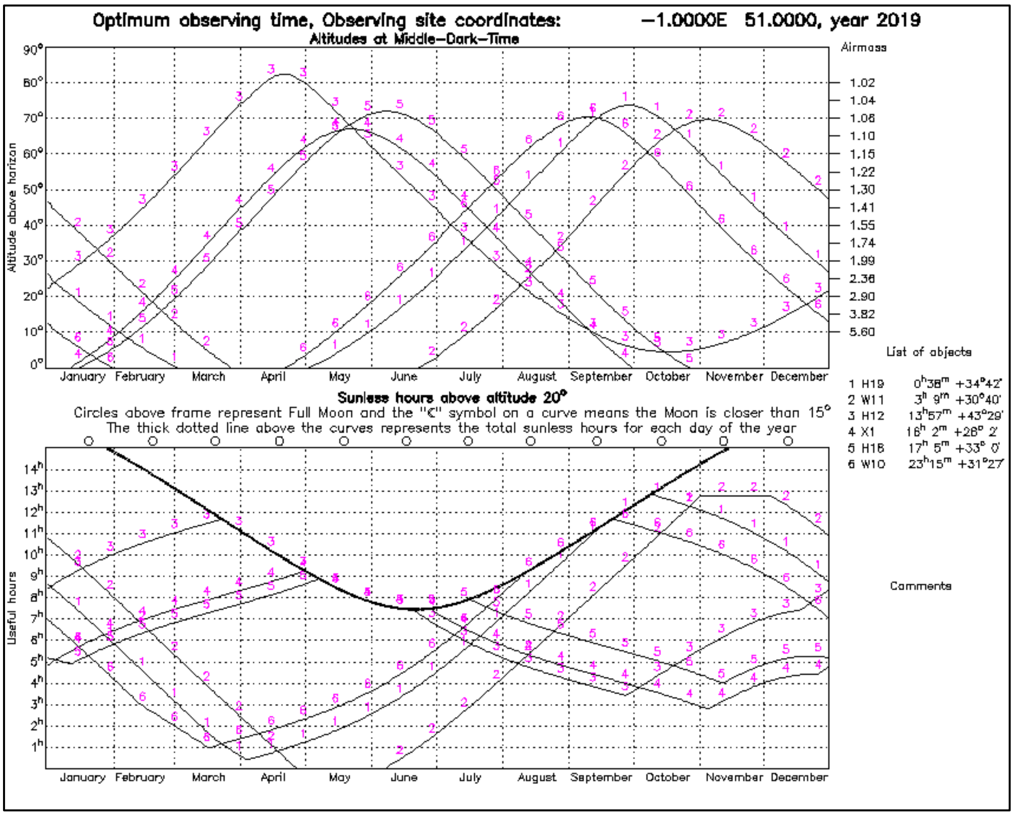


Figure 3.2. Object visibility output

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

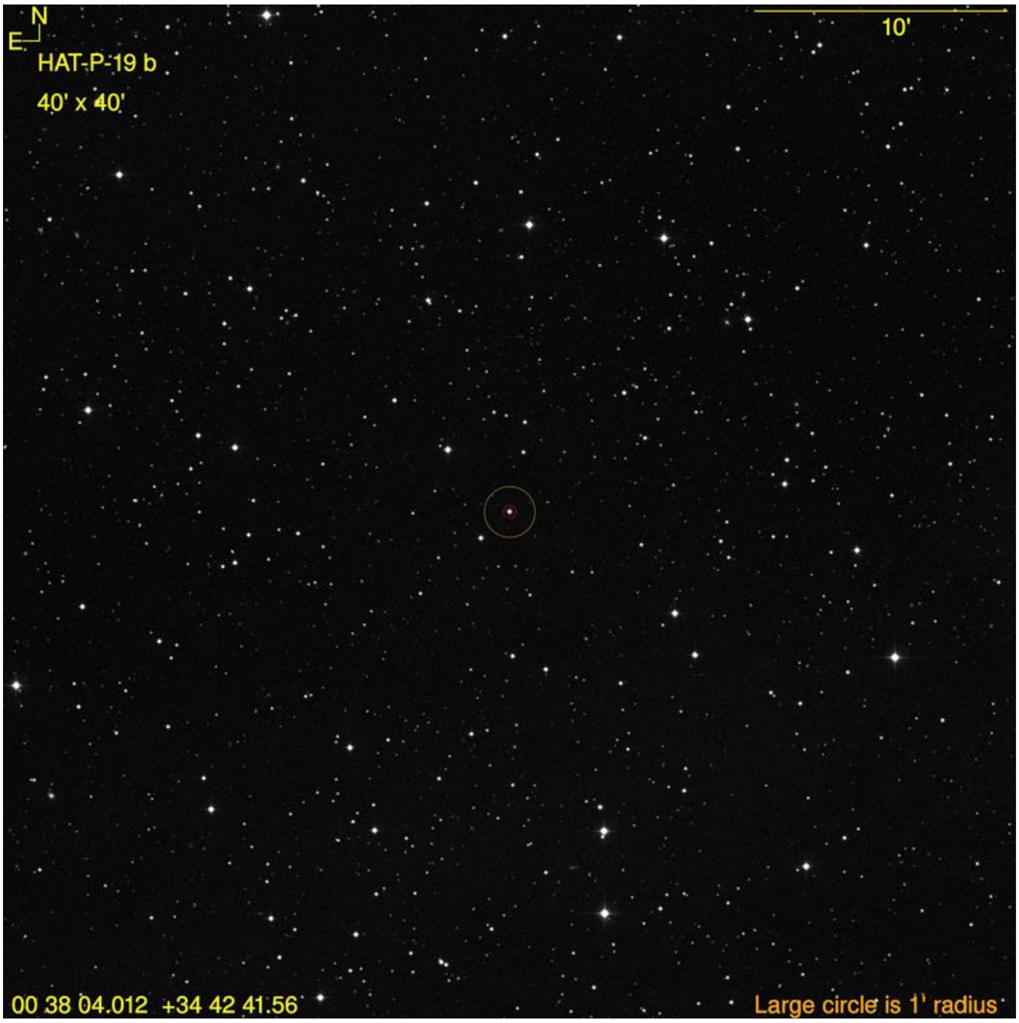


Figure 3.3. Annotated image showing location of HAT-P-19 b

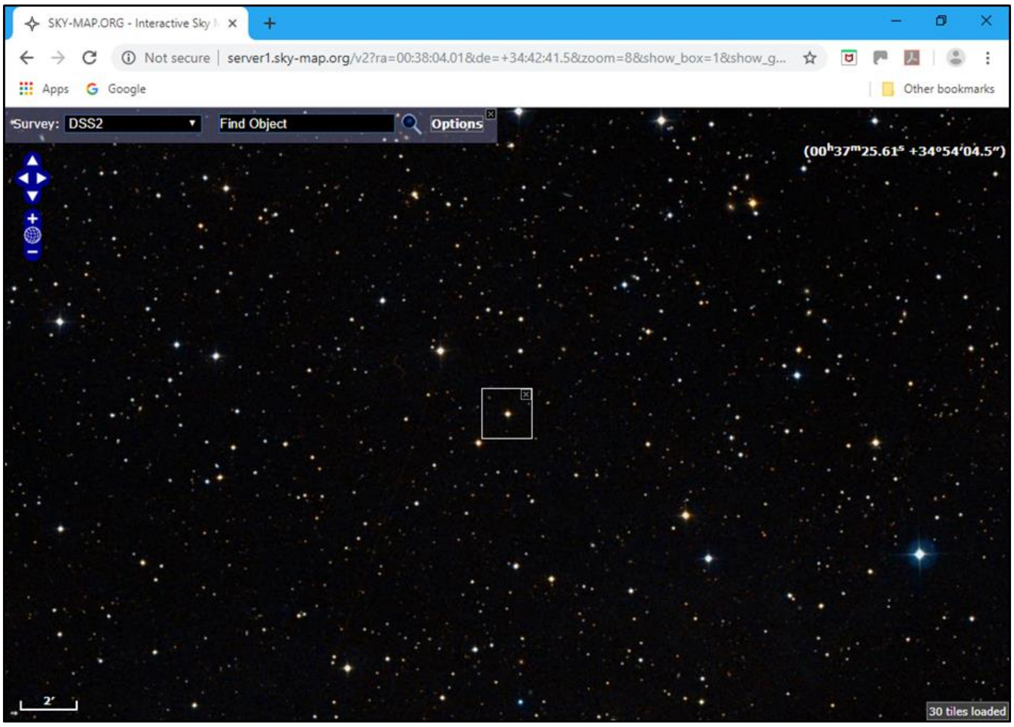


Figure 3.4. Skymap chart showing location of HAT-P-19 b

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

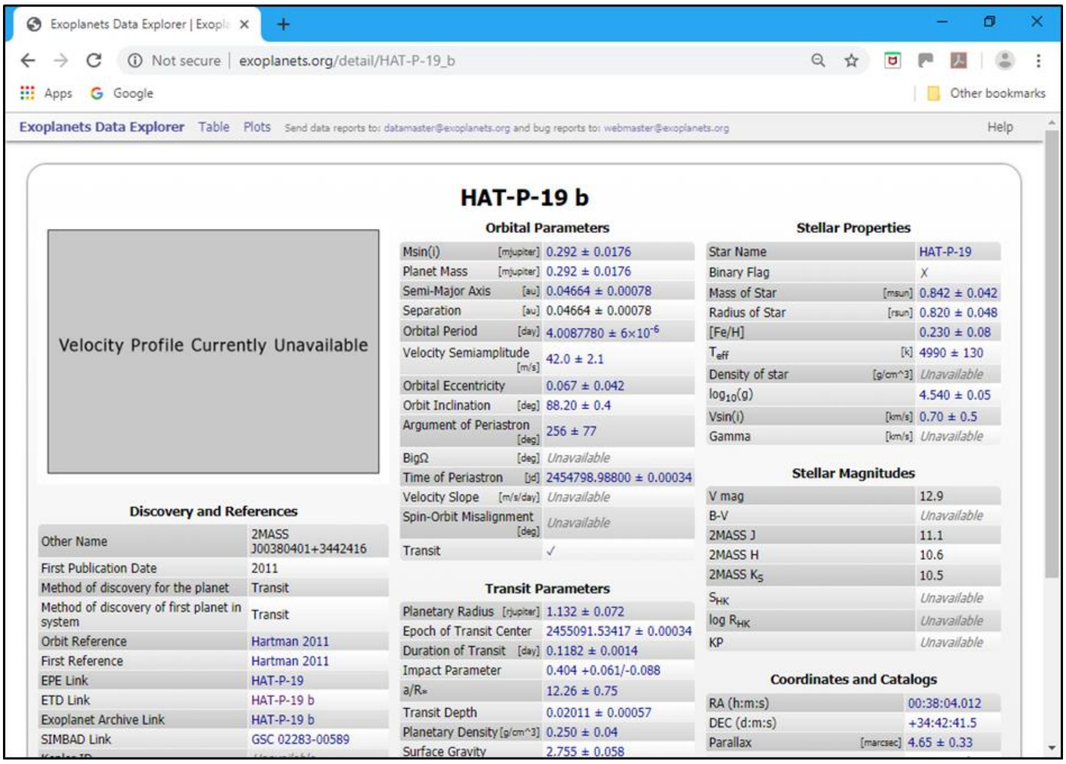


Figure 3.5. Exoplanet.org data for the HAT-P-19 exoplanetary system.

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.

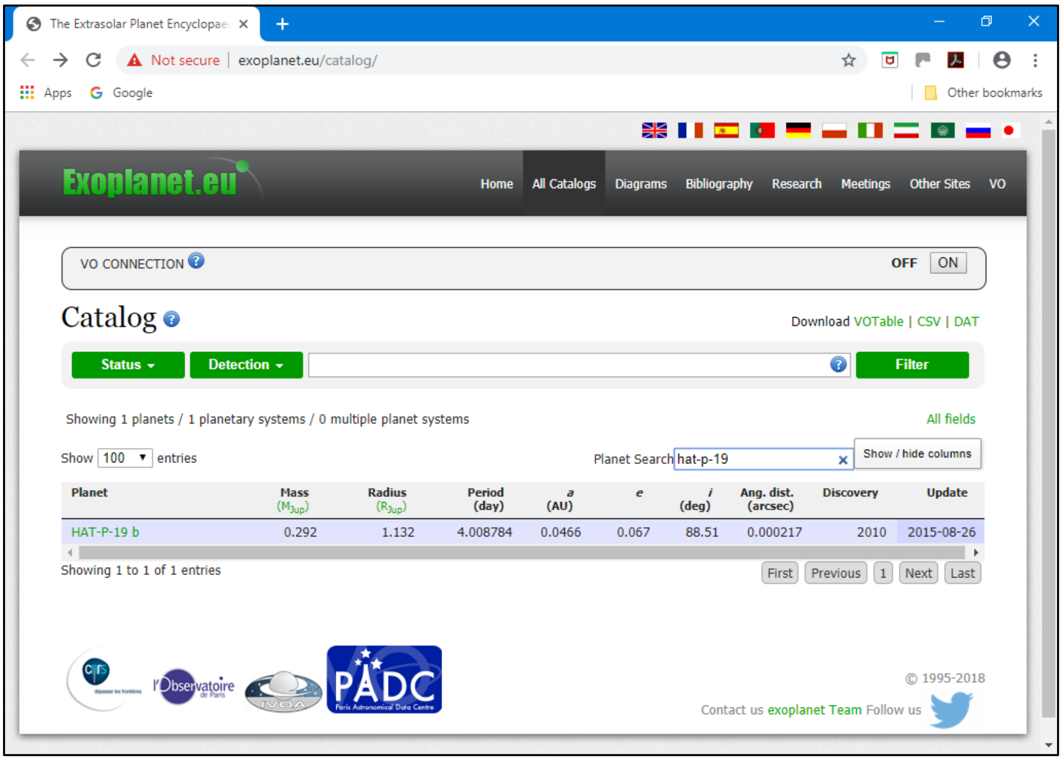


Figure 3.6. Exoplanet.eu entry for HAT-P-19

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.

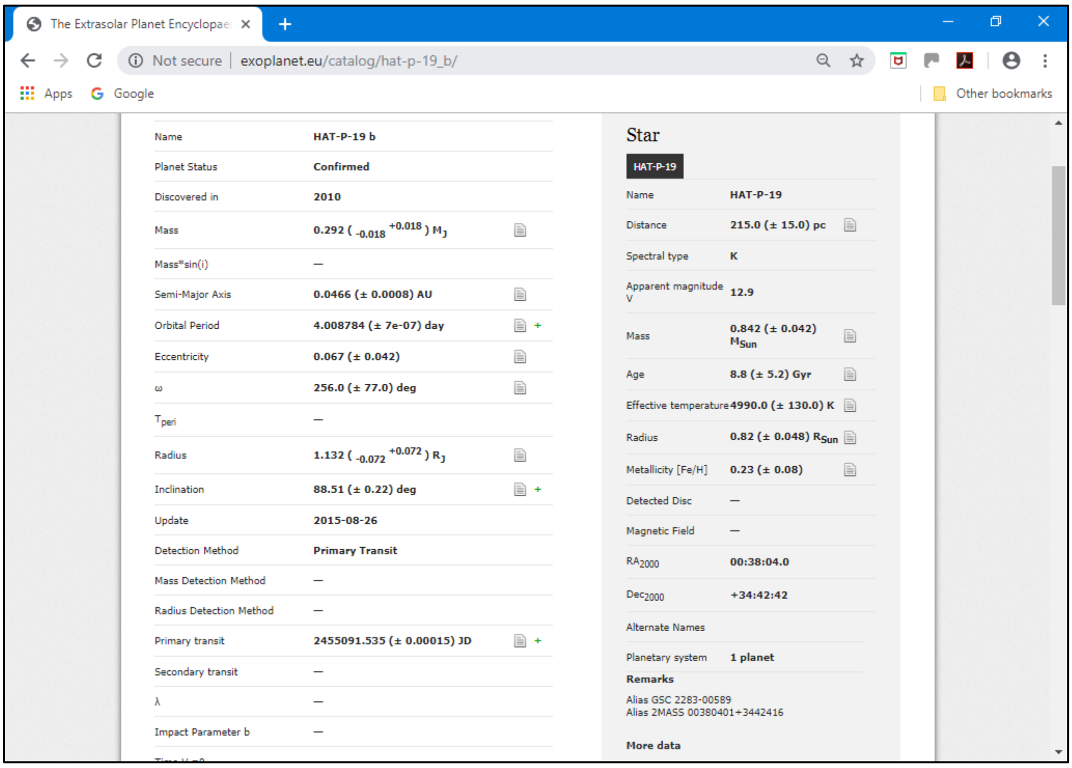


Figure 3.7. More Exoplanet.eu catalog data

(c) The free planetarium program [Stellarium](#) 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	b	19 02 17.756	+38 24 03.1	3	2
Kepler-11	d e f g	19 48 27.622	+41 54 32.8	6	1

Kepler-19	b	19 21 41.002	+37 51 06.4	3	3
WASP-47	b	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 http://catserver.ing.iac.es/staralt/ 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.

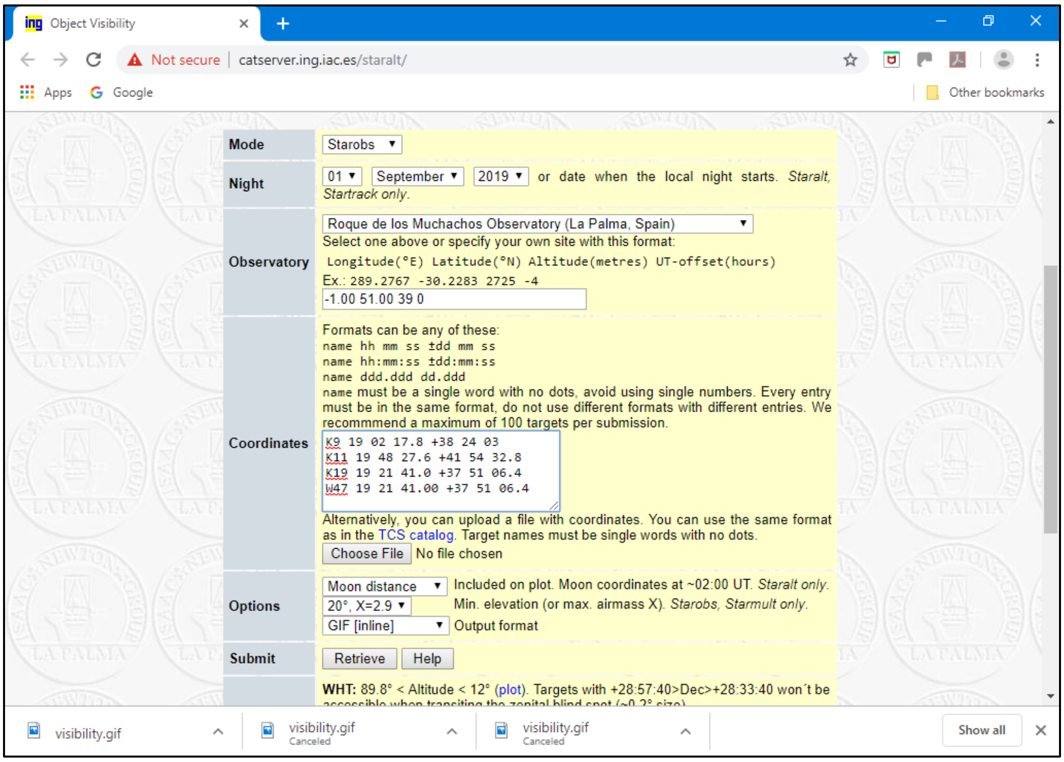


Figure 4.1. Object visibility inputs

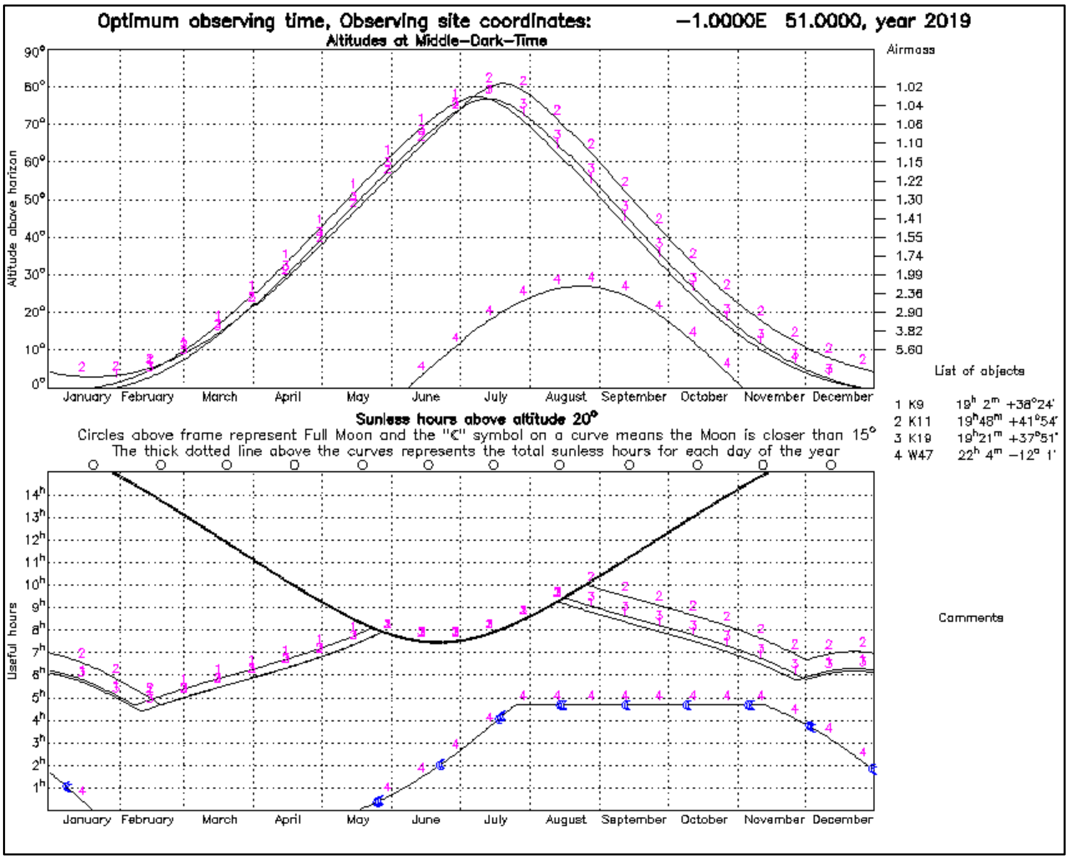


Figure 4.2. Object visibility output

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 TRESCA 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.

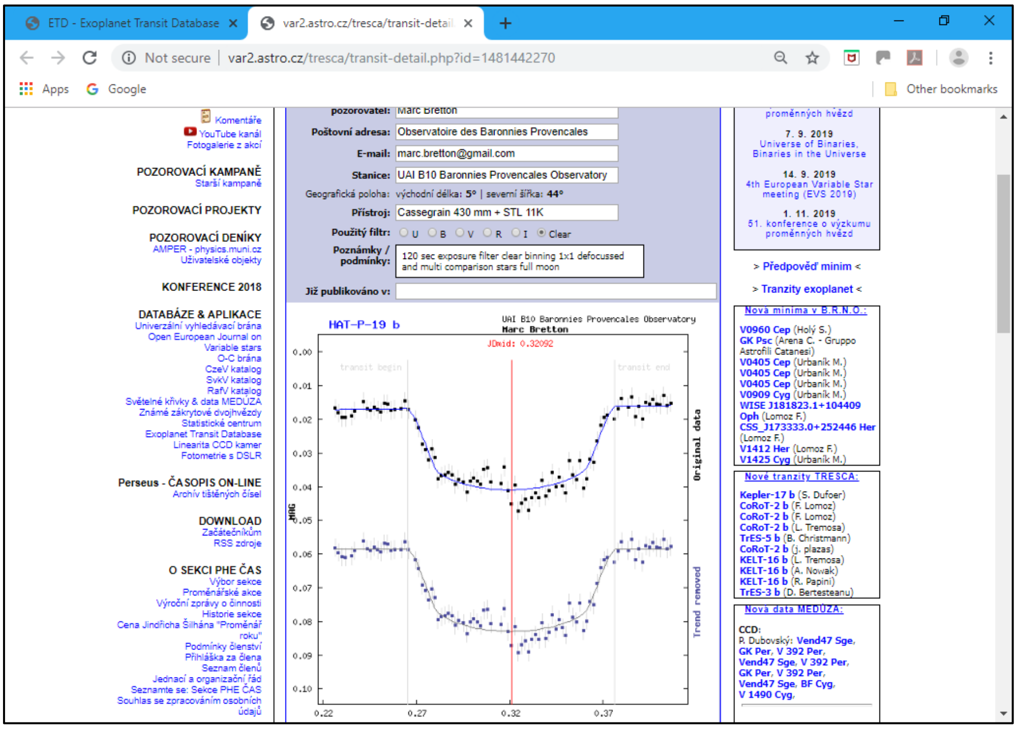


Figure 5.1. Transit light curve for HAT-P-19b   Credit Marc Breton/TRESCA

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 NASA Exoplanet archive. 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.

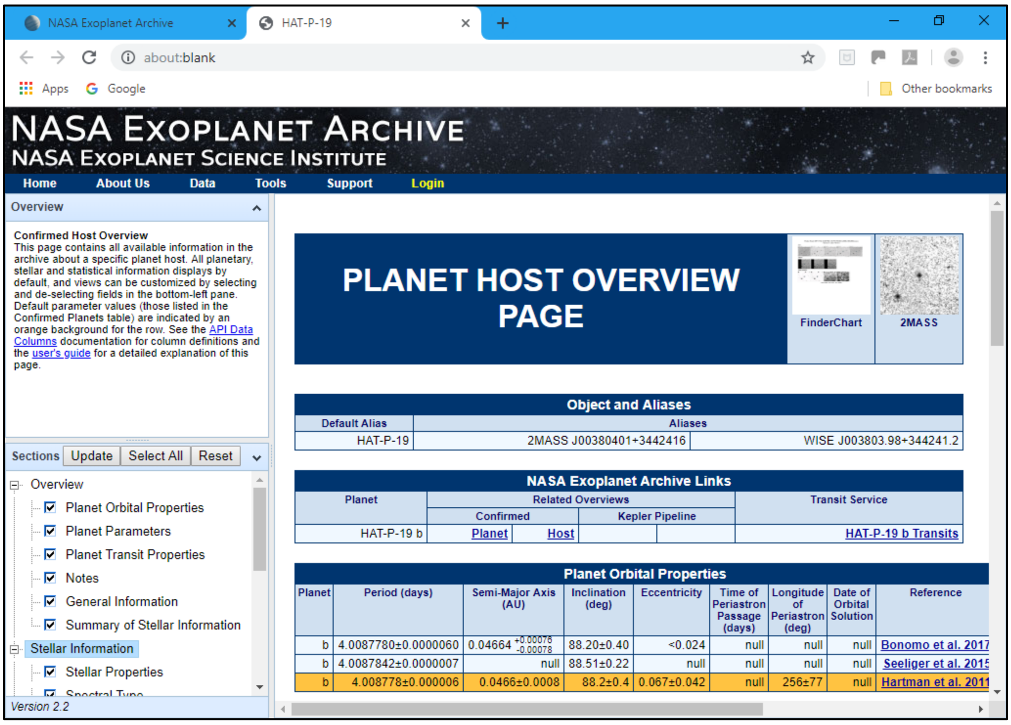


Figure 6.1. Data on HAT-P-19 exoplanetary system

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

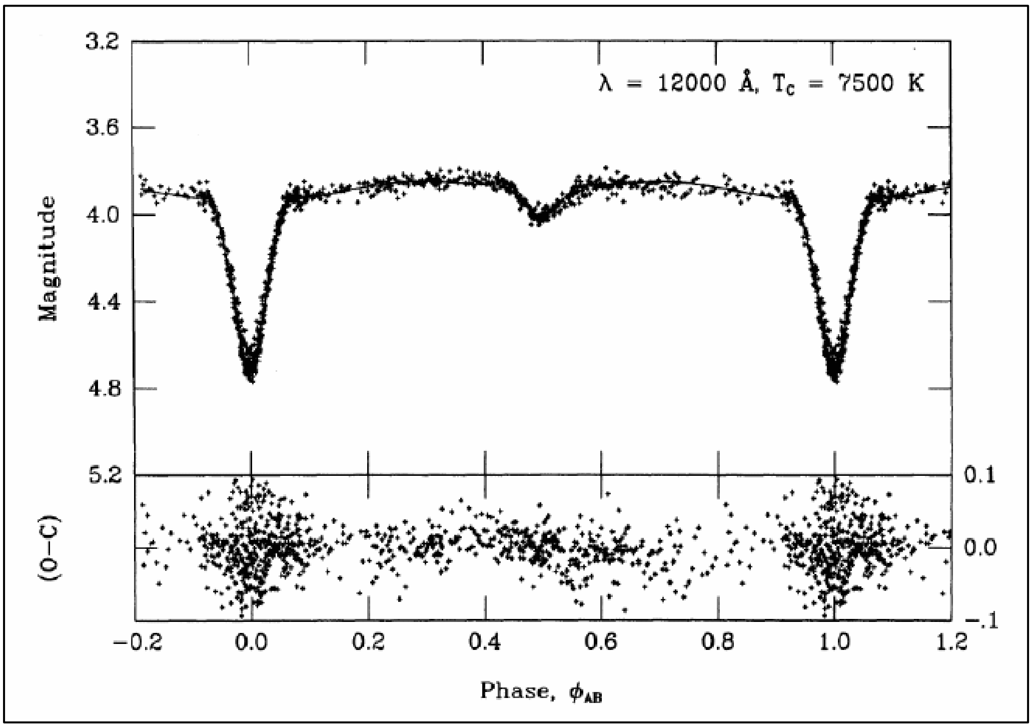


Figure 6.2. Example of an eclipsing binary light curve Credit AAVSO

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

Notifying other exoplanet observers can be done via the BAA Exoplanet forum 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. NEO Confirmation Page, AAVSO VSX, CBAT 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 http://www.astronomerstelegram.org/ 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.

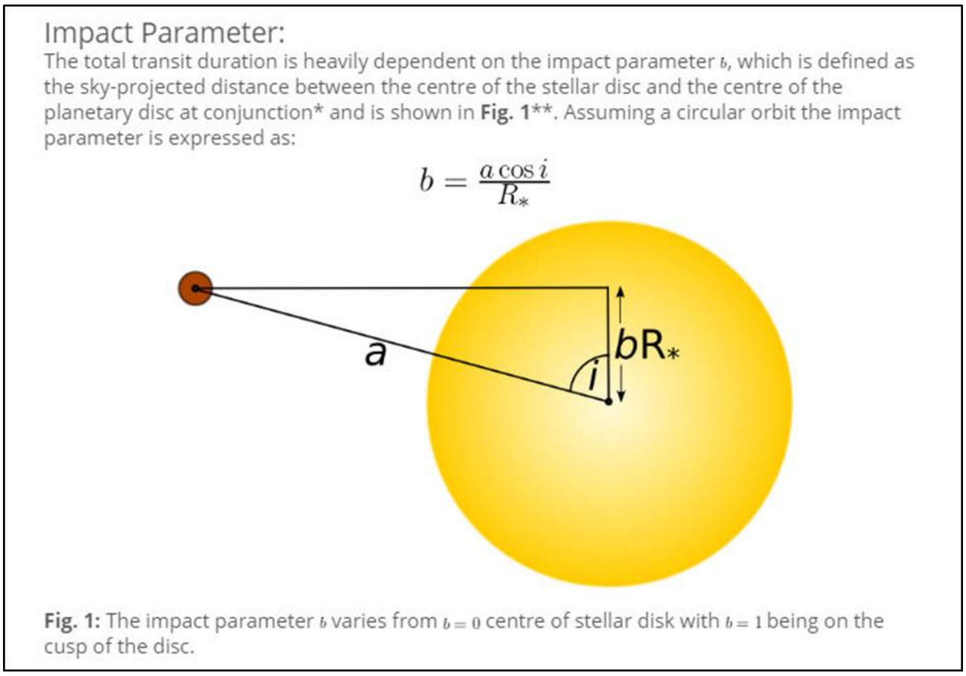
Data from Exoplanets.org for HAT-P-19 b;
- impact parameter (b) = 0.404
- semi-major axis (a) = 0.04664 au = 6977245 km
- stellar radius (R*) = 696265 km
- orbital inclination (i) = 88.9 degrees

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 https://www.paulanthonywilson.com/exoplanets/exoplanet-detection-techniques/the-exoplanet-transit-method/ and the relevant section is shown in Figure A1.


Impact Parameter:

The total transit duration is heavily dependent on the impact parameter b, which is defined as the sky-projected distance between the centre of the stellar disc and the centre of the planetary disc at conjunction* and is shown in **Fig. 1****. Assuming a circular orbit the impact parameter is expressed as:

$$b = \frac{a\cos i}{R_*}$$

Fig. 1: The impact parameter b varies from $b = 0$ centre of stellar disk with $b = 1$ being on the cusp of the disc.

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.

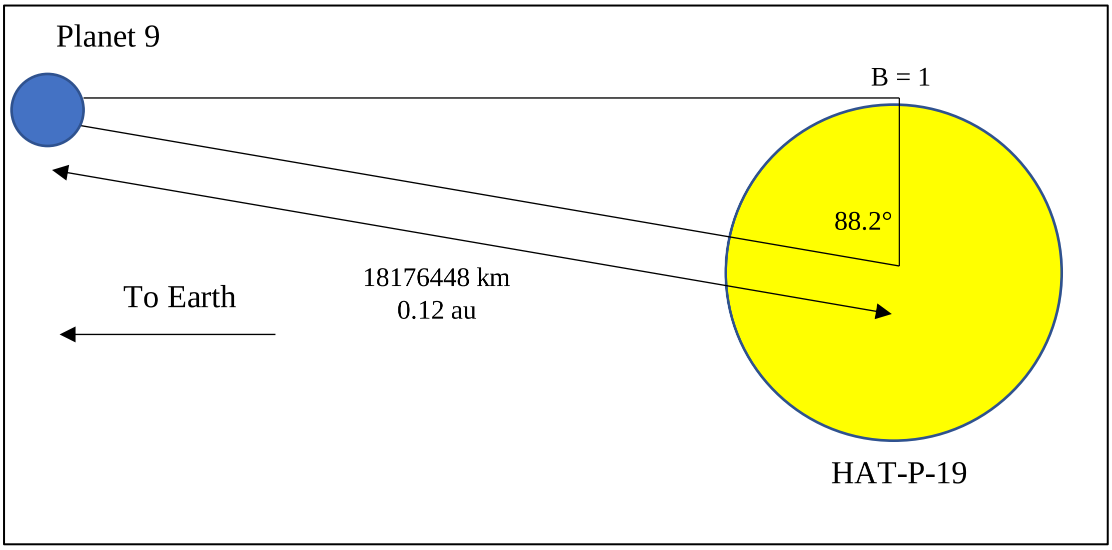


Figure A2. Limits to planet discovery using HAT-P-19 data

Appendix B Titius-Bode law – its application to exoplanetary systems

B1 Introduction

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_Exoplanetary_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.

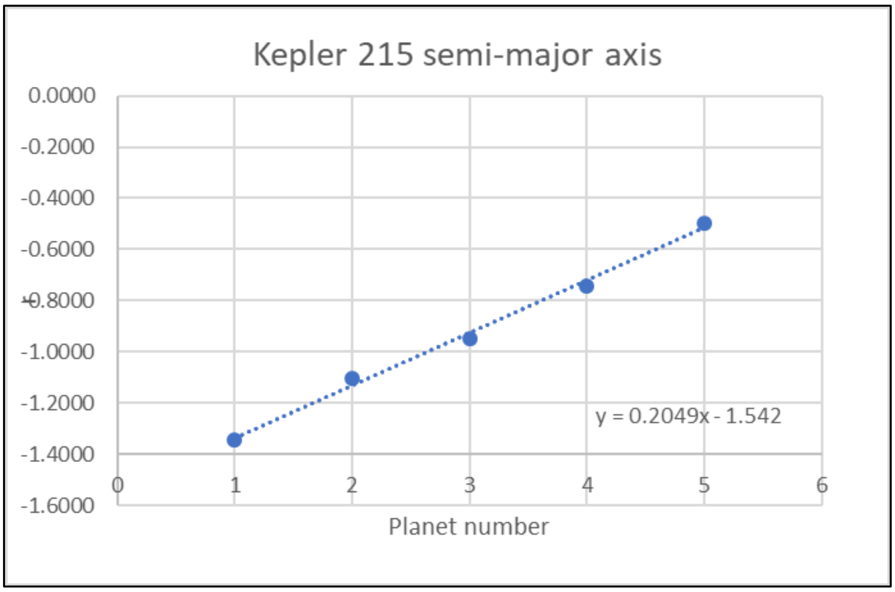


Figure B1. Log of semi-major axis vs planet number

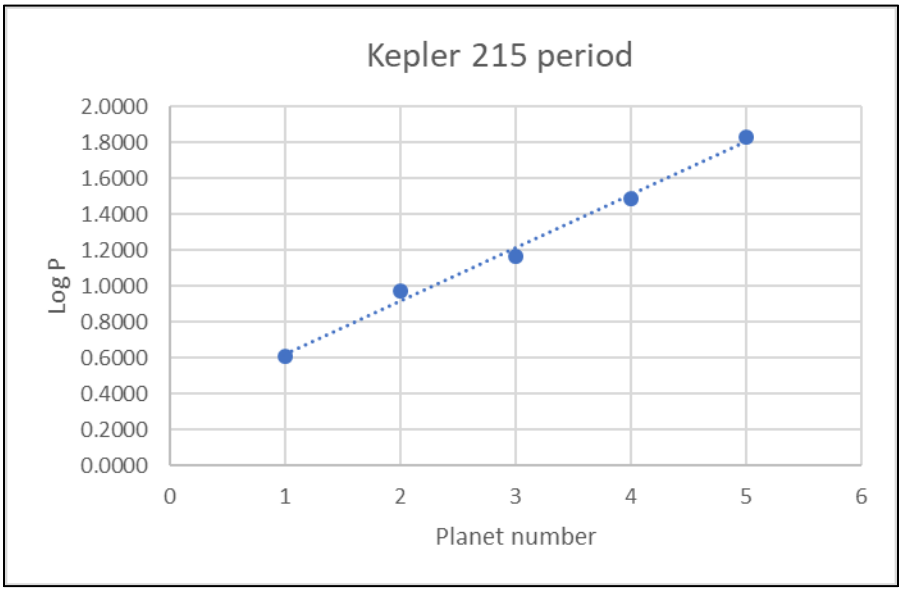


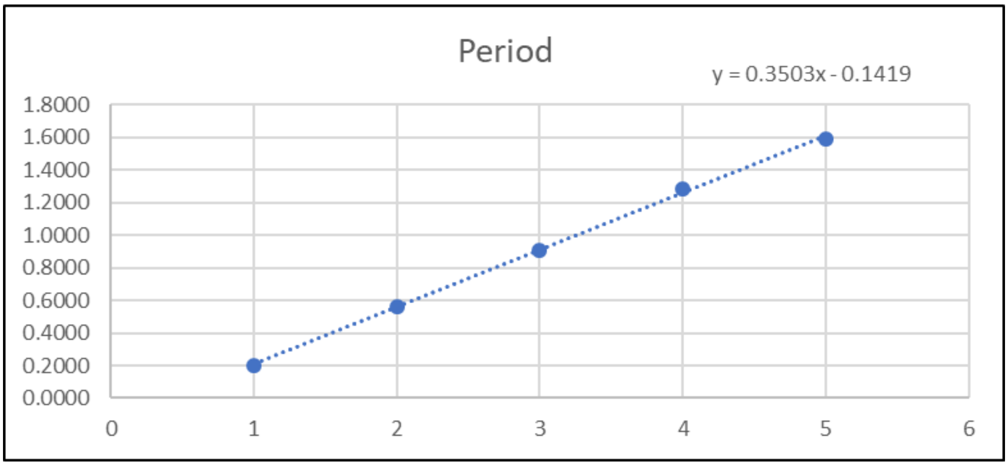
Figure B2. Log of period vs planet number

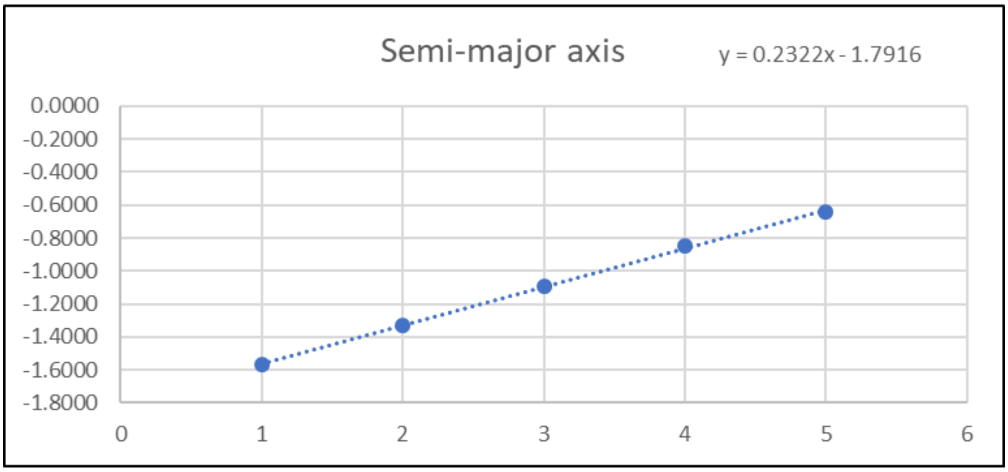
B2 Data for targets listed in 4.2, Table 4.1

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

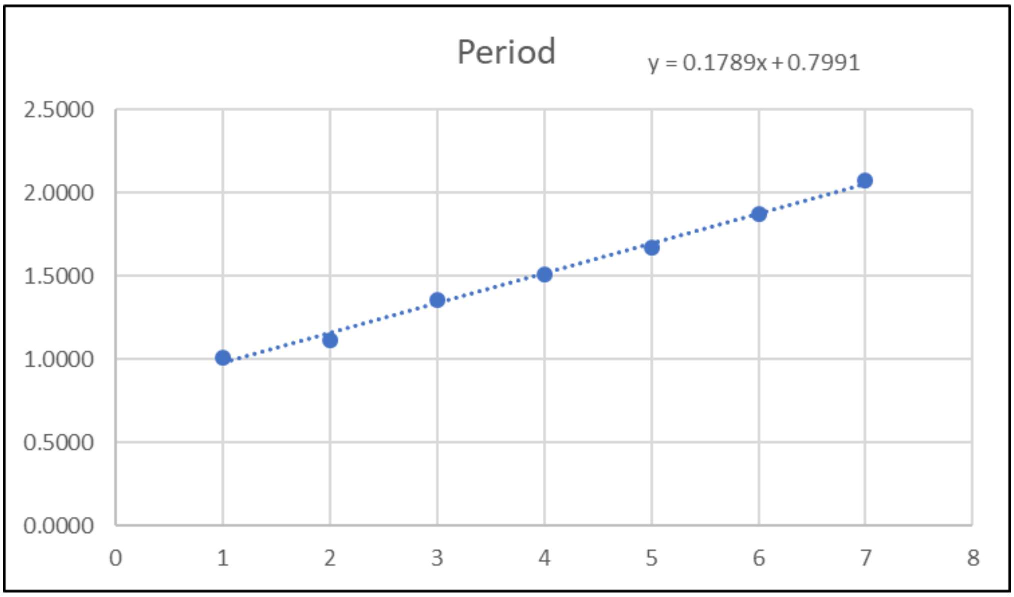
Kepler-9					
RA 19 02 17.756, Dec +38 24 03.1					
TB number	**Planet ID**	**SMA (au)**	**Log SMA**	**Period (days)**	**Log Period**
1	d	0.0273	-1.5638	1.5929	0.2022
2	y	0.0471	-1.3272	3.6199	0.5587
3	z	0.0804	-1.0950	8.1096	0.9090
4	b	0.1430	-0.8447	19.2389	1.2842
5	c	0.2270	-0.6440	38.9853	1.5909

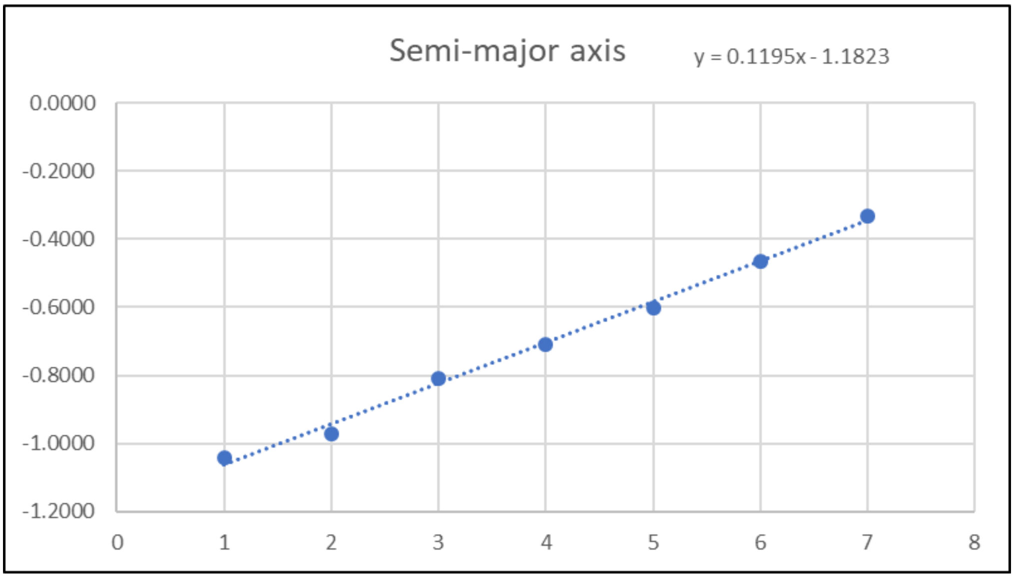




Kepler-11

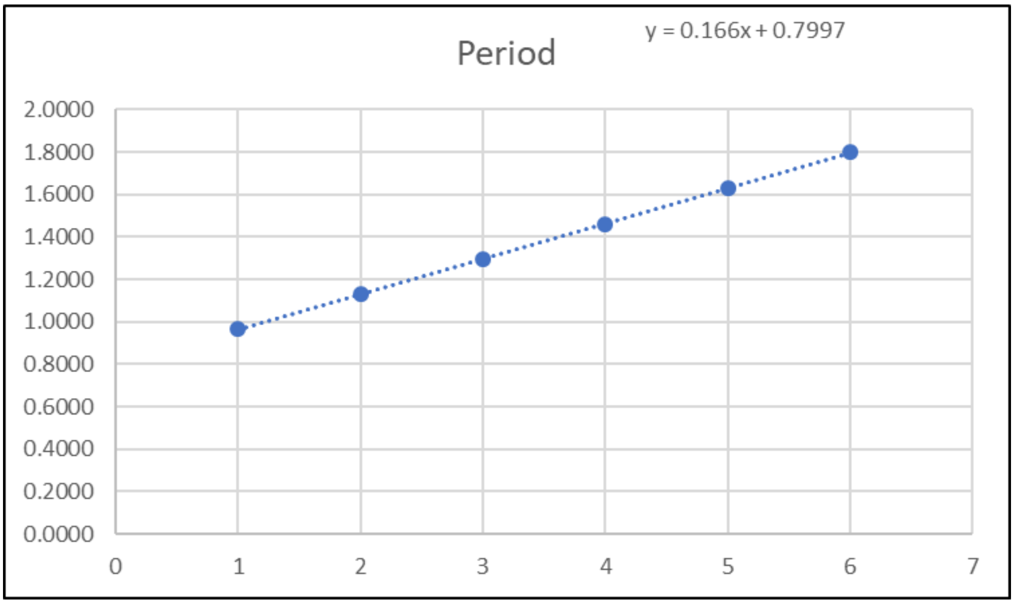
Kepler-11					
RA 19 48 27.622, Dec +41 54 32.8					
TB number	Planet ID	SMA (au)	Log SMA	Period (days)	Log Period
1	b	0.0910	-1.0410	10.3039	1.0130
2	c	0.1070	-0.9706	13.0241	1.1147
3	d	0.1550	-0.8097	22.6845	1.3557
4	e	0.1950	-0.7100	31.9996	1.5051
5	f	0.2500	-0.6021	46.6888	1.6692
6	x	0.3425	-0.4654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

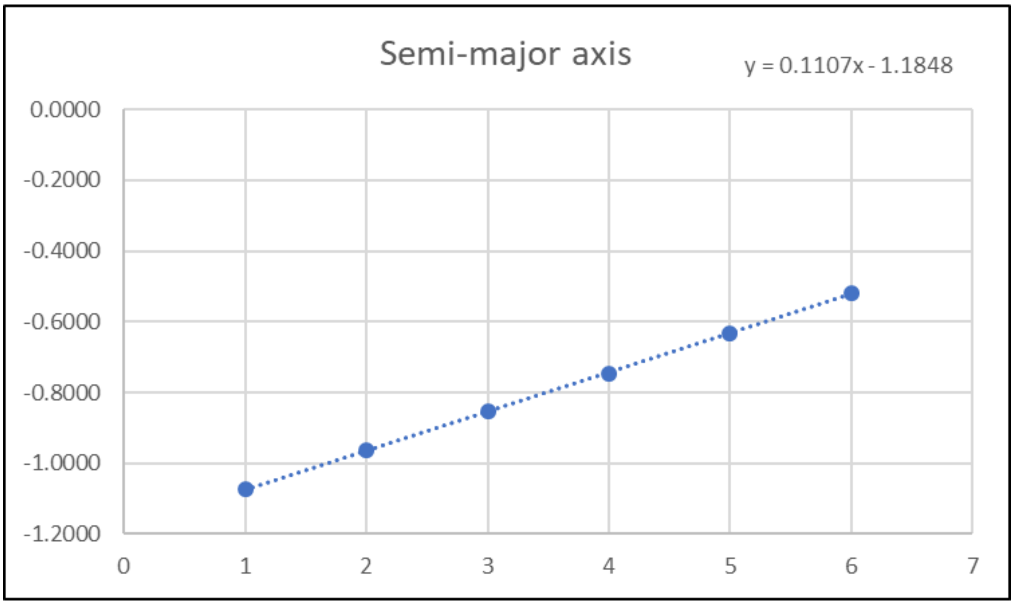




Kepler-19

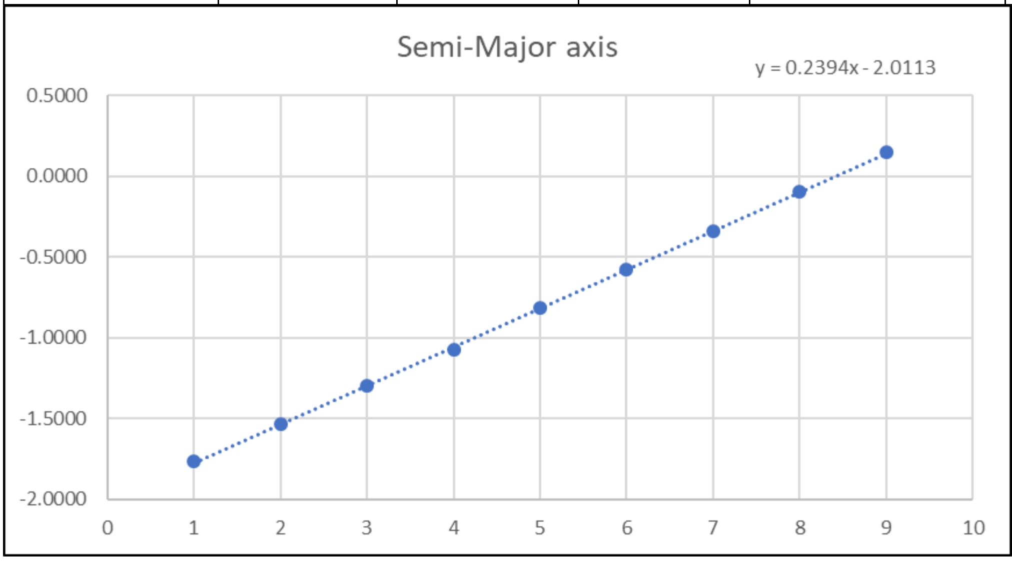
Kepler-19					
RA 19 21 41.002, Dec +37 51 06.4					
TB number	**Planet ID**	**SMA (au)**	**Log SMA**	**Period (days)**	**Log Period**
1	b	0.0846	-1.0726	9.2872	0.9679
2	x	0.1088	-0.9634	13.5425	1.1317
3	y	0.1404	-0.8528	19.8472	1.2977
4	c	0.1796	-0.7457	28.7310	1.4584
5	z	0.2337	-0.6314	42.6285	1.6297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

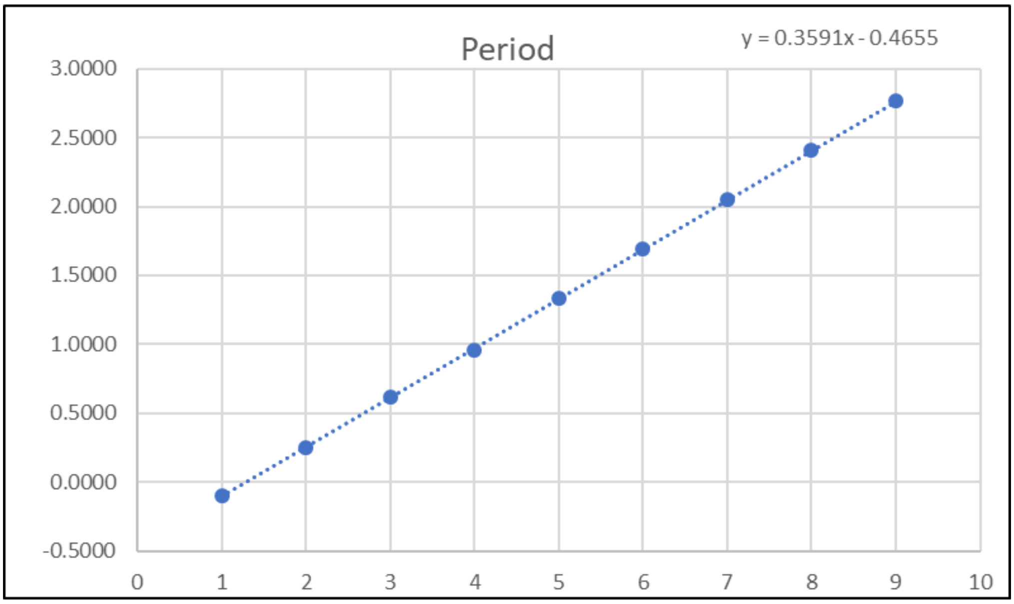




WASP-47

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	e	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	y	0.4618	-0.3355	111.7378	2.0482
8	z	0.8015	-0.0961	255.4465	2.4073
9	c	1.4100	0.1492	588.5000	2.7697





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