Eclipse timing variations to detect possible Trojan planets in binary systems

R. Schwarz*, Á. Bazsó, B. Funk and R. Zechner

Institute for Astronomy, University of Vienna, A-1180 Vienna, Türkenschanzstrasse 17, Austria

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ABSTRACT
This paper is devoted to study the circumstances favourable to detect Trojan planets in close binary-star-systems by the help of eclipse timing variations (ETVs). To determine the probability of the detection of such variations with ground based telescopes and space telescopes (like former missions CoRoT and Kepler and future space missions like Plato, Tess and Cheops), we investigated the dynamics of binary star systems with a planet in tadpole motion. We did numerical simulations by using the full three-body problem as dynamical model. The stability and the ETVs are investigated by computing stability/ETV maps for different masses of the secondary star and the Trojan planet. In addition we changed the eccentricity of the possible Trojan planet. By the help of the libration amplitude $\sigma$ we could show whether or not all stable objects are moving in tadpole orbits. We can conclude that many amplitudes of ETVs are large enough to detect Earth-like Trojan planets in binary star systems. As an application, we prepared a list of possible candidates.

Key words: celestial mechanics – methods: numerical – (stars): planetary systems – (stars):binaries: general

1 INTRODUCTION
The first extra solar planet was discovered in the early 1990s by Wolszczan & Frail (1992). Today the statistics of the observations showed that the architecture of our solar system seems to be unique compared with exoplanetary systems. At the moment we know about 1900 exoplanets in more than 1200 planetary systems, among them more than 100 exoplanets are in binary-star systems and 20 are in multiple-star systems. The data of all planets are collected in the Exoplanet-catalogue maintained by J. Schneider1; whereas the binary and multiple-star systems can be found separately in the binary catalogue of exoplanets2 maintained by R. Schwarz. For nearby Sun-like stars, approximately 70 percent are confirmed to be double or multiple systems (~ 75% for O-B stars, Verschueren et al. (1996), Mason, Gies, & Hartkopf (2001); ~ 67% for G-M stars, Mayor et al. (2001)). Statistics of solar-type dwarfs were studied by Tokovinin (2014) with a distance-limited sample of 4847 targets. A field population was found of about 54% for single stars, 33% binary stars, 8% triple systems, 4% for quadrupole systems, 1% for systems $N > 4$.

According to the work of Rabl & Dvorak (1988) one can distinguish three types of planetary orbits in a binary star system:

(i) S-Type, where the planet orbits one of the two stars;
(ii) P-Type, where the planet orbits the entire binary;
(iii) T-Type: a planet may orbit close to one of the two equilibrium points $L_4$ and $L_5$ (Trojan planets).

From the dynamical point of view the binary star systems are particularly interesting. For the circular restricted three-body problem (CR3BP) it has been shown by Gascheau (1843) and Routh (1875) that only for mass ratios in the interval $0 \leq \mu \leq \mu_{\text{crit}}$ the librational motion is linearly stable (here $\mu = m_2/(m_1 + m_2)$, and $\mu_{\text{crit}} = (1 - \sqrt{23/27})/2 \approx 0.0385$). However, former studies of Erdi et al. (2009) and Sicardy (2010) could show that there exist stable orbits beyond Gascheaus value ($\mu_{\text{crit}}$), in the planar case. Whereas, Bazsó et al. (2013) could also show that in the spatial restricted three-body problem. However, even the extended stability region limits the possibility to find Trojans in double stars, because the necessary mass ratios are relatively rare.

Most observations of planets in binaries are focused on $\mu \approx 0.5$ (stars have similar masses) and are restricted sun like stars. Nevertheless the dynamical study of Schwarz, Süli, & Dvorak (2009) could show with a few real
binary systems that the T-Type configuration may be not only of theoretical interest. Therefore we show a distribution (Fig. 1) of the mass ratio of all detected exoplanets in binaries. The most common mass ratios are 0.25 and 0.5. The frequency of the interesting mass ratios (μcrit) for the Trojan configuration is around 3 percent. When we compare Fig. 1 with the statistics of the nearby Sun-like stars the value is larger, it is around 10 percent. Druchennov & Mayor (1991). However, if one considers also systems with a brown dwarf as companion the number of possible candidates would be larger (as shown in our candidate list Tab. 3), due to their substellar masses.

Our work was motivated by the huge number of Trojans which were found in the solar system around different planets (Earth, Mars, Jupiter, Uranus and Neptune). The possibility of Trojan planets in exoplanetary systems was discussed in several dynamical investigations like e.g. Naungher (2002), Laughlin & Chambers (2002), Erdi & Sándor (2003), Dvorak et al. (2004), and Schwarz et al. (2007a). Theoretical studies predict that Trojans are a by-product of planet formation and evolution, see the hydrodynamic simulations of a protoplanetary disk, like in the work of Chiang & Lithwick (2007) and Beaugé et al. (2007). Whereas Pierens & Raymond (2014) studied the orbital evolution of co-orbital planets embedded in a protoplanetary disc. The investigation on the possibility of a migration-induced resonance locking in systems containing three planets, namely an Earth-like planet, a super-Earth and a gas giant with one Jupiter mass Podlewski-Gaca & Szuszkiewicz (2014) found that the super-Earth planet captures the Earth-like planet into co-orbital motion temporarily. In case of binary systems the formation or capture scenario for possible Trojan planets are not yet investigated.

Ford & Gaudi (2006) and Ford & Holman (2007) examined the sensitivity of transit timing variations (TTVs) for a possible detection of Trojan companions. They demonstrated that this method offers the potential to detect terrestrial-mass Trojans using existing ground-based observatories. Janson (2013) reported a systematic search for extrasolar Trojan companions to 2244 known Kepler Objects, but no Trojan candidates were found. In a theoretical work of Vokrouhlík & Nesvorný (2014), they studied the TTVs for planets in the horseshoe regime by using semi-analytical models.

This paper is divided into two parts: the first part investigates the stability of Trojan planets in binary systems, whereas the second part is devoted to the possible detection of Trojan planets by the help of eclipse timing variations (ETV).

2 NUMERICAL SETUP

2.1 Models

We studied the planar full three-body problem (3BP) with numerical integrators. In this problem three finite bodies, the primaries (m1 = primary star, m2 = secondary star) revolve about their common center of mass, starting on circular orbits (e2 = 0), and a third body mTrov = Trojan moves under their gravitational influence in the same orbit as m2 close to the equilibrium point L4 60 degree ahead of the secondary star.

We have regarded all the celestial bodies involved as point masses and integrated the dimensionless (the semi-major axis set to one) equations of motion for an integration time up to $T_c = 10^5$ and $10^6$ periods of the secondary star for the stability maps and $T_c = 10^7$ periods for special cases shown in chapter 3. For our simulations we used the Lie-method with an automatic step-size control to solve the equations of motion (Hanslmeier & Dvorak 1984, Lichtenegger 1984, Eegl & Dvorak 2010).

2.2 Initial conditions

The computations were accomplished only in the vicinity of $L_4$ ($L_5$ is symmetric in the 3BP). For the calculations of the stability maps we varied the eccentricities of the Trojans ($e_{Trov}$=Trojan planet) from $e_{Trov}$ = 0.01 up to $e_{Trov}$ = 0.5. In addition, we varied the mass of the secondary object from $m_2 = 10^{-3} M_{\odot}$ ($M_{\odot}$ corresponds to 1 Solar mass) until the end of the stability border with a map size of 235 x 40 values ($m_2$ x $e_{Trov}$). The lower limit of $m_2$ presents planets of about 2 Jupiter masses as shown in our stability investigations. In case of the ETV’s we started our investigations at masses equal to substellar objects (approximately 13 Jupiter masses). The stability border changes because we also calculated the stability maps for different masses of the host star $m_1=1, 2$ and $3 M_{\odot}$. For $m_1 = 1 M_{\odot}$ the stability border lies at $m_2 = 0.045 M_{\odot}$, for $m_1 = 2 M_{\odot}$ at $m_2 = 0.087 M_{\odot}$ and for $m_1 = 3 M_{\odot}$ at $m_2 = 0.130 M_{\odot}$.

To get a good estimation about occurring perturbations on the secondary star (to measure ETVs) we used Trojan planets with different sizes: Mars, Earth, Neptune and Jupiter, which corresponds to $10^{-3} M_{\odot}$.

2.3 Methods

For the analysis of the orbit we used the method of the maximum eccentricity $e_{max}$. In former studies we found a good agreement with chaos indicators (as shown in Bazsó et al. 2013) like the Lyapunov characteristic indicator (LCI), like in Schwarz et al. (2007b). The $e_{max}$ method uses as an indication of stability a straightforward check based on the
maximum value of the Trojans eccentricity reached during the 
total integration time. If the Trojan’s orbit becomes 
parabolic (ε_{max} \geq 1) the system is considered to be unstable. 
The ε_{max} is defined as follows:

\[ ε_{\text{max}} = \max_{t \leq T_c} (ε). \] (1)

To analyse the orbital behaviour of the third body m_3 
(e.g. tadpole, horseshoe, or satellite), we used the amplitude 
of libration, as done in the work of Freistetter (2006) and 
Schwarz, Funk, & Bazsó (2013).

The classification of the orbit was done by checking the 
libration amplitude σ which is defined as the difference be- 
tween the mean longitude of the Trojan and the secondary 
star (λ_{TRO} - λ_2). λ_{TRO}, λ_2 are given by λ_{TRO} = \bar{ε} + M, 
λ_2 = \bar{ε}_2 + M_2 were \bar{ε}, \bar{ε}_2 are the longitudes of ascending 
ode of the Trojan body and of the m_2 and M_{TRO}, M_2 are 
the mean anomaly of the third body respectively of the 
secondary star. As for the ε_{max} we determined the maximum 
libration amplitude σ_{max} for the total integration time:

\[ σ_{\text{max}} = \max_{t \leq T_c} (σ). \] (2)

In the case of a large libration amplitude the Trojan 
may become a horseshoe orbit or may be ejected out of 
the Trojan region after a close approach with the secondary 
body. The value of σ_{max} should be smaller than 180° for 
tadpole orbits.

As indicated by the results of the stability analysis, an 
exoplanet in a T-type orbit may be stable in the vicinity of 
a binary star system. The gravitational perturbation of this 
planet may affect the motions of the two stars and cause 
their orbits to deviate from Keplerian. In an eclipsing binary, 
these deviations result in variations in the time and duration 
of the eclipse.

We determined the ETVs by calculating the perturbed 
case, where the planet induced constant rate of apsidal pre- 
cession is removed by a linear fit. We also took into account 
the long-term effects caused by the binaries motion around 
the system center of mass.

3 STABILITY

First of all we investigated the stability of the Lagrangian 
point L_4 in the planar three-body problem to determine the 
stability limits and to investigate whether the orbits are still in 
Trojan motion or not, by the help of σ_{max}. Our studies 
showed that all stable orbits stay in tadpole motion. In addition 
we used different masses of the primary and secondary 
star, which might be useful for future observations of differ- 
ent stars. We computed the stability maps by changing the 
mass of the secondary and the eccentricity of the Trojan. 
An example is shown in Fig. 2 for the 3 different masses of 
the primary star (1, 2 and 3 M_{Sun}).

As one can see the stability maps do not start at zero (x 
and y axes in Fig. 2). That means the initial mass of the 
secondary body is 0.001 M_{Sun} \sim M_{Jup} and e_{TRO} = 0.005. How- 
ever, we focus on the stability region from m_2 \geq 10M_{Jup}, 
because lower masses (planet-like masses) of the secondary 
are not interesting for binary (like) star-systems and initially 
circular orbits (e_{TRO} = 0) do not produce detectable ETV 
signals. An example of the stability maps is given in Fig. 2 
which is divided into 3 different graphs, showing different 
masses of the primary star (m_1). Whereas, the upper graph 
depicts the stability map for m_1 = 1M_{Sun}, the middle one 
depicts m_1 = 2M_{Sun} and the lower one m_1 = 3M_{Sun}. We can 
conclude that the number of stable orbits do not differ much, 
as summarized in Tab. 1 where we also show the studies for 
different masses of the Trojan planet (from Earth mass up to 
Jupiter mass). In principle the number of stable orbits do 
not change very much for the different masses of the Tro- 
jan. Nevertheless, the shape of the stable region (gaps) are 
changing when we change the mass of the secondary star. 
The gaps are mainly caused by secondary resonances which 
were investigated in the work of Schwarz, Funk, & Bazsó 
(2012) for large mass ratios and in Schwarz, Funk, & Bazsó 
(2013) for low mass ratios. In addition, one can see that the 
Trojan body can have larger initial eccentricity for larger mass 
of the primary star m_1, this is especially well visible for small 
masses of m_2. The maximum stable eccentricity ε_{ini} = 0.245 
is valid for m_2 = 0.01 (which corresponds to a binary-like 
star system with a brown dwarf) and for different masses 
of central star (m_1) M_{TRO} = 1 M_{Jup}, \mu_{crit} = 0.04060 for 
1 M_{Sun}, \mu_{crit} = 0.08185 for 2 M_{Sun} and \mu_{crit} = 0.12365 
for 3 M_{Sun}. Also the limit of the stable region increases with 
a more massive central star: for m_1 = 1M_{Sun} the limit 
amounts m_2 = 0.041, for m_1 = 2M_{Sun} the limit amounts 
m_2 = 0.082 and for m_1 = 3M_{Sun} we have the largest value 
m_2 = 0.12. The stability limit changes because of the differ- 
ent mass ratio \mu = m_2/(m_1 + m_2) as we know from the circu- 
lar restricted three-body problem. In addition, we made long 
term integrations, represented in Fig. 3 by the help of cuts 
of the stability maps shown in Fig. 2 (cuts for e_{TRO} = 0.035). 

| mass of the primary | mass of the Trojan | number of stable orbits | percent of stable orbits |
|---------------------|-------------------|------------------------|-------------------------|
| 1 Earth             | 734               | 21.839                 |                          |
| 1 Neptune           | 729               | 21.690                 |                          |
| 1 Jupiter           | 639               | 19.012                 |                          |
| 2 Earth             | 1523              | 22.947                 |                          |
| 2 Neptune           | 1517              | 22.857                 |                          |
| 2 Jupiter           | 1404              | 21.154                 |                          |
| 3 Earth             | 2316              | 23.363                 |                          |
| 3 Neptune           | 2305              | 23.252                 |                          |
| 3 Jupiter           | 2168              | 21.870                 |                          |
When we are looking for extrasolar planets in T-Type configuration we are interested in the ETV signal of the secondary star caused by an additional planet. This method is particularly important in the case when the planet’s orbit may not be in the line of sight. However, such planets cause perturbations in the orbit of the transiting star, leading to detectable ETVs. These were investigated for TTVs in several articles like e.g. Miralda-Escudé & Adams (2005; Holman & Murray 2005) and Agol & Steffen (2007). The feasibility of the detection of extrasolar planets by the partial occultation on eclipsing binaries was investigated by Schneider & Chevreton (1990). Therefore, we set our goal to show which planet sizes for the T-Type configuration are detectable in the ETV signal of the secondary star with current observational equipment. In order to approximate the detectability of possible extrasolar planets in T-Type motion by means of ETVs we used the work of Sybilsky, Konacki & Kolodskii (2010). In principle they determined the sensitivity of the eclipse timing technique to circumbinary planets (exoplanets in P-Type motion) for space-based photometric observations. They showed that the typical photometric error (detectable timing amplitude dT) for CoRoT is about dT = 4 sec for a brightness (L) of 12 [mag] and dT = 16 sec for L=15.5 [mag]. Kepler has a dT = 0.5 sec for L=9 [mag] and a dT = 4 sec for L=14.5 [mag]. Future space missions will support the effort to detect new planets and smaller planets like for example: PLATO (Planetary Transits and Oscillations of stars) will monitor relatively nearby stars to hunt for Sun-Earth analogue systems (Rauer et al. 2014). TESS (Transiting Exoplanet Survey Satellite) space mission is dedicated to detect nearby Earth or super-Earth-size planets on close-in orbits around the brightest M dwarfs (Ricker et al. 2014). CHEOPS (Characterising ExOPlanets Satellite) will examine transiting exoplanets of known bright and nearby host stars (Broeg et al. 2013). For our investigations we will use as detection criterion the photometric precision of CoRoT dT_{crit} = 16sec.

In our studies we investigated the amplitude of the ETV signals, therefore we varied the mass of the secondary body; starting with a binary like system m_2 = 13MJ_{Sun} (13 Jupiter masses corresponds to the lowest mass of a brown dwarf). In addition, we varied the eccentricity of the Trojan planet whereas the secondary body moves in a circular orbit. We used the stability analysis for the study of the ETV signals, which is presented in Fig. 2 for different masses of the Trojan body M_{Jup}, for 1 M_{Sun} (upper graph) 2 M_{Sun} (middle graph) and 3 M_{Sun} (lower graph). Whereas, m_1 ~ 1M_{Sun} represent Sun-like stars and m_1 = 1 M_{Sun} depicts brighter stars. But we did not take into account less massive stars.
Table 2. Detectable timing amplitude \( dT \) for different masses of the primary star (first column) and different type of the Trojan bodies are given in the second column starting with Mars mass \((m_{T Trojan} = 0.032271 \cdot 10^{-6} M_{Sun})\) then Earth mass \((m_{T Trojan} = 0.30019 \cdot 10^{-5} M_{Sun})\), Neptune mass \((m_{T Trojan} = 0.51684 \cdot 10^{-3} M_{Sun})\), and Jupiter mass \((m_{T Trojan} = 0.9547 \cdot 10^{-3} M_{Sun})\). The third column represents the minimum \( dT \) and the last column depicts the percentage of all possible detectable signals \((dT_{crit})\) within the stable region, presented as bold line in Fig. 4 and Fig. 5.

| mass of the primary Trojan bodies \([M_{Sun}]\) | type of | minimum of | percent lie in the \(dT_{crit}\) |
|---------------------------------|--------|------------|-----------------|
| 1 | Mars | 4.3s | 40 |
| 1 | Earth | 24.2s | 100 |
| 1 | Neptune | 7.2m | 100 |
| 1 | Jupiter | 1.82h | 100 |
| 2 | Mars | 3.5s | 15 |
| 2 | Earth | 10.4s | 89 |
| 2 | Neptune | 2.1m | 100 |
| 2 | Jupiter | 0.82h | 100 |
| 3 | Mars | 2.6s | 3 |
| 3 | Earth | 6.0s | 77 |
| 3 | Neptune | 1.5m | 100 |
| 3 | Jupiter | 0.39h | 100 |

\( (m_1) \), because of the critical mass ratio \( \mu_{crit} \), which means that the secondary star would be a planetary object instead of a brown dwarf. As one can see the eccentricity of possible Trojan planets is limited by their eccentricity, that means Trojan planets can not have larger eccentricities than \( e_{T Trojan} = 0.2 \) for \( m_2 \geq 0.01 \). This is also well visible in Fig. 4 and Fig. 5 were we present contour plots for terrestrial-like planets. Fig. 4 shows Trojans with Earth mass and Fig. 5 shows Trojans with Mars mass. The most important contours are the stability limit (outer border) and the border with \( dT_{crit} = 16s \). In case of an Earth-like Trojan planet with \( m_1 = M_{Sun} \) all stable orbits produce a detectable ETV signal \((dT_{crit} \geq 16s)\). The figures 4 and 5 showed that with larger mass of the central star \((m_1 = 2, 3 M_{Sun})\) the stability limits increase, because of that Trojans can have larger eccentricities. However, the number of detectable ETV signals shrinks with larger \( m_1 \) and amplitude \( dT \) have smaller values too, as concluded in Tab. 2. This is mainly important for terrestrial like Trojan planets. In case of \( M_{T Trojan} \) is equal to Jupiter or Neptune mass all stable orbits produce a detectable ETV signal. As represented in Tab. 2 where the third column show the minimum amplitude of the ETV signal \( dT \) and fourth column depicts the number of detectable ETV signals within the stable region. We can summarize that possible terrestrial-like planets are detectable in binary star systems by the help of eclipse timing variations with restrictions.

5 LIST OF CANDIDATES FOR BINARY (LIKE) SYSTEMS

As an application we prepared a list of possible candidates, which fulfil the most important dynamical and observational conditions. In case of double stars it is very difficult to find candidates, because the important parameters like semi-major axis \( a \) and mass ratio \( \mu \) of the primary bodies are not or only partly given. Maybe this problem will change in future, because of the data of the space mission GAIA\(^3\) which will make a survey of one billion stars with many binary star systems. Ever et al. (2012) and binary-like systems de Bruijne (2012). For our search we used the ”Wash-

\(^3\) Global Astrometric Interferometer for Astrophysics
We found 24 systems with a mass ratio smaller than the critical mass ratio \( \mu_{\text{crit}} \), the list of candidates decreases to 68 candidates. Concerning to the condition that the distance to the central star should be not too far (that means \( a \leq 1 \) AU because of long observation time) we found only 10 candidates. The data of all planets are taken from the Exoplanet-catalogue maintained by J. Schneider.

### Table 3. List of candidates to detect possible Trojan planets in binary-like systems. The list is sorted according to the semi-major axis \( a_2 \) of the brown dwarf. All systems were detected by TTVs except for those marked with a star (which were detected by radial velocity).

| Name       | mass \([M_{\text{Jup}}]\) | \(a\) in \([\text{AU}]\) | \(m_1\) \([M_{\odot}]\) | \(\mu \leq \mu_{\text{crit}}\) |
|------------|--------------------------|-------------------------|--------------------------|-------------------------------|
| WASP-18 b  | 10.43                    | 0.020                   | 1.24                     | 0.00796                       |
| KELT-1 b   | 27.38                    | 0.025                   | 1.335                    | 0.01919                       |
| XO-3 b     | 11.79                    | 0.045                   | 1.41                     | 0.00791                       |
| CoRoT-27 b | 10.39                    | 0.048                   | 1.05                     | 0.00935                       |
| CoRoT-3 b  | 21.77                    | 0.057                   | 1.41                     | 0.01435                       |
| HD 162020 b* | 14.4                   | 0.074                   | 0.75                     | 0.01799                       |
| Kepler-39 b | 18                      | 0.155                   | 1.1                      | 0.01537                       |
| Kepler-27 c | 13.8                    | 0.191                   | 0.65                     | 0.01985                       |
| HD 114762 b* | 10.98                  | 0.353                   | 0.84                     | 0.01232                       |
| HD 202206 b* | 17.4                  | 0.890                   | 1.13                     | 0.01448                       |

#### 6 CONCLUSIONS

We have carried out a parameter study for a variety of binaries with different mass-ratios of the primary bodies and different orbital elements of the Trojan planet. The stability analysis has shown that there exist a stable region for planets – gas giants as well as terrestrial like planets – in T-type motion for low eccentricities \( e_{Tro} \leq 0.25 \). Our results have shown that binary-like systems (the secondary body is a brown dwarf) and binary systems with low-mass stars are good candidates to discover new planets by eclipse timing of the secondary star, agreeing with the work of Schneider & Doyle (1995). At this point we have to concede that from an observational point of view M-stars are better candidates than brown dwarfs. Nevertheless, ETV signals of brown dwarfs would be detectable too. We found that for all stable initial conditions an Earth-like Trojan planet would produce detectable ETV signals if the primary star has 1 \( M_{\odot} \). This is also valid for Jupiter and Neptune type Trojan planets, but also for not Sun-like stars \( (m_1 = 2M_{\odot} \) and \( m_1 = 3M_{\odot} \)). Unexpectedly, we found that even Trojan planets with Mars mass would be detectable, but under favourable circumstances. As an application we prepared a list of possible candidates for the detection possible Trojan planets of binary and binary-like systems. In case of binaries we found 24 candidates, but for only a single system (Antares, \( \alpha \) Sco) the semi-major axis \( a \) is constrained. In addition, we made a list of candidates for binary-like stars which is given in Tab. 3 where we found 10 candidates.

We can conclude that possible terrestrial-like planets are detectable in binary star systems by the help of eclipse timing variations with restrictions. However, future space

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Figure 5. ETV map for \( L_4 \) in the planar \((i = 0^\circ)\) three-body problem for possible Trojan planets with one Mars mass, for \( 1M_{\odot} \) (upper graph), \( 2M_{\odot} \) (middle graph), and \( 3M_{\odot} \) (lower graph). The different lines presents the values of the amplitude of the ETV signal \( dT \) in [s]. The outer (bold) line represents the stability border.

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Mason Visual Double Star Catalogue'\(^{\dagger}\) (Mason et al. 2001). We found 24 systems with a mass ratio smaller than the critical one \((\mu \leq 0.04)\). But we found only one system where the semi-major axis from the secondary star \( a \) is given, namely Antares \((\alpha \) Sco) with \( a = 2.9 \) AU (Worley & Heintz 1983) and \( \mu \sim 0.016 \). Finally, we would like to mention that the distance of the secondary star should not be larger than 1 AU, because of the long observation time span.

At the moment we know about 1900 exoplanets in more than 1200 planetary systems, among them 93 planets have masses larger than 10 Jupiter masses. We classified them as binary like systems, because these objects are brown dwarfs. When we look at mass ratios which fulfil the criterion that \( \mu \leq \mu_{\text{crit}} \), the list of candidates decreases to 68 candidates. Concerning to the condition that the distance to the central star should be not too far (that means \( a \leq 1 \) AU because of long observation time) we found only 10 candidates. The data of all planets are taken from the Exoplanet-catalogue maintained by J. Schneider.
missions will have a better photometric precision which will enlarge the number of detectable ETV signals.

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