PLANETENBEWEGUNG IN STERNSYSTEMEN

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DI 13:15 – 14_45 SE 1

Motivation:

- Binary and Multi-Star Systems in the Solar neighbourhood: >60%
- Do the gravitational perturbations allow planetary formation ?
- Information about the area of formation
- Long-term stability is of great interest
  → search for habitable planets

OUTLINE:

1. Binary Stars and Exoplanets (Overview)	EPL
2. Resonances I (MMRs & SRs)	AB
3. Resonances II (Kozai & Evection Resonance)	AB
4. Stability of Planetary Motion	EPL
5. Chaosindicators (short introduction LCE, FLI)	EPL
7. Habitable Zones (HZ) I: Introduction and Concepts	EPL
8. HZ II: HZs in Binary Stars	AB

OUTLINE - continue:

9. Semi-analytical method (SAM) I: (Tools– FFT,SigSpec, SR)	AB
10. SAM II: Application to real Binary Systems	AB
11. Terrestrial Planet Formation in Binary Stars	EPL
12. Water Transport into the HZ	AB
13. Influence of the Second Star	EPL
14. Comparison to the Solar System	EPL

I. Binary Stars and Exoplanets

The observation of **Mizar (ζUMa)**
by **Giovanni Battista Riccioli in 1650**
was considered to be the first observation of a double star for a long time (see Aitken, 1964).

Meanwhile, it is known that already in
1617 Galileio Galilei
and his friend and former student **Benedetto Castelli**
observed the same object and made the same conclusion about the stellar multiplicity.

The term **double star** is used for two stars that are close enough but with clearly different true distances from the sun.

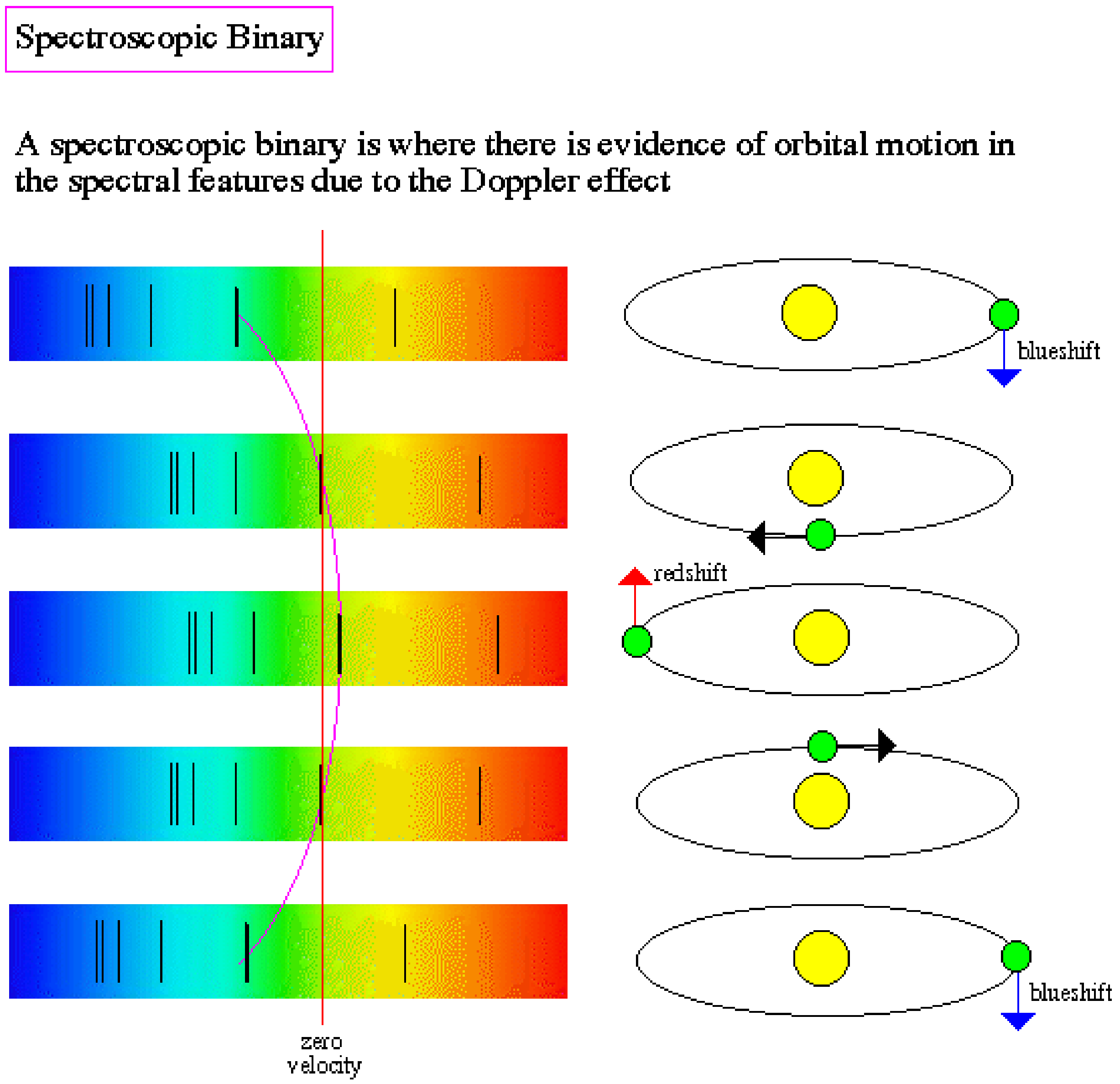
1802: Sir William Herschel introduced the term *binary* for the first time when he published about 700 double stars that he observed since 1779 (see Heintz, 1978).

He determined the changes of the relative positions of the stars which led to the conclusion that he observed binary systems (see Herschel, 1803).

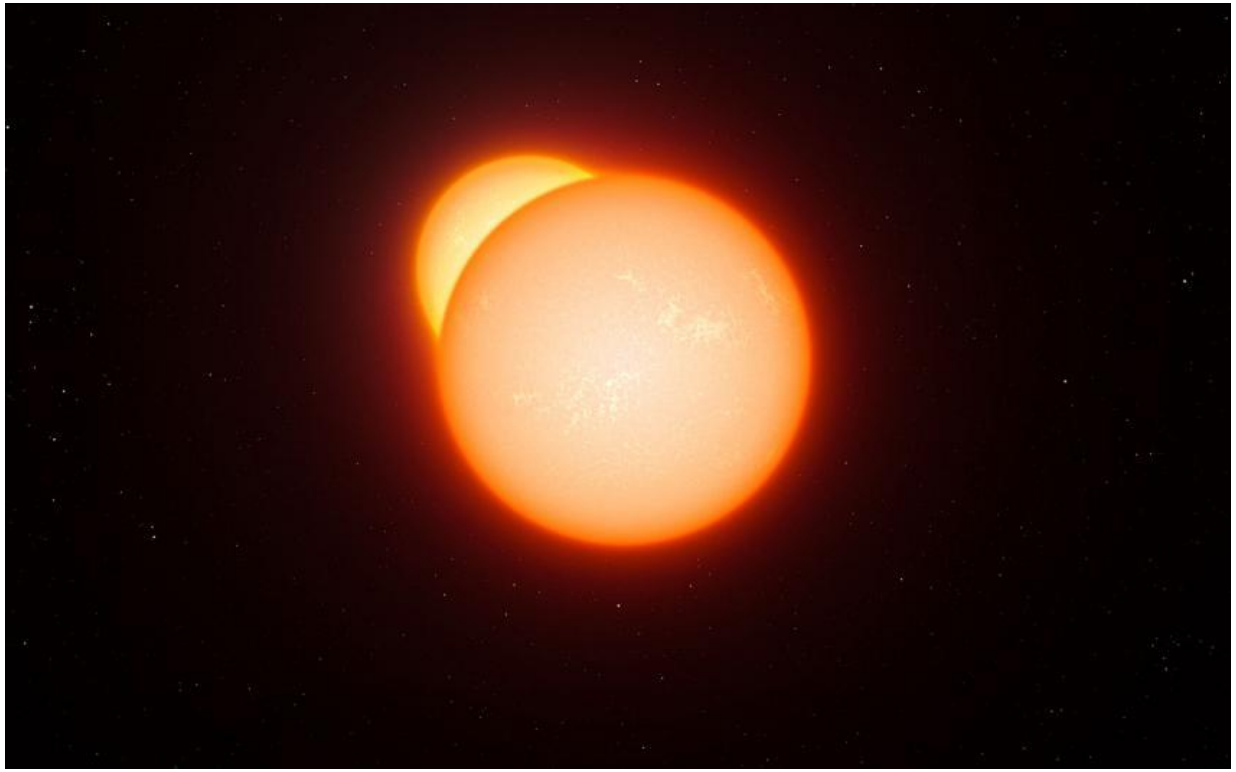
Observations of more and more binary stars led to a classification into different groups:

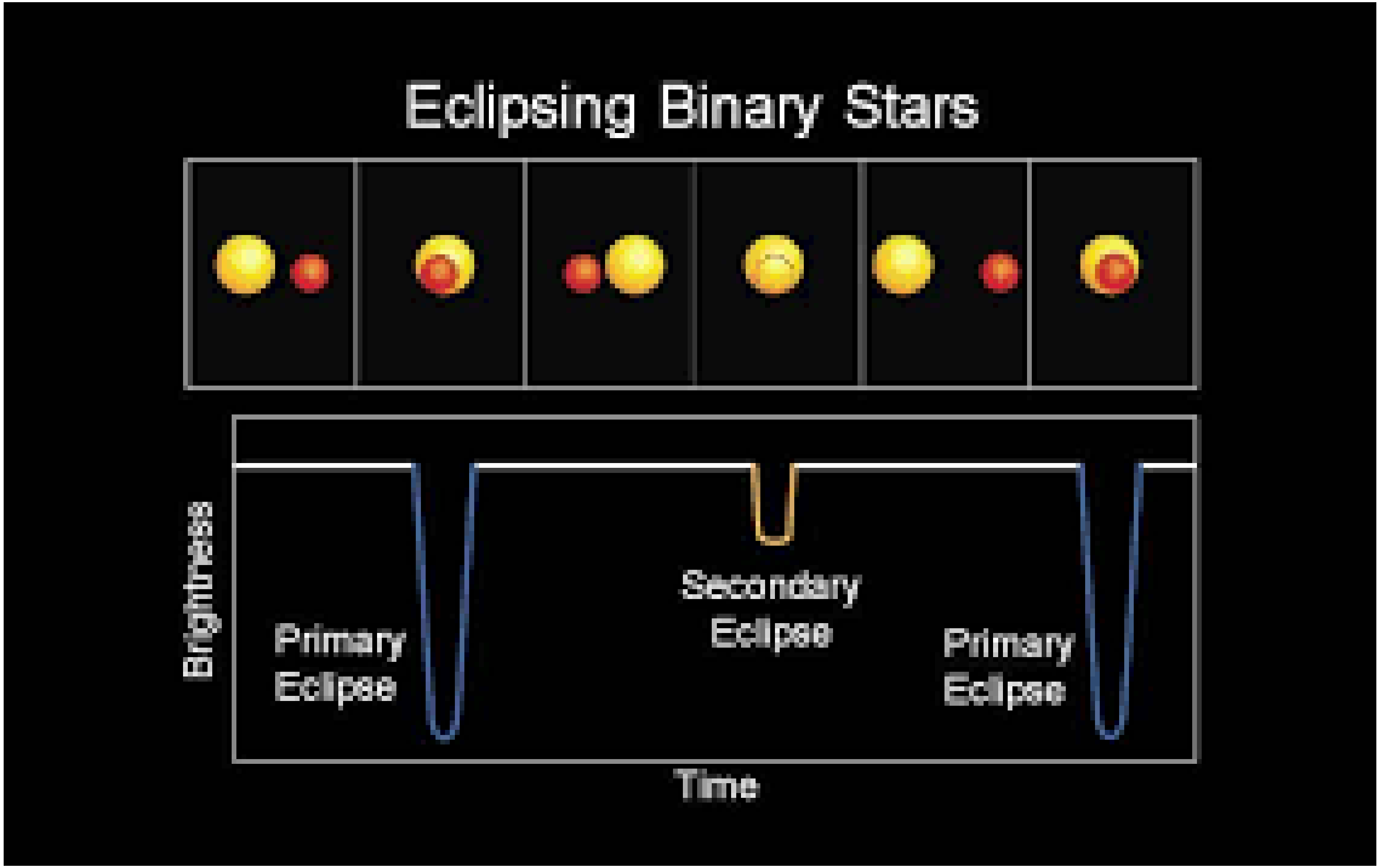
Visual binaries: when the two stars have a wide enough distance to be viewed seperately in a telescope. The first observed binary stars belong to this category.

Spectroscopic binaries:
the two stars have a close distance even when they are observed through a telescope.
It is difficult to resolve the parameters of each components separately



Eclipsing binaries: two very close stars that cause an eclipse when one passes in front of the other while observing them. From the periodic change in brightness one can determine easily the orbital period.




Eclipsing Binary Stars
Brightness
Primary
Eclipse
Secondary
Eclipse
Primary
Eclipse
Time

Astrometric binaries: observations make believe that they are single-stars as their companions cannot be seen, maybe they are too dim or hidden due to the much brighter primary star. Therefore, one can only infer a secondary star from the motion of the primary.

For dynamical studies the stellar distance is of importance which leads to a distinction of **wide and close binary stars**.

The orbital periods can reach from less than an hour or a few days to hundreds of thousands of years.

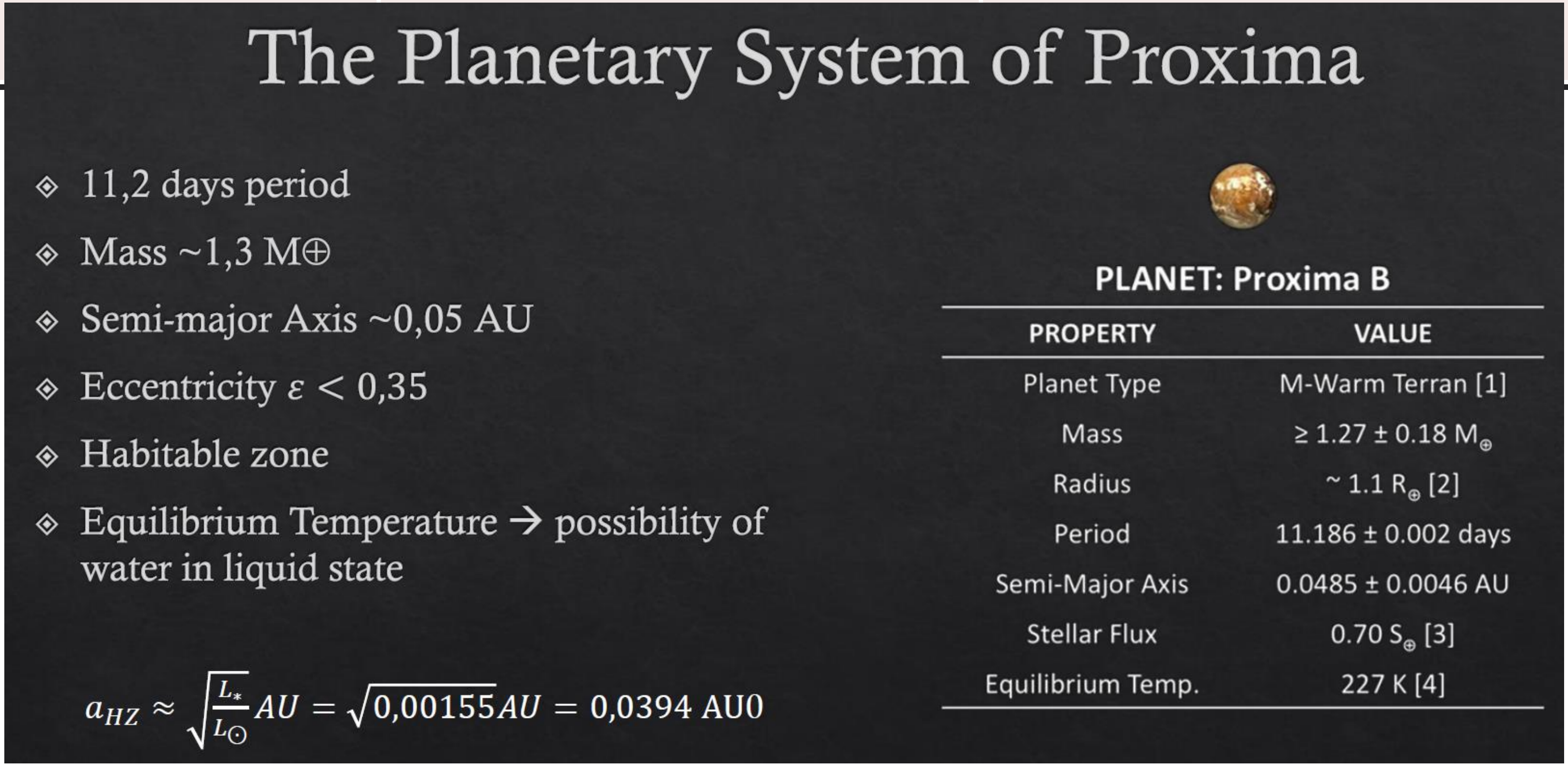
Our closest neighbouring star belongs to a triple systems consisting of a close binary (α Centauri AB) and a far away perturbing star (Proxima Centauri).

α Cen AB and Proxima

Characteristics	A	B	Proxima
Spectral Type	G2V	K1V	M5,5V
Mass	1,106 $M_\odot$	0,937 $M_\odot$	0,122 $M_\odot$

α Cen AB and Proxima

Characteristics	A	B	Proxima
Spectral Type	G2V	K1V	M5,5V
			0,122 $M_\odot$



The Planetary System of Proxima

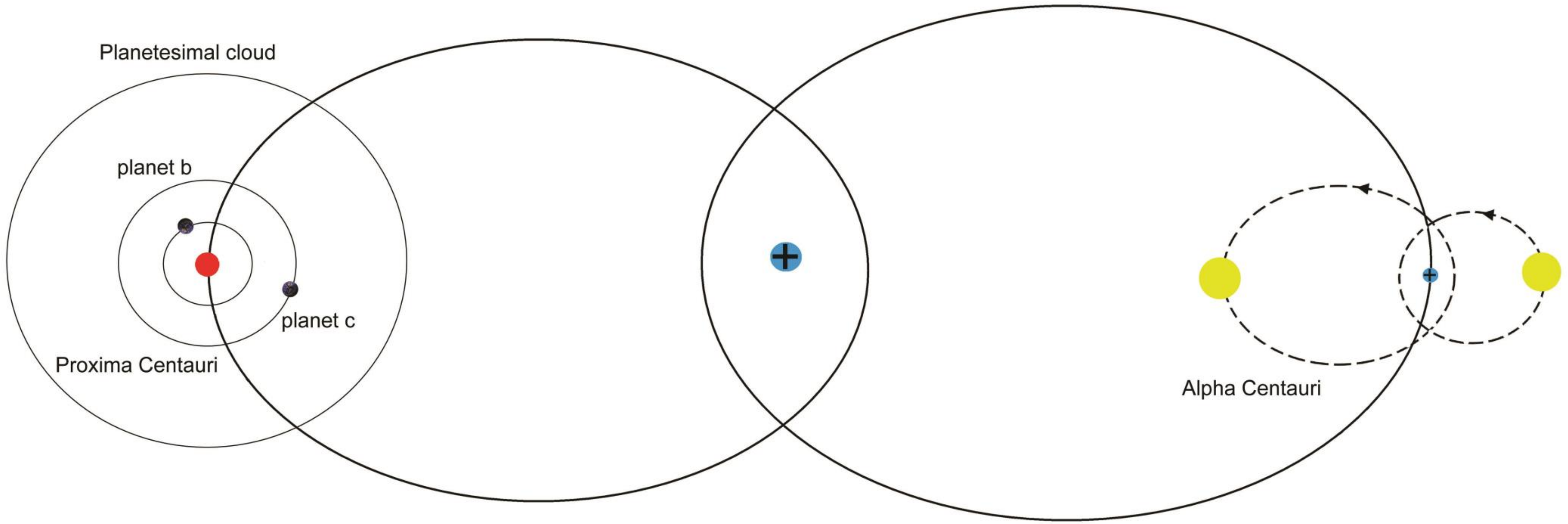
- 11,2 days period
- Mass ~1,3 $M_\oplus$
- Semi-major Axis ~0,05 AU
- Eccentricity $\varepsilon < 0{,}35$
- Habitable zone
- Equilibrium Temperature → possibility of water in liquid state

$$a_{HZ} \approx \sqrt{\frac{L_*}{L_\odot}} AU = \sqrt{0{,}00155} AU = 0{,}0394 \text{ AU0}$$

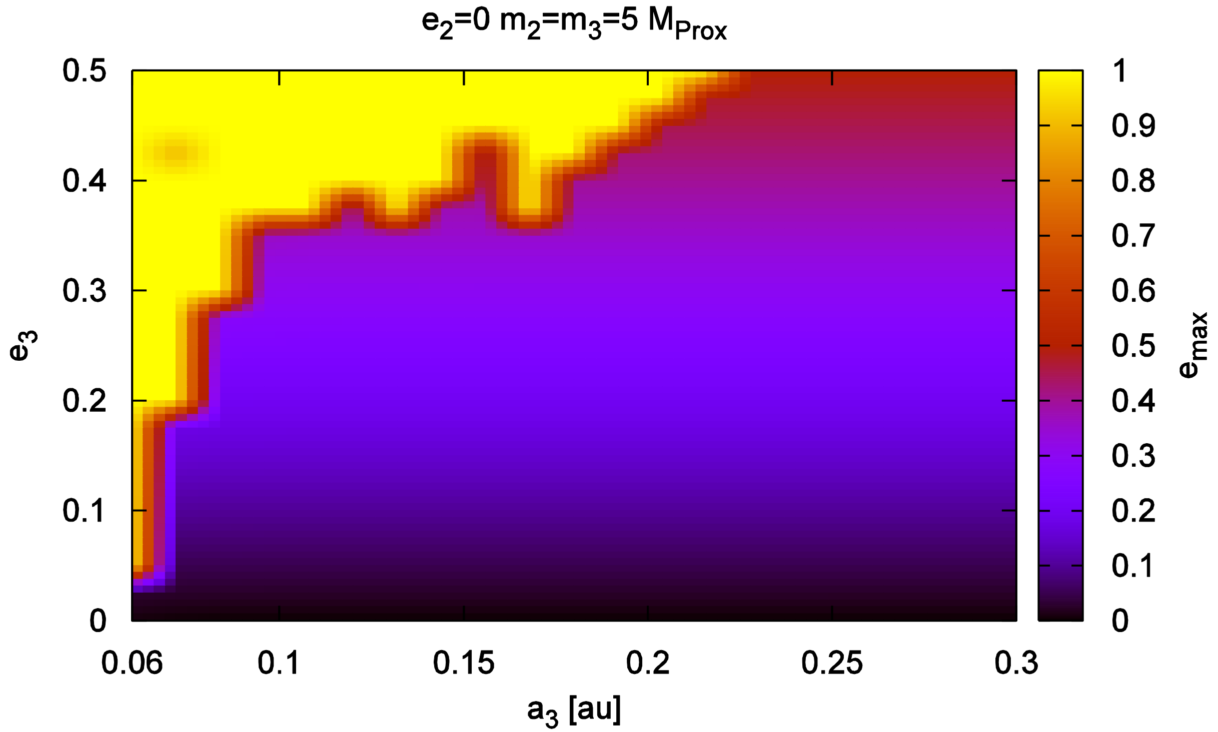
PLANET: Proxima B

PROPERTY	VALUE
Planet Type	M-Warm Terran [1]
Mass	$\geq 1.27 \pm 0.18\ M_\oplus$
Radius	~ 1.1 $R_\oplus$ [2]
Period	11.186 ± 0.002 days
Semi-Major Axis	0.0485 ± 0.0046 AU
Stellar Flux	0.70 $S_\oplus$ [3]
Equilibrium Temp.	227 K [4]

The Alpha Centauri Configuration



Stability of a 2nd Planet

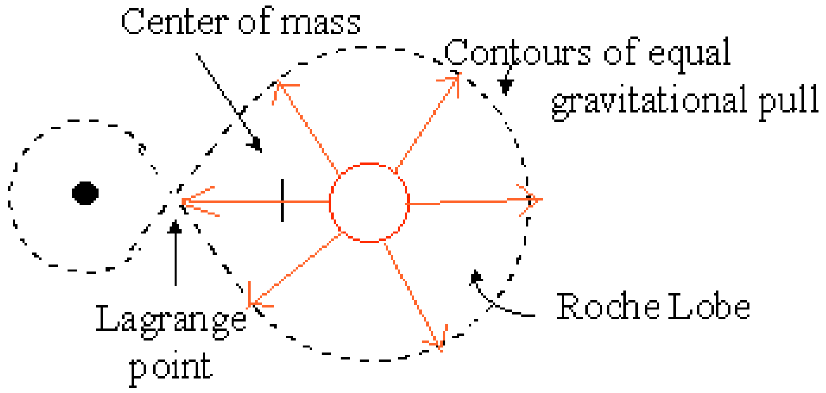


Wide binaries with separations of several 1000 au of the two stars have an independant evolution with very little impact from their companion so that they are considered like single-stars.

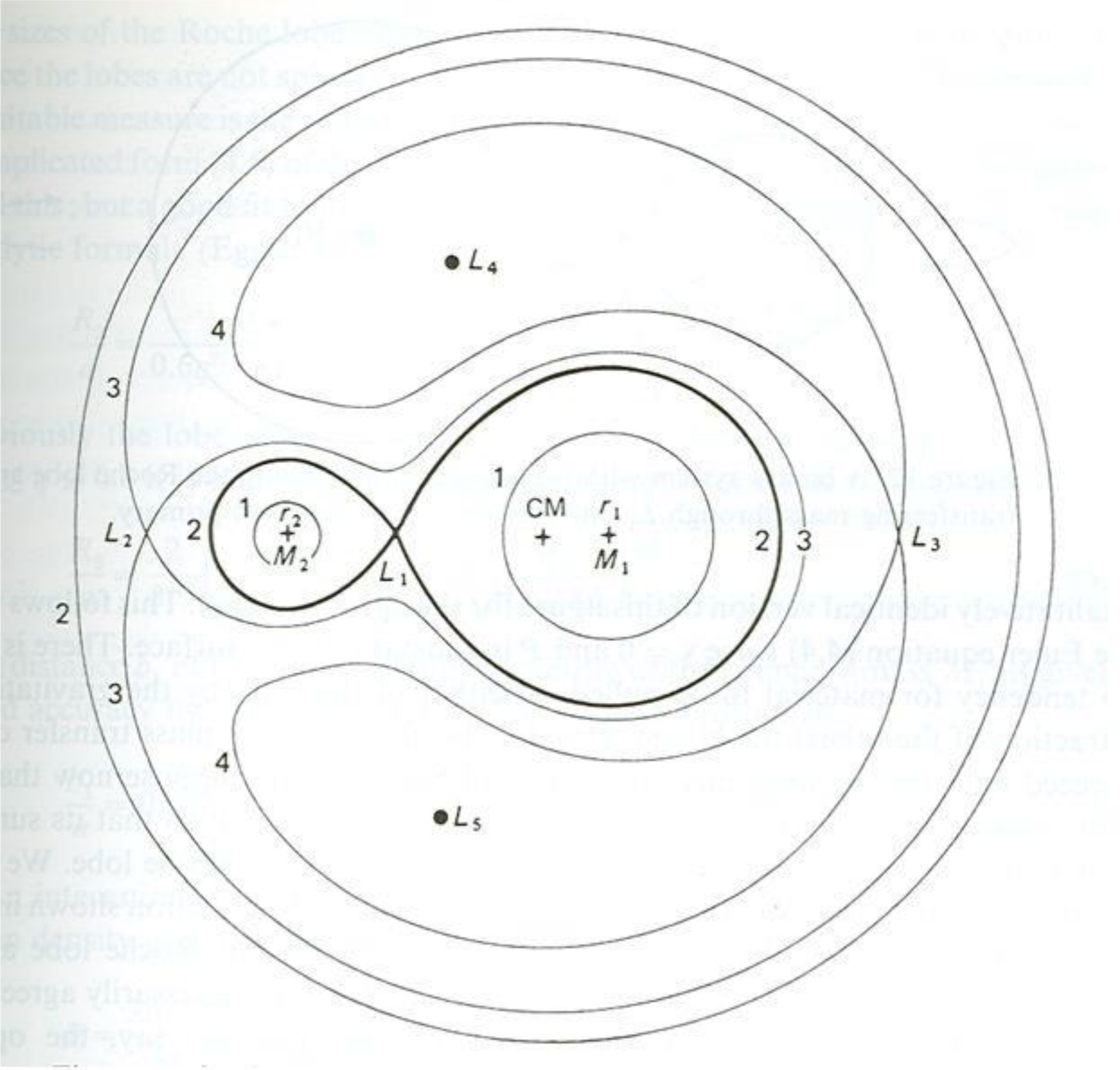
Close binaries are charactrized by a graviational influence of their compainion stars. Therefore, these systems are interesting for dynamical studies.

In case the distance is only a multiple of the stellar radii then the gravitational interaction could influence the stability of the bodies leading to a destruction of a body in the worst case.

In this context, the **Roche lobe** defines a critical area around each star where the Lagrangian equilibrium point L_1 serves as contact point of the two areas in a close binary system.



Roche equipotentials



Roche lobe radius

$$\frac{R_2}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1+q^{1/3})}$$

From fits to numerical calculations of lobes (Eggleton 1984)

For 0.1 < q < 0.8 is approximately

$$\frac{R_2}{a} = 0.462\left(\frac{M_2}{M_1 + M_2}\right)^{1/3}$$

Average density is then

$$\overline{\rho} = \frac{3M_2M_\Theta}{4\pi R_2^3} \cong 115P_{hr}^{-2} \text{ g cm}^{-3}$$

Hence, another classification can be introduced:
Detached binaries: where each star is inside its Roche lobe without gravitational interaction of the other stellar component so the two stars will evolve separately.

Semi-detached binaries: when one component fills the Roche lobe while the other does not. In that case, there can be a mass transfer (gas) from the Roche-lobe filling component to the otherstar which is important for the evolution of the binary system.

Contact binaries: when both stars fill their Roche lobes so that a common envelope can be formed which surrounds both stars. Depending on the mass and the type of the two objects such a binary could lead to a merging of both bodies.

The idea that stars are born in multiple systems was formulated first by Larson in 1972. Observations of the mixture of single, binary and multiple stars at different ages and in different environments result most probably from the dynamical evolution as part of the early stellar evolution.

Binary stars are the most common multiple star systems where two stars are orbiting a common center of mass. The brighter star is usually classified as primary star S_A and the dimmer component is the secondary star S_B.

Nowadays, observations suggest that a **considerable fraction of stars** in the solar neighbourhood are members of **binary and multiple star systems**.

Duquennoy & Mayor (1991) and Raghavan et al. (2010) established that in the solar neighbourhood ($d < 25$ parsec) about **40–45 % of all sun-like stars (spectral types F6-K3)** are members of binary and multiple star systems, independent of whether or not they are hosting planets.

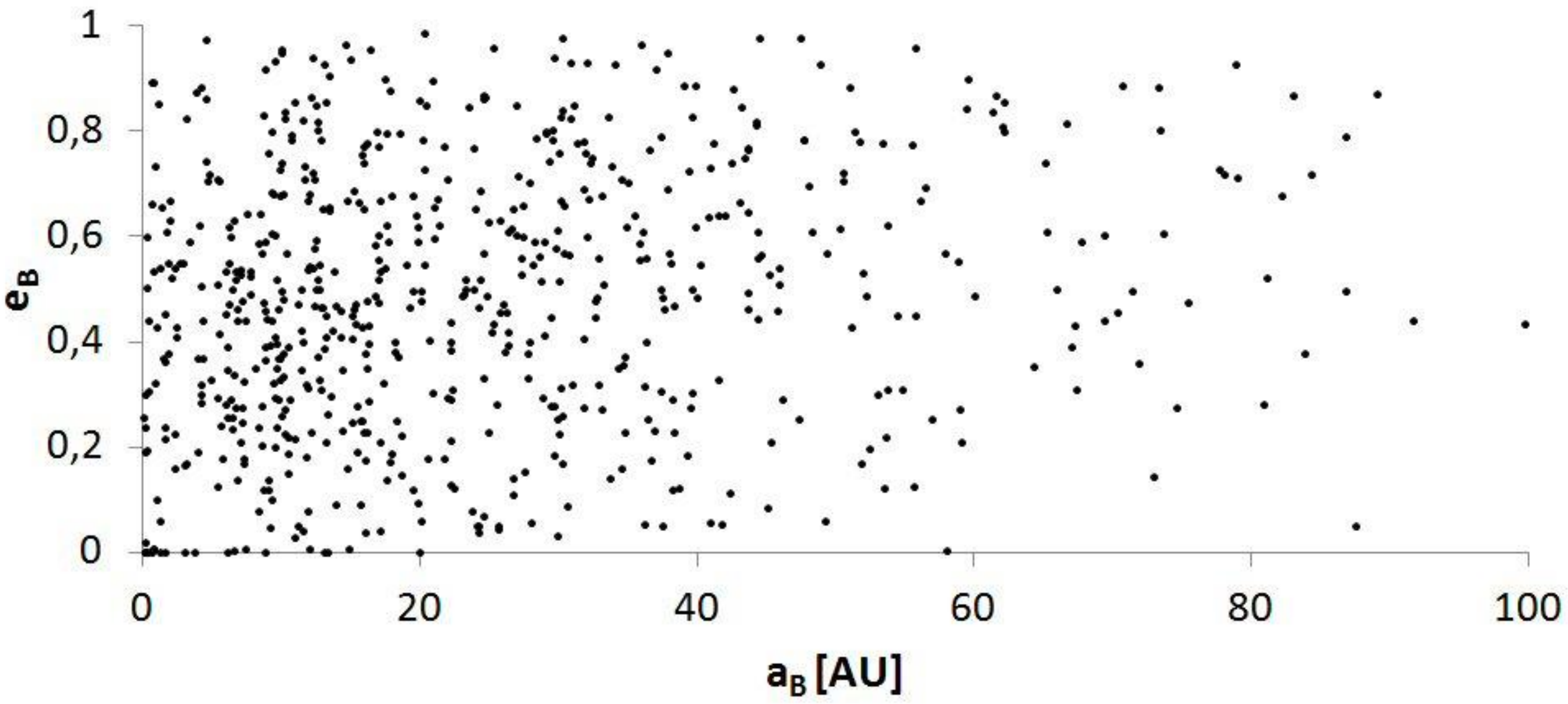
Tokovinin (2014) deduced a fraction of **33 % of binary stars** from a sample of about 4800 F-/G-type main-sequence stars within 67 parsec of the Sun.

For a more detailed report on this topic see the **review of Duchêne & Kraus (2013)**.

Recently, Schwarz *et al.* (2016) summarized the observations of about 20 catalogues of published binary star systems where each catalogue provides information on either a few dozen or up to some thousands of systems.

The major catalogue is certainly the *Washington Double Star Catalogue*[1] (WDS) which is a collection of more than 130,000 binaries. The key parameters for dynamical studies of planetary motion in binary star systems are the separation of the two stars, i.e. the binary's semi-major axis (a_B), and the eccentricity (e_B) of their orbits.

[1] http://ad.usno.navy.mil/wds/



the distribution of a_B and e_B for about 660 binary star systems published in the WDS. The fact that a_B and e_B are known only for a small fraction of observed binary star systems indicates the difficulty for dynamical studies due to the lack of observational information.

This Figure shows clearly that eccentricity is uncorrelated with a_B. The lower density for larger a_B reflects the lack of information (or observations) of wide binary systems

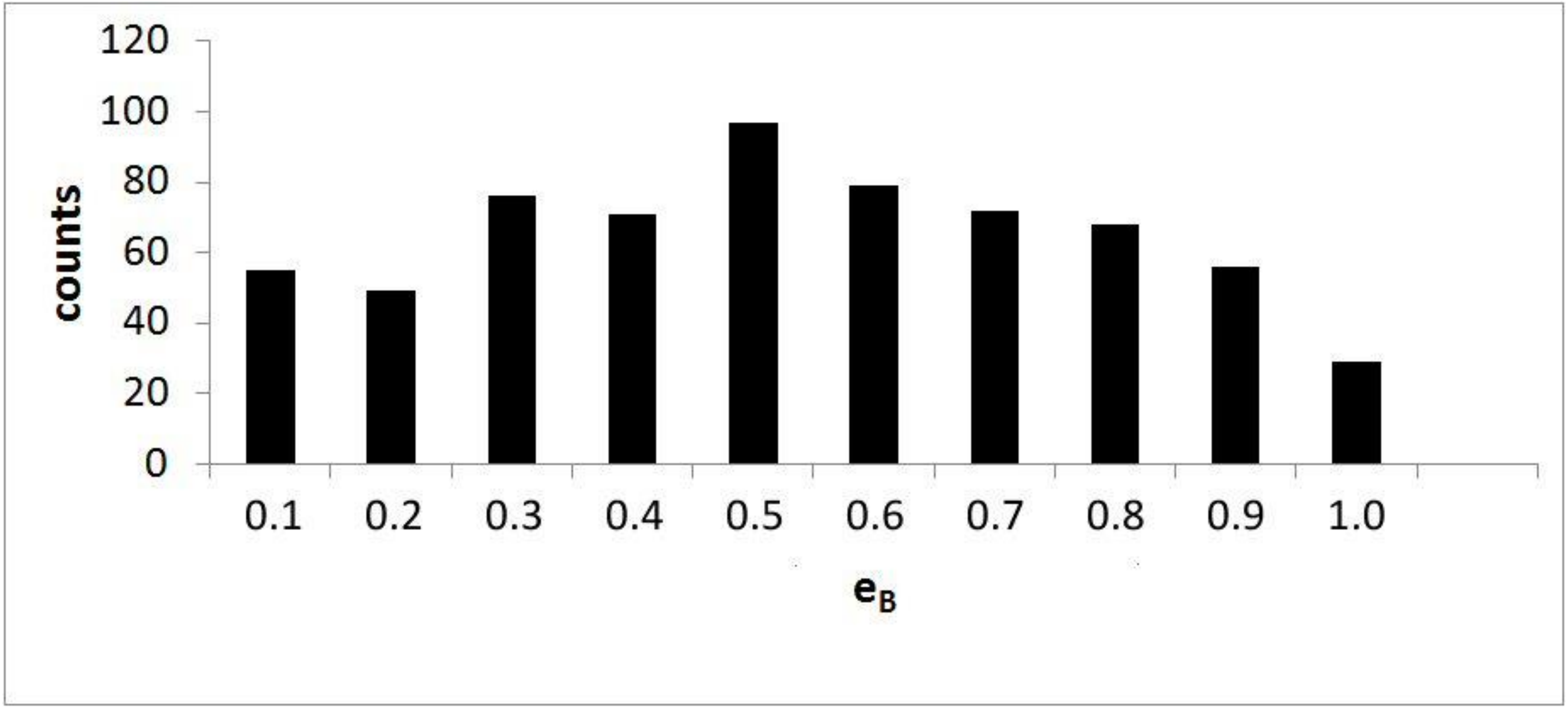


Figure 1.1, we show the distribution of the eccentricity of the 660 binary stars. The plot indicates a slight peak at $e_B = 0.5$. It should be noted that the information of a_B and e_B cannot be provided without large errors from the observations. This restricts also the accuracy of dynamical studies.

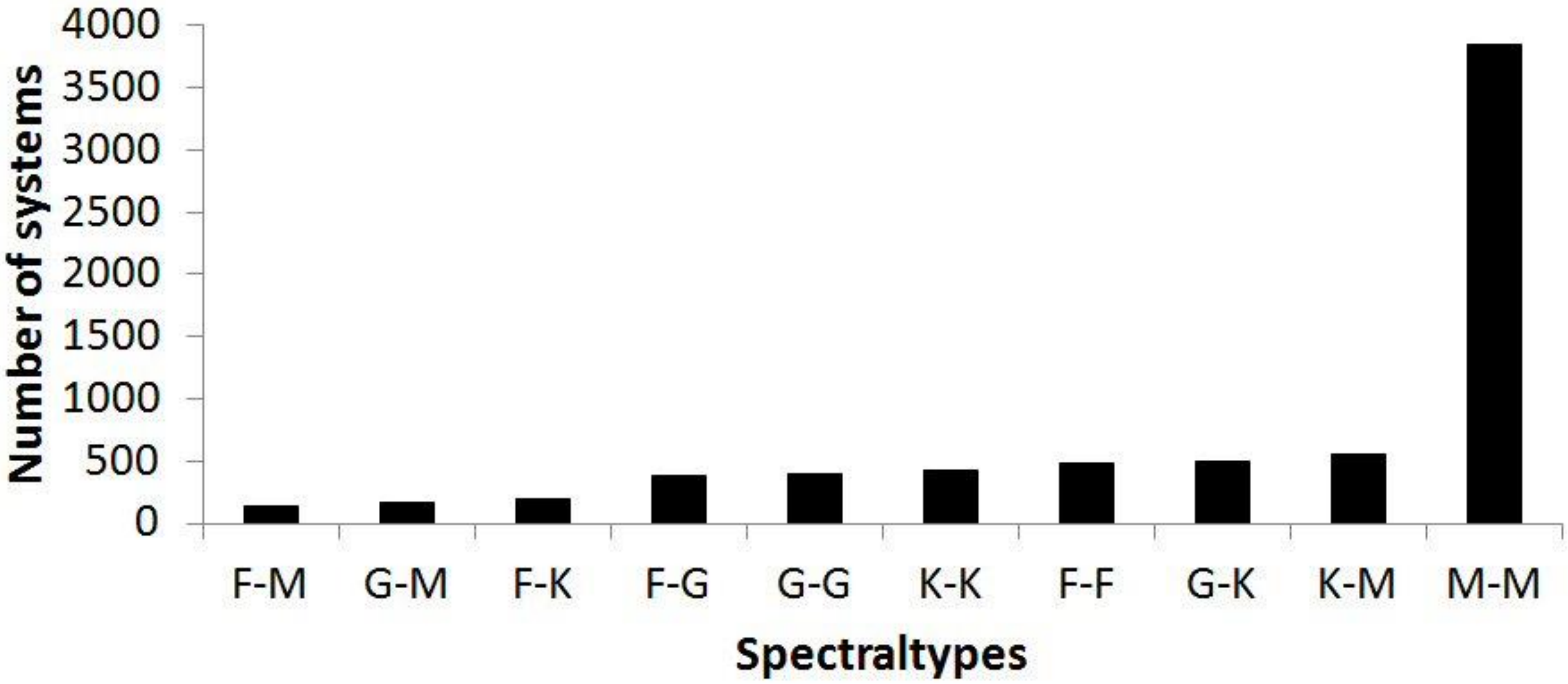
In astrophysics, binary stars are very useful because they provide the best method to determine the mass of a distant star since they orbit around their common center of mass. Since a large fraction of stars in the solar neighbourhood form binary or multiple star systems, they are important for our understanding of processes by which stars form.

Exoplanets

The detection of extra-solar planets in binary and multi-stellar systems showed that planetary companions are not restricted to single-stars. However, we cannot conclude whether these environments are more hostile for the presence of planets or not (see e.g. Boss, 2006; Bromley and Kenyon, 2015; Jang-Condell, 2015). A study by Armstrong *et al.* (2014) using the *Kepler* data suggests an occurrence rate of coplanar circumbinary planets similar to that for single stars.

Habitability:

host-stars of spectral types F, G, K and M as the life-times of these stars on the main sequence is sufficiently long to permit the evolution of life (as known on Earth) on a terrestrial-like planet in the habitable zone (see Kasting *et al.*, 1993a).



Number of systems
4000
3500
3000
2500
2000
1500
1000
500
0
F-M
G-M
F-K
F-G
G-G
K-K
F-F
G-K
K-M
M-M
Spectraltypes

Binary Catalogue

77 Exoplanetary systems in binary stars
18 systems in multiple star systems

STAR-DATA

HOME	Planet-Data	DOWNLOAD	csv	dat (txt)

SYSTEM	discovery	Spectral Type	Distance [parsec]	m_binary [m2/(m1+m2)]	a_binary [AU]	e_sec	number of planets	planets motion S-type, P-type	Exoplanet catalogue	comments	m1 [m_sun]	m2 [m_sun]
Fomalhaut / TW PsA	2014	A3V / K4V	7.7	0.275	57400		1	S	Fomalhaut b		1.92	0.73
HD38529 AbcB	2000-2002	G4VI / M3.0V	40.00	0.169	12042		2	S	HD 38529	Debris disk (>86 AU)	1.48	0.3
HD20782b / HD20781	2006	G2V / K0V	36.02	0.457	9080	0.24	1	S	HD 20782		1.00	0.84
HD125612 Ab-dB	2007-2009	G3V / M4	52.82	0.143	4759	0.00	3	S	HD 125612		1.1	0.184
HD222582 AB	1999	G5 / M3?	42.00	0.233	4746		1	S	HD 222582	secondary (red dwarf)	0.99	0.3
XO-2 b	2007	K0 V / K0 V	150.00	0.500	4600		1	S	XO-2		0.98	0.98
HD147513 AbB	2003	G3-G5V / DA2 VII	12.90	0.414	4451		1	S	HD 147513	HD147513 B w. dwarf	0.92	0.65
HD 213240 AbC	2001	G4 IV / M	40.75	0.107	3898		1	S	HD 213240	ref.(HD 213240 C)	1.22	0.146
Gl 777 AbcB	2003-2005	G6IV / M4.5V	15.89	0.161	2846		2	S	HD 190360	secondary (red dwarf)	1.04	0.2
HD89744 AbcB	2000/2013	F7V / L0V	40.00	0.054	2456		2	S	HD 89744	2nd. (heavy brown dwarf)	1.4	0.08
91 Aqr (HD 219449, GJ 893.2)	2003	K0III / ?	45.50	--	2248		1	S	91 Aqr		2.5	
HD101930 AaB	2005	K1V / M0-1	30.49	0.474	2200		1	S	HD 101930		0.74	0.666
ADS16402 BbA	2006	G0V / G0V	139.00	--	1550		1	S	HAT-P-1		1.12	1.16
HD80606b / HD80607	2003	G5V / G5V	58.40	0.500	1200	0.5	1	S	HD 80606	e_planet >>,because of second star	0.98	0.98
55 Cnc Ab-fB	1996-2007	G8V / M3.5-4V	13.02	0.120	1050		5	S	55 Cnc		0.95	0.13
HD11964 AbcB (GJ 81.1 A)	2005	G5 / K4	33.98	--	1010		2	S	HD 11964		1.125	
HD142022 AbB	2005	K0V / ?	35.87	--	794		1	S	HD 142022 A		0.99	
Ups And Ab-eB	1996-2010	F8V / M4.5V	13.47	--	702		4	S	ups And A		1.27	
HD188015 AbB	2004	G5IV / ?	52.60	--	684		1	S	HD 188015 b		1.09	
HD75289 AbB (HR3497)	1999	G0V / ?	28.94	0.118	620		2	S	HD 75289	HR3497 AB (r. dwarf)	1.05	0.14

Binary Catalogue of Exoplanets
http://www.univie.ac.at/adg/schwarz/multiple.html

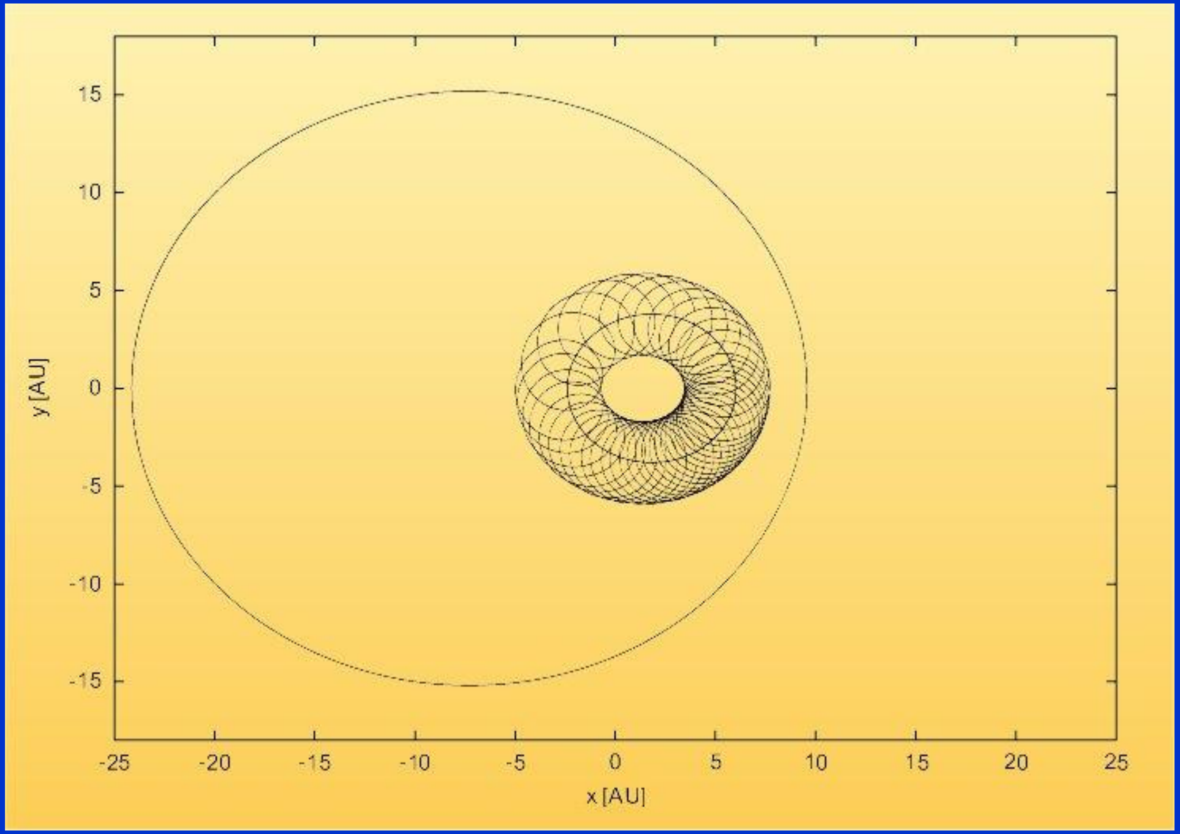
Gamma Cephei

Primary and Secondary:

$m_1 = 1.6\ M_S$
$m_2 = 0.4\ M_S$
a = 21.36 AU
e = 0.44

Planet:

$m_P = 1.7\ M_{jup}$
a = 2.15 AU
e = 0.2



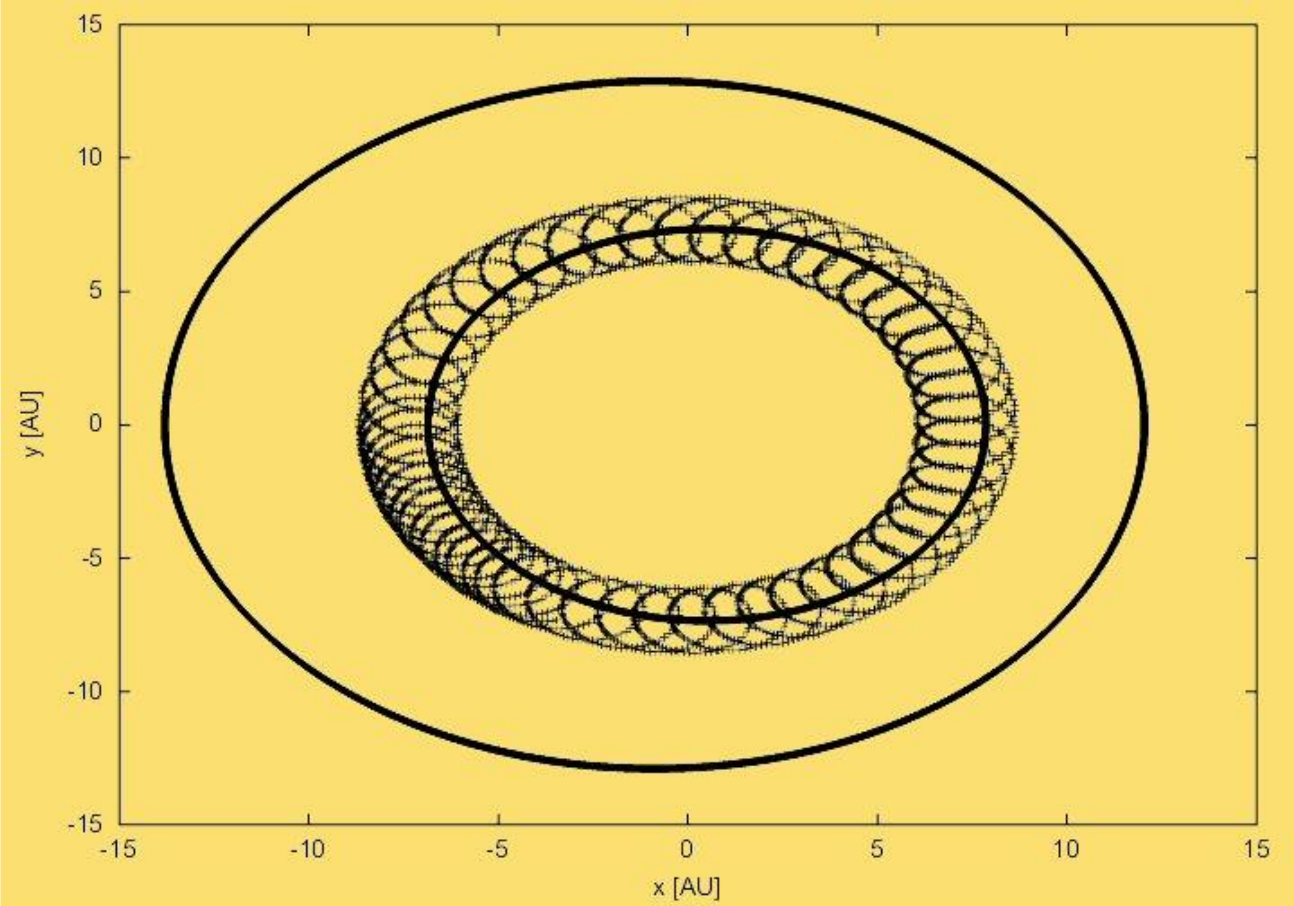
HD 41004 A

- *The orbital parameters were taken from the Geneva planetary search group*
- *Masses are Minimum Masses*

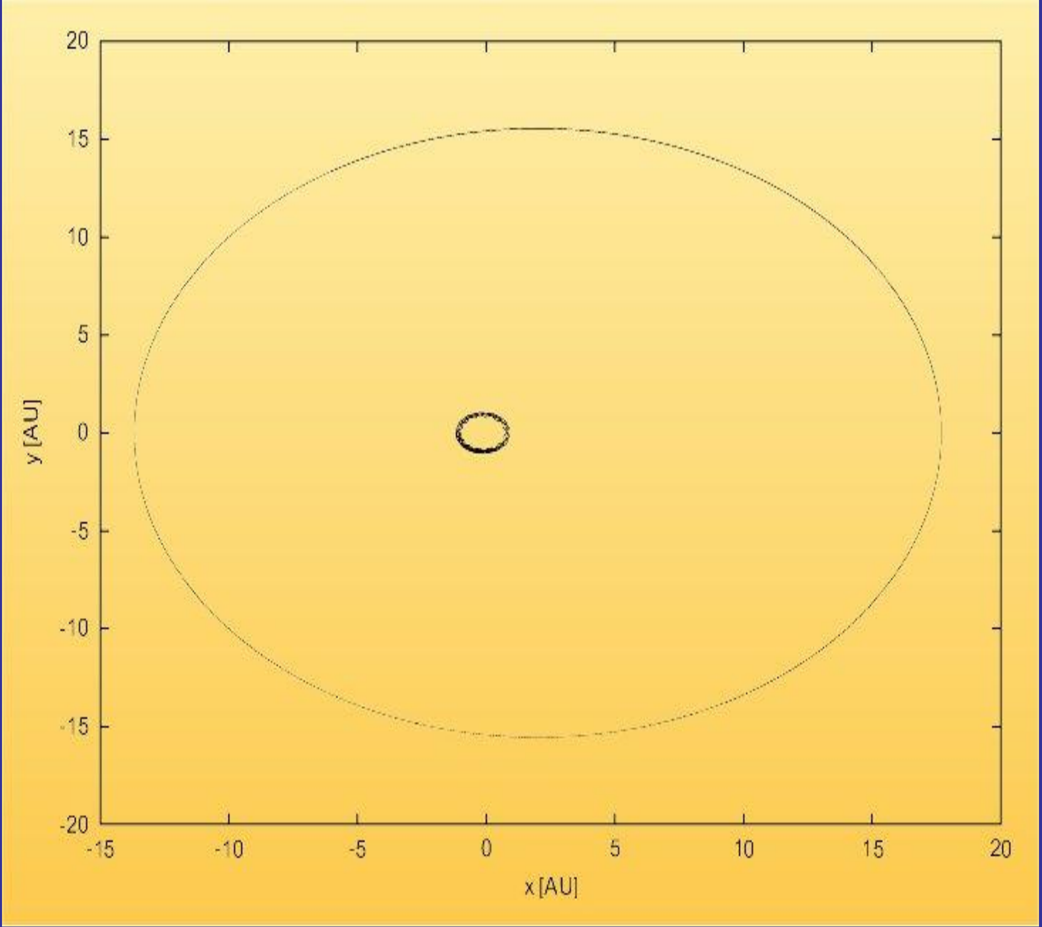
$M_{star1} = 0.7\ M_{Sun}$

Planet
$m \sin i = 2.3\ M_{jup}$
$a = 1.31$ AU
$e = 0.39 \pm 0.17$
$\omega \approx 114^{o}$

Star 2
$m = 0.4\ M_{Sun}$
$a = 21$ AU
$e = 0.1$



Gliese 86



Primary and Secondary:

$m_1 = 0.79\ M_S$

$m_2 = 0.0477$ MSun → 0.5 MSun

a = 18.75 AU → 20 AU

e = ?

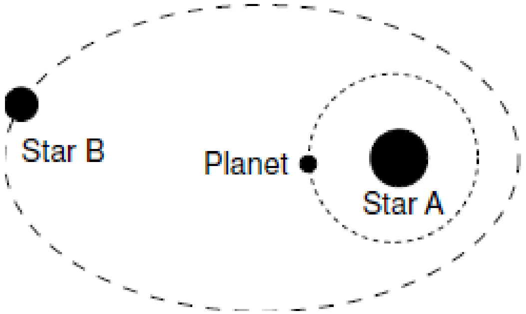
Planet:

$m_P = 4$ Mjup

a = 0.11 AU

e = 0.046

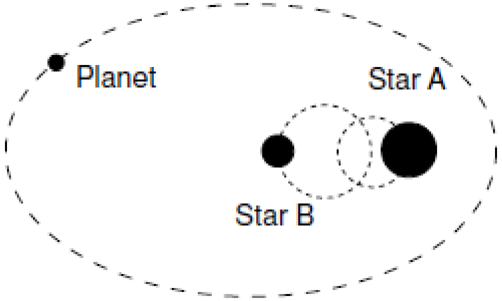
Different Types of Planetary motion

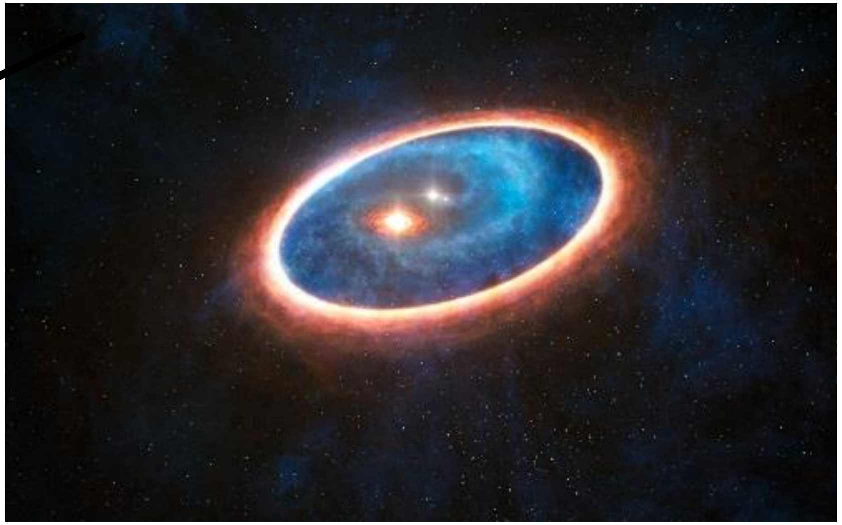


CircumStellar

S-type

CircumBinary





P-type

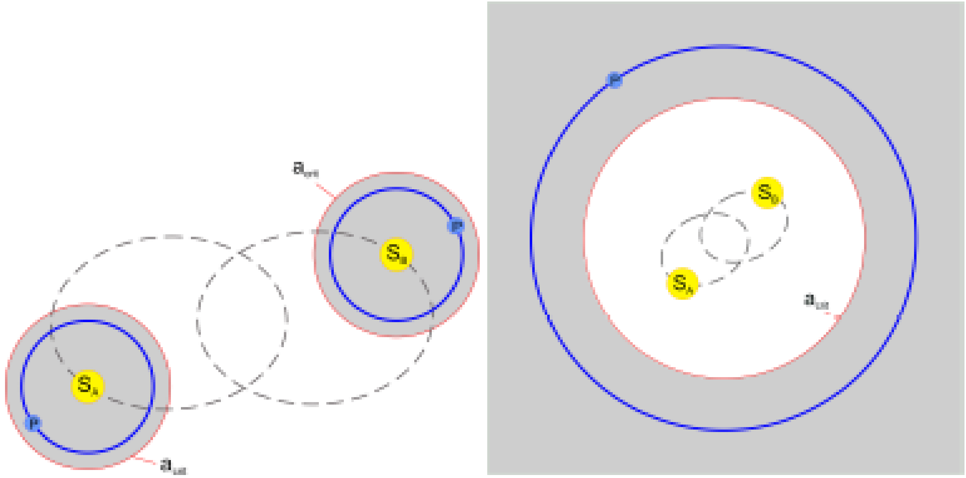


Figure 2.2 Different types of planetary motion in binary star systems. *Left*: S-type; *Right*: P-type

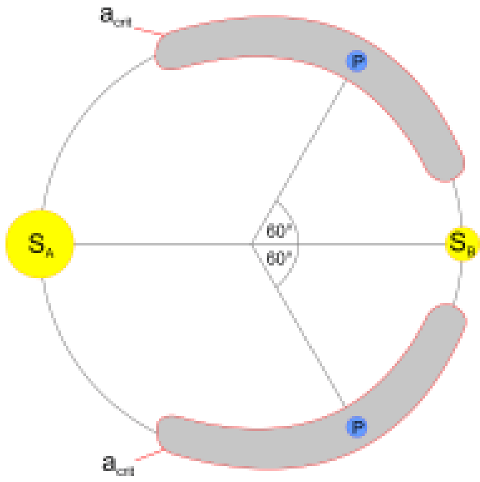
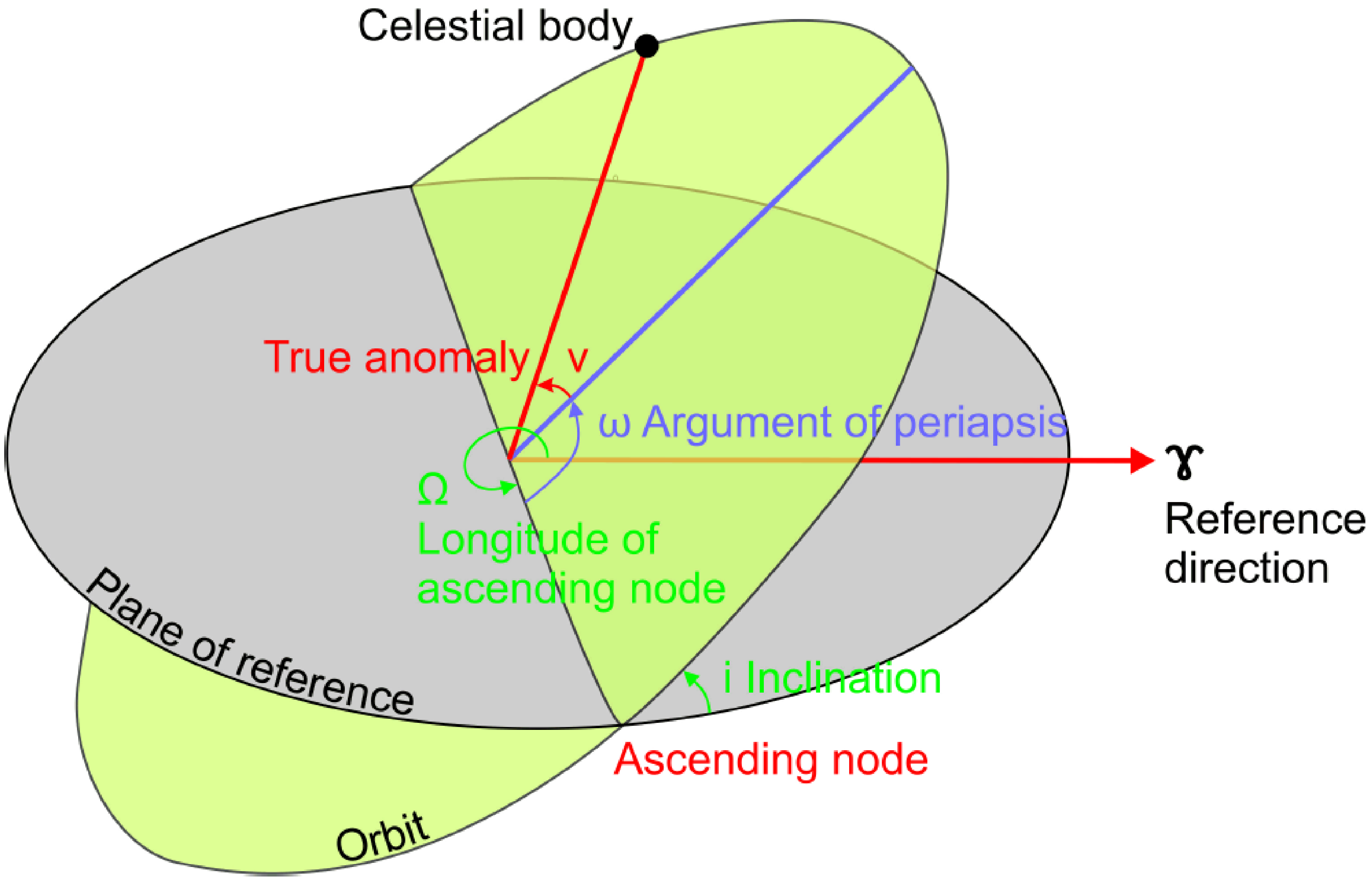


Figure 2.3 T-type planetary motion in binary star systems

Orbital Elements

In dynamical astronomy, planetary orbits are usually described by a set of six orbital elements. The size and the shape of the orbit are defined by the semi-major axis a and the eccentricity e. The orientation in space is determined by three angles: the inclination i, the argument of perihelion ω, and the longitude of the ascending node Ω. The mean anomaly M defines the position of the celestial body in the orbit.

Orbital Elements



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