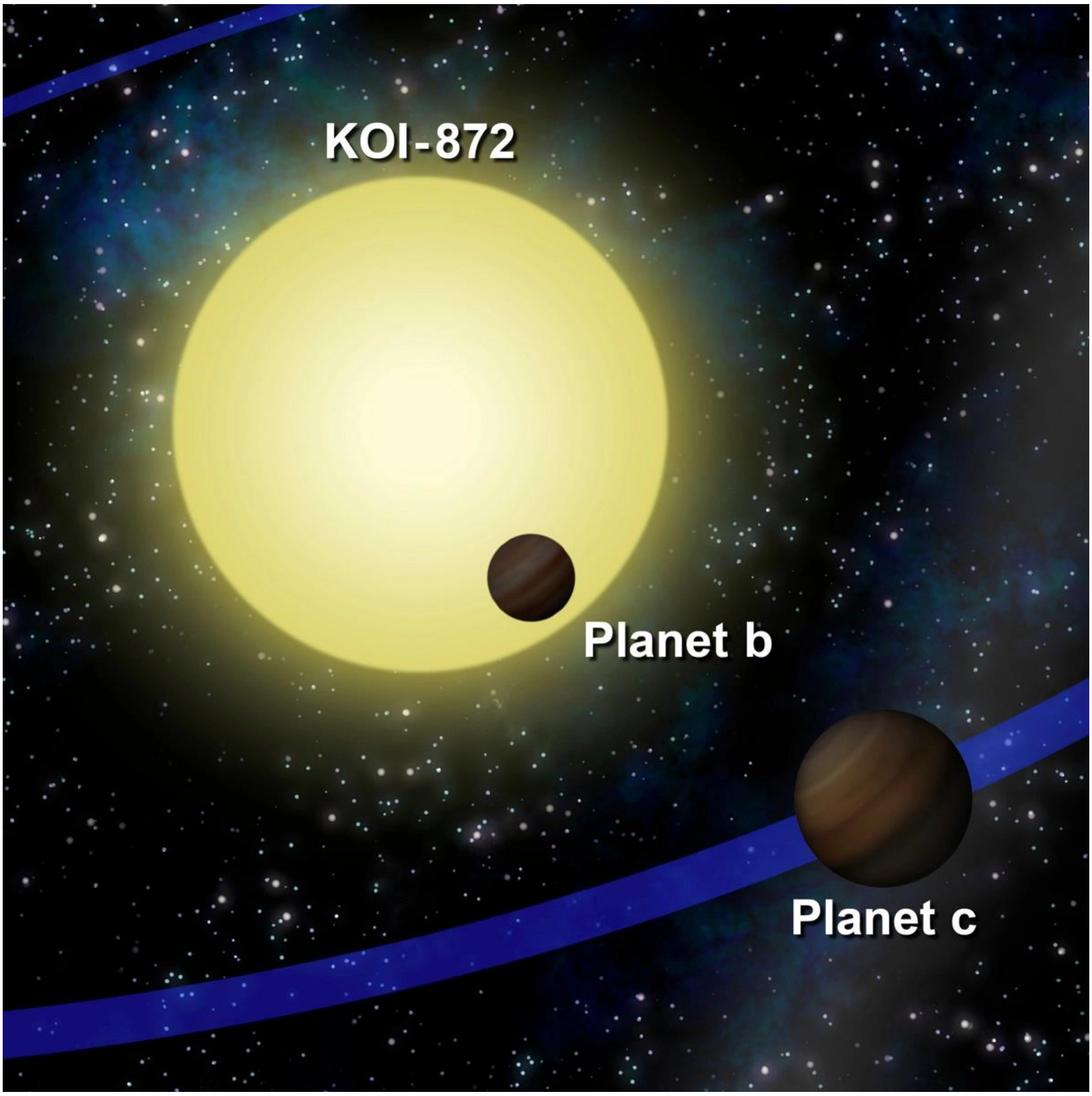
# Project – EXPLORE 2000

# EXoPLanet Orbit REsearch 2000

### A collaboration between the AAVSO Exoplanet Section and the BAA Exoplanet Division




Using Kepler Telescope transit data of planet "b," scientists predicted that a second planet "c," about the mass of Saturn, orbits the distant star KOI-872. Image credit: Southwest Research Institute

Updated 2025 June 10

**Contents**



## 1.0 Introduction

This project builds on;

- Siegfried Vanaverbeke' s proposal - Chart 1
- Presentations given at the webinars 'Variations on an Exoplanet Theme-Part 2' held on 2025 February 22 and Variations on an Exoplanet theme held in 2023 September 30

The objective of this project is to obtain and analyse observations of exoplanet transits by participation in ExoClock with the aim of better understanding the characteristics of exoplanetary systems i.e.

- detection of additional planets
- ascertaining eccentricity of planetary orbits
- causes of orbital decay e.g. tidal interaction with the host star

Transit Timing, Duration and Depth measurements all help to achieve this aim.

To achieve this aim amateur astronomers will be able to;

- use existing software
- develop new applications
- work with existing data from ground-based and space-based observatories
- provide additional observations of selected targets

A flowchart showing the various aspects of the project and how they link together is shown in Chart 2

For those who may wish to pursue further related education the Open University's MSc in Space Science and Technology has a final flagship project module in which students spend 600 hours on project work from November to September each year. One project theme that has become popular is Exoplanets. Students use two 50cm-class remotely-operated telescopes on Mt Teide, Tenerife. MSc dissertations typically have a well-defined research question and a list of objectives which allow the research question to be addressed. Students are expected to perform a comprehensive literature search and review - continuously updated during the project - offer a robust defence of their research methodology, make observations using our professional-class telescopes to draw conclusions, their implications and proposals for further work.

## 2.0 Project Phases

**Phase 1** – Definition

- targets
- observational procedures (as defined in ExoClock)
- analysis; Software packages are listed in the Observation and Analysis document

**Phase 2** – Announcement

1) Roger Dymock to arrange an on-line ZOOM meeting to include;

- Rodney Buckland
- Dennis Conti
- Pieter Vuylsteke
- Siegfried Vanaverbeke

Objective will be to agree the way forward

2) Circulate the plan for feedback from members

3) Review feedback and incorporate into project documents as appropriate

4) Following this initial announcement organise an on-line meeting to describe the further phases. Structure of this meeting may

- include all interested parties
- be divided into groups e.g.; AAVSO members, BAA members and OU students separately

Suggestions for the initial meeting – probably all-day on-line will be necessary

a) Overview of project

b) Tutorials including;

- a selected target or targets (to be updated as new ones become available)
- introduction to ExoClock
- how to obtain the transit data e.g. from space observatories e.g. Exoplanetpie
- how to extract the TTVs e.g using Exoplanetpie
- how to obtain Radial Velocity data - will look to Siegfried Vanaverbeke for guidance here

- how to combine TTV and RV data e.g to identify new planets in the system or to enhance our knowledge of planetary characteristics - again SV or perhaps some of Rodney Buckland's Open University students
- software must be supported and have full instructions as to how to use
- what do we do with results? e.g. keep participants updated and publish

**Phase 3** – Implementation (includes suggestions from Siegfried Vanaverbeke)

1) Set up a dedicated forum for this project

    Proposal is to use AAVSO forum mechanism

2) Organise on-line meetings and tutorials
3) Set up a method for identifying targets
    (a) Time-sensitive targets
    (b) ExoClock targets exhibiting TTVs (which also allows participants to both support this project to support and the Ariel mission).
    (c) Targets are listed in a separate document
4) Ensure all available on-line material is available to both AAVSO and BAA members
5) Develop best practices for imaging and analysis

    Identify areas where amateurs with specific imaging and/or analysis skills can best contribute

6) Pro-am collaboration

    Make necessary arrangements, for example, to identify targets, share data (with ExoClock for example) and assist with analysis.

**Phase 4** – Publication of results

## 3.0 Software

To be successful both existing and new applications will require detailed user guides and on-going support from the developers. This is the case for the two applications listed below. In addition, tutorials will be developed and made available to participants.

### 3.1 Transits

HOPS and AstroImageJ can produce transit light curves from observations

### 3.2 TTVs

ExoPlanetPie can extract TTVs from transit data. See Observation and Analysis document for details of various analysis software packages.

## 4.0 TTVs and Radial Velocity data

### 4.1 Combining TTV and Radial Velocity data

Email 2025 May 3 from Siegfried Vanaverbeke.

Regarding the RVs, a proposal has been submitted at CAHA (Calar Alto Spain) to use the CARMENES spectrograph to observe a sample of targets with known warm Jupiters (from TESS mostly orbital periods 10.0 < P < 100 d) which would be observed by the CARMENES spectrograph to determine their masses. Additional photometry of transits with TTV measurements would further help to constrain the orbital architectures. In this way the amateur and professional teams would be able to work together as we have already done for an object which is about to be published.

If we don't have RVs, it becomes more challenging, but we have sufficient tools like Nauyaca, exostriker, own codes etc. to give it a good try.

### 4.2 Radial Velocity determination facilities

Three facilities specialising in using the radial velocity technique to search for exoplanets are HARPS, CARMENES and MARVEL

A collaboration with radial velocity surveys such as HARPS and CARMENES is being explored.

**High Accuracy Radial velocity Planet Searcher (HARPS)**

ESO's La Silla Observatory is home to one of the most successful planet finders in the history of astronomy: HARPS, or High Accuracy Radial velocity Planet Searcher. Attached to the ESO 3.6-metre telescope, HARPS searches nightly, and with unparalleled accuracy, for exoplanets. Today it leads the field, regularly generating astounding results that will present fresh challenges for future telescopes like the ELT. But what does HARPS do to detect these planets? It is all matter of perspective. As we are so far from the stars, we cannot see their exoplanets directly. Instead, HARPS detects minute wobbles in the stars' motion. Stars and their exoplanets are bound together by gravity, so an exoplanet orbits its distant parent star, just as the planets of the Solar System orbit the Sun. But a planet in orbit around a star exerts its own gentle pull, so that the orbital centre of the system is a little away from the centre of the star and the star itself orbits about this point. We can detect this as a small regular movement of the star to and fro along our line of sight. This tug of war between any star and its exoplanets can be seen (or rather, measured) by HARPS, with an incredible precision. HARPS picks up small changes in the star's radial velocity (i.e. along the line of sight), which can be as little as a gentle walking pace of 3.5.

**Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs (CARMENES)**

CARMENES is a next-generation instrument built for the 3.5m telescope at the Calar Alto Observatory by a consortium of German and Spanish institutions. It consists of two separated spectrographs covering the wavelength ranges from 0.52 to 0.96 μm and from 0.96 to 1.71 μm with spectral resolutions R = 80,000-100,000, each of which performs high-accuracy radial-velocity measurements (~1 m $s^{-1}$) with long-term stability. The fundamental science objective of CARMENES is to carry out a survey of ~300 late-type main-sequence stars with the goal of detecting low-mass planets in their habitable zones. We aim at being able to detect 2 $M_{Earth}$ planets in the habitable zone of M5V stars.

**University KU Leuven' Marvel project**

Radial velocity measurements are needed to characterise the orbit and mass, and complete the picture of densities and composition of the exoplanet systems found. The ARIEL mission (ESA, launch 2028) will characterise exoplanet atmospheres with infrared spectroscopy. Characterisation of stellar activity using optical ground spectroscopy is key to retrieve the planet atmosphere spectral footprint in ARIELs spectra. To enable the scientific harvest of the TESS, PLATO and ARIEL space missions, the Institute of Astronomy will use MARVEL: Four telescopes are linked via optical fibres to a custom-built spectrograph, which is kept stable in a vacuum chamber to allow the simultaneous measurement of the radial motions of 4 stars.

**5.0 Transits – variations in timing, duration, depth – project outline**

Chart 1 Siegfried Vanaverbeke's proposal for this TTV project.

Refer to the Observation and analysis document for a more detailed approach and links to the various software packages.

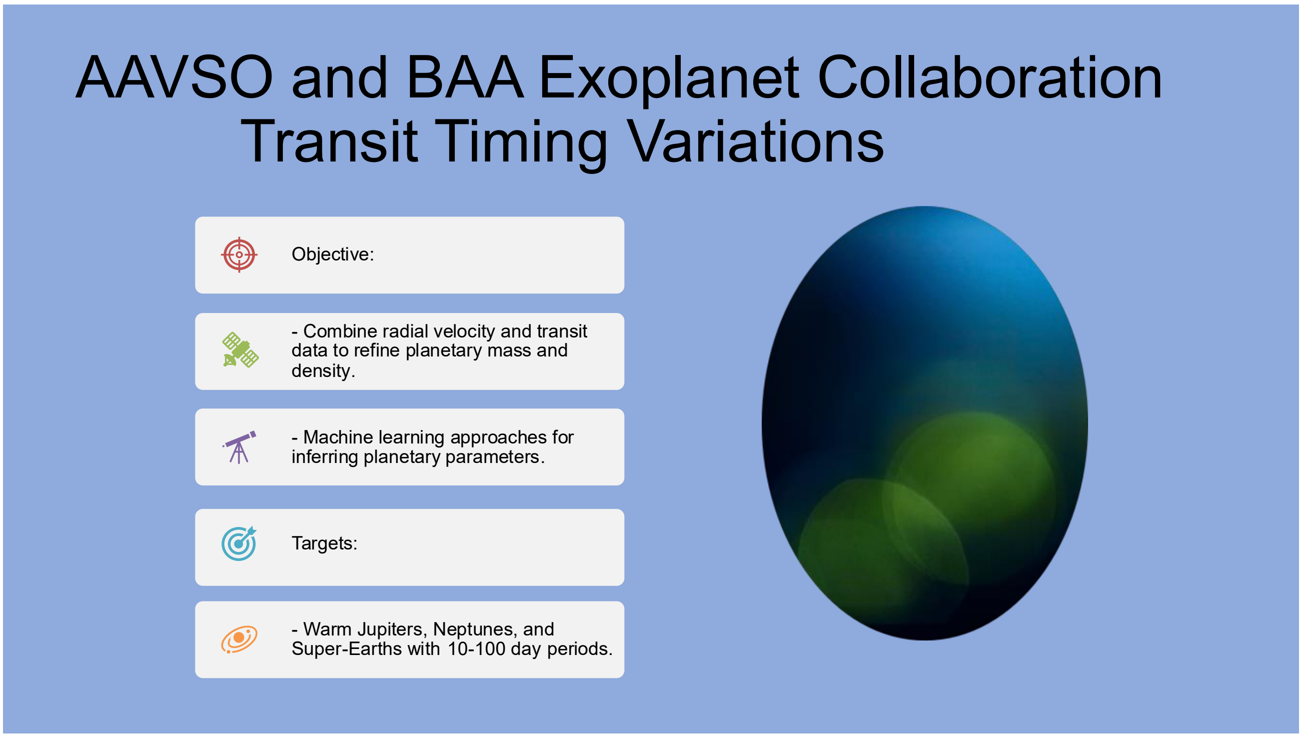
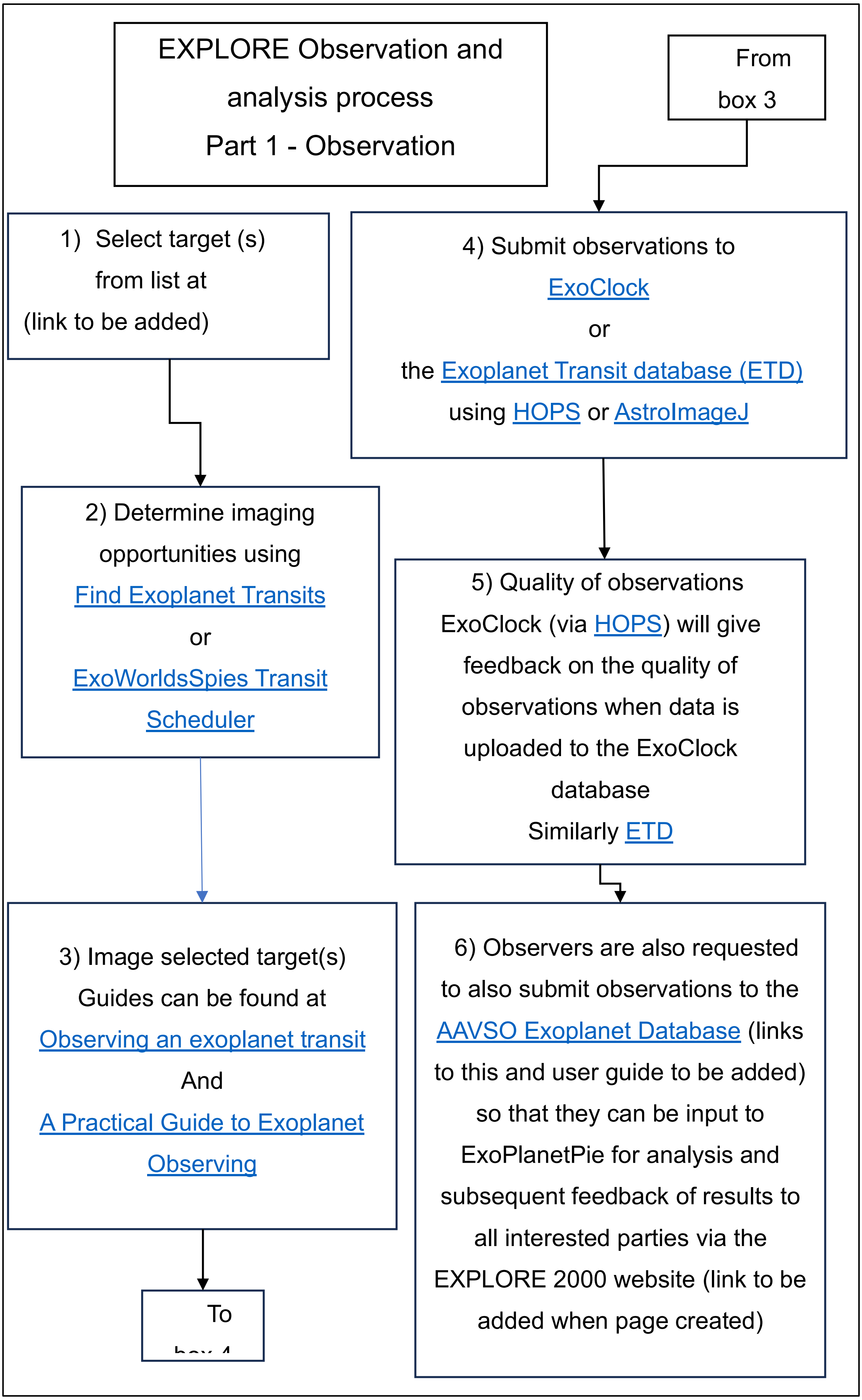



Chart 1. Siegfried Vanaverbeke’s proposal for this TTV project


EXPLORE Observation and analysis process
Part 1 - Observation
From box 3
1) Select target (s) from list at (link to be added)
2) Determine imaging opportunities using Find Exoplanet Transits or ExoWorldsSpies Transit Scheduler
3) Image selected target(s)
Guides can be found at Observing an exoplanet transit
And
A Practical Guide to Exoplanet Observing
To
4) Submit observations to ExoClock or the Exoplanet Transit database (ETD) using HOPS or AstroImageJ
5) Quality of observations
ExoClock (via HOPS) will give feedback on the quality of observations when data is uploaded to the ExoClock database
Similarly ETD
6) Observers are also requested to also submit observations to the AAVSO Exoplanet Database (links to this and user guide to be added) so that they can be input to ExoPlanetPie for analysis and subsequent feedback of results to all interested parties via the EXPLORE 2000 website (link to be added when page created)

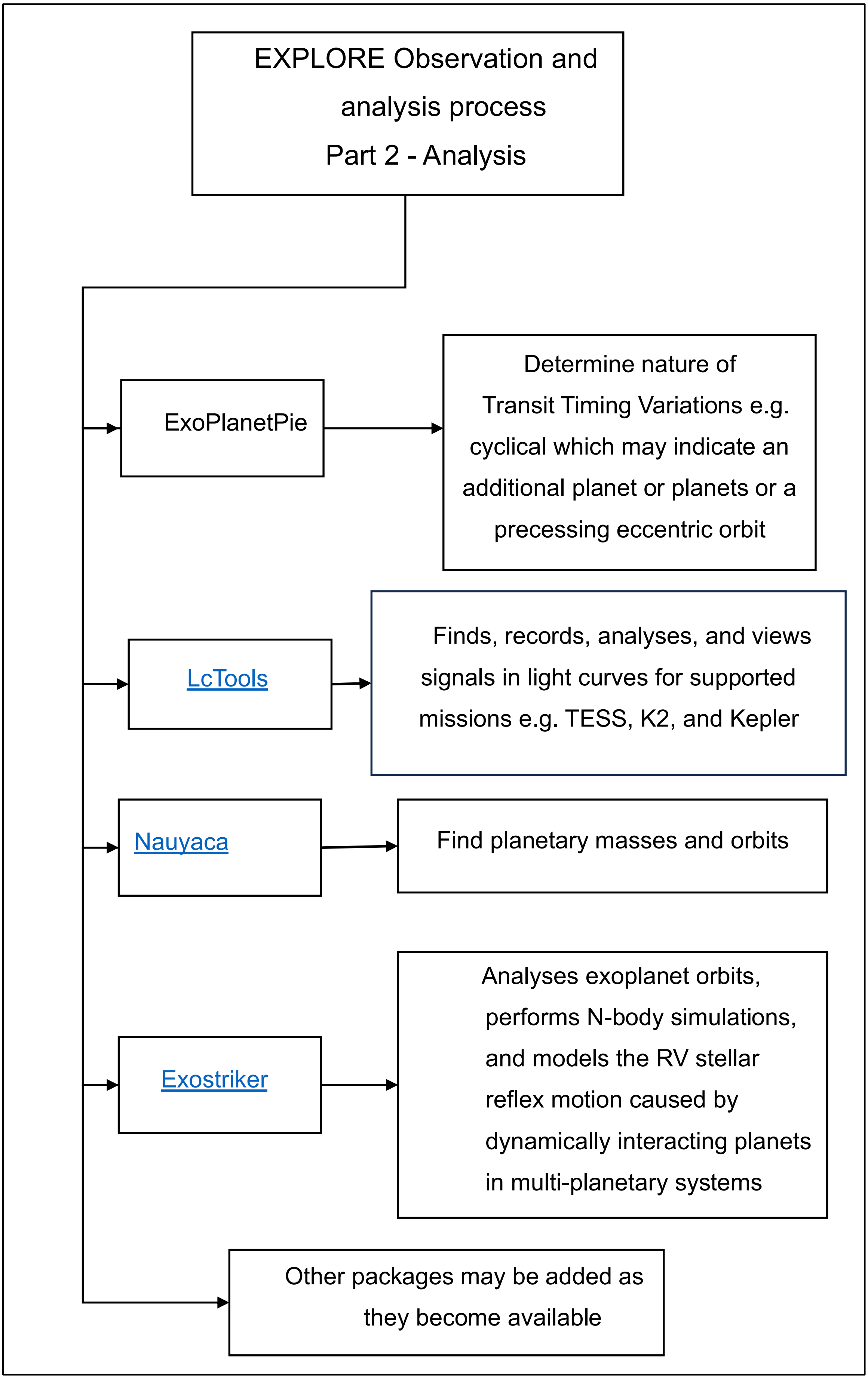

EXPLORE Observation and analysis process
Part 2 - Analysis
ExoPlanetPie
Determine nature of Transit Timing Variations e.g. cyclical which may indicate an additional planet or planets or a precessing eccentric orbit
LcTools
Finds, records, analyses, and views signals in light curves for supported missions e.g. TESS, K2, and Kepler
Nauyaca
Find planetary masses and orbits
Exostriker
Analyses exoplanet orbits, performs N-body simulations, and models the RV stellar reflex motion caused by dynamically interacting planets in multi-planetary systems
Other packages may be added as they become available

Chart 2. Observation and analysis flowchart

## 6.0 References

**AAVSO Exoplanet Section**

**BAA Exoplanet Division**

**Exoplanetpie;** is available from Pieter Vuylsteke at pieter.vuylsteke'at'gmail.com

**Paper**; Nauyaca: a New Tool to Determine Planetary Masses and Orbital Elements through Transit Timing Analysis

Code is available at https://github.com/EliabCanul/nauyaca

**Machine learning – a Simulation-Based Inference (SBI)**

Extract from Siegfried Vanaverbeke's emails dated 2025 February 27 and 2025 March 3.

The machine learning method used is simulated based inference and to my knowledge this is a relatively new tool in machine learning. The method assumes given prior distributions for the model parameters, and then uses a "simulator" to generate synthetic datasets including observational uncertainty. The simulated datasets form pairs of (parameters, synthetic data) which sample the likelihood function. A neural network is then trained to predict the training data from the model parameters, and finally the priors and the likelihood samples are combined to compute the posterior distribution of the model parameters. This is explained in the pdf manual and implemented in the python package SBI. The are many details that can be changed and I am also new to this method. The "simulator" in our case is a model for a two-planet system with two planets in a 2:1 resonant configuration orbiting a star in the same plane. I leave all orbital parameters fixed in this first experiment and only vary the masses of the two planets. The simulator returns the TTVs of both planets+observational noise, computes GLS periodograms of their time series and considers the periodograms as the output of the simulator. We then apply SBI on a huge set of synthetic training data and check if this model will be able to infer the posterior distributions of the masses of the planets given TTV data and the periodograms.

Master thesis : Exoplanet Orbital Characterization Using Simulation-Based Inference

**Nested sampling**

Classical methods such as nested sampling will also play an important role. These methods are iterative methods to sample the likelihood function given a model and data. They are now quite routinely used in astronomy and physics.

Roger Dymock

BAA Asteroids and Remote Planets Section, Assistant Director Exoplanets Division