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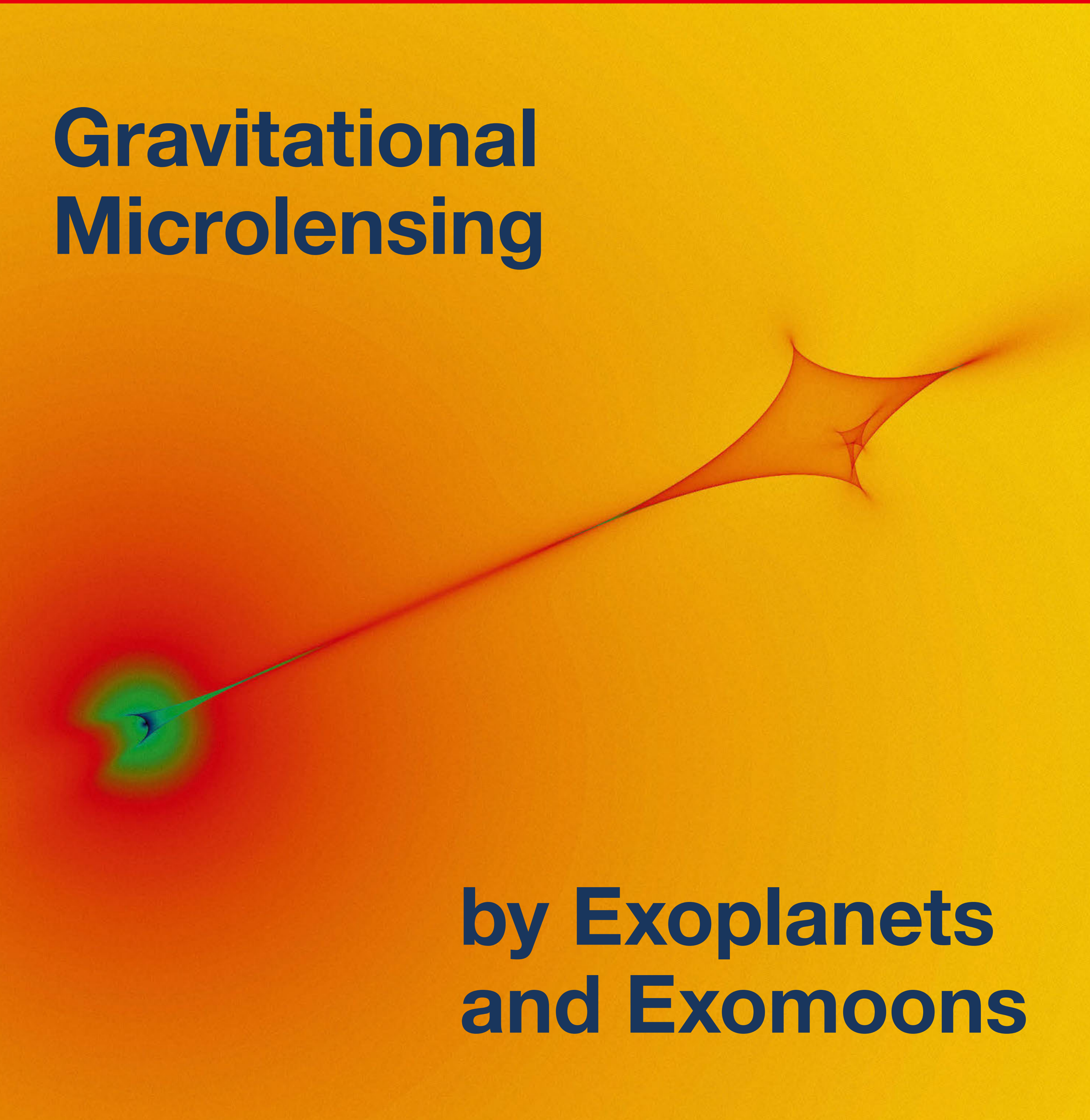
Gravitational Microlensing by Exoplanets and Exomoons



Editorial

Since Copernicus (1473–1543) was not able to measure brightness variations of the stars due to Earth's revolutionary motion around the Sun, he inferred that stars must be very far away from Earth. During the 16th and 17th Centuries scholars began gradually to realise that the Universe, i.e., the sphere of fixed stars enclosing our Solar System, might not be finite but infinite. Philosophical arguments by Thomas Digges (1546–1595) or Giordano Bruno (1548–1600) supported this view. Galileo (1564–1642) provided evidence from observations of the Milky Way using his telescope.
In his *Cosmotheoros* posthumously published in 1698, Christiaan Huygens (1629–1695) estimated the distances to the fixed stars by comparing the apparent magnitudes of the Sun and Sirius. He found Sirius to be 27 664 times farther away from Earth than the Sun. Already in 1690, he speculated about the existence of planets orbiting other stars than the Sun carrying extra-terrestrial life. He thus may be considered the "inventor" of extrasolar planets.
During the 17th and 18th centuries, the value of the solar parallax was measured using Mars oppositions and transits of Venus with increasing accuracy. At least since that time it was realised that our solar system and the cosmos must be huge. As a reaction to this "horror vacui" every celestial body was thought to be inhabited, even the Sun and the stars. The "plurality of the worlds" became an established world picture prevailing until the 20th century.
Space probes sent out to almost all solar system bodies demolished this world view abruptly. They seemed not to be inhabited as previously assumed, and life appeared not to be a matter of course. Astrophysics and interdisciplinary science recognised the very special conditions required to create life. Moreover, these conditions need to be very selective and restricting, depending not only on physical and chemical parameters but particularly on stable and stabilising habitable environments in space and on ground.
Today, the existence of extra-terrestrial life seems to be quite likely for statistical reasons. However, it is very hard to find evidence from bio-markers identified in exoplanetary spectra as long as it is not clear what life actually is. Furthermore, our Solar System and particularly our Earth-Moon System have a special history resulting from a series of very unlikely events that happened successively in an assortative and even choreographic way. Thereby it is supposed that the Moon is ascribed a critical role for the origin and evolution of life on Earth.
The topic of this issue is based on the talk "Exoplanets: In Search of Terra-2" by Prof. Dr. Joachim Wambsganss held on October 31, 2018, in the Pro ISSI seminar series. He pointed out that gravitational microlensing takes the potential not only to detect Earth-like exoplanets, but even Moon-like exomoons. He referred to results published by Liebig and Wambsganss (2010), from where material was used for this issue.

Andreas Verdun
Zimmerwald, December 2019

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Title Caption
Simulation of the caustic structure (magnification pattern) resulting from the configuration consisting of a host star (left), exoplanet (right, larger structure), and exomoon, (right, smaller structure within the exoplanet's caustic structure).

Gravitational Microlensing by Extrasolar Planets and Moons

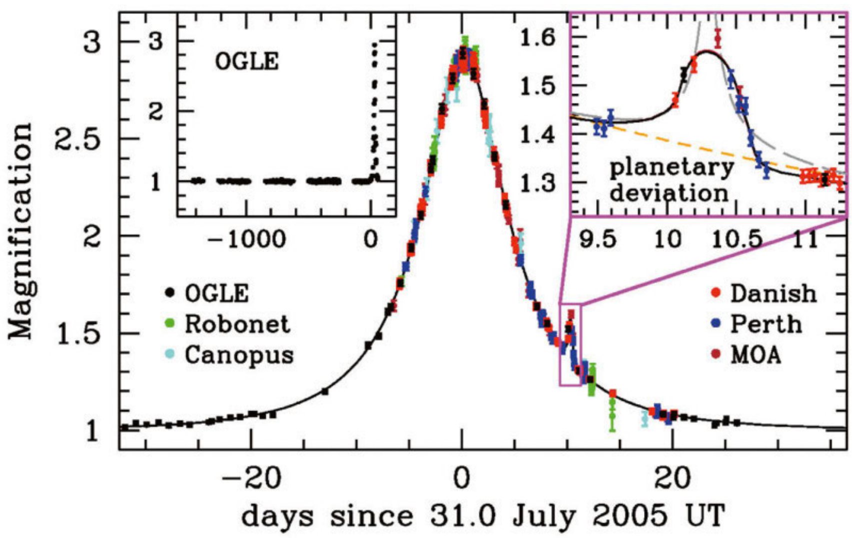
By Prof. Dr. Joachim Wambsganss, Astronomisches Rechen-Institut (ARI), Zentrum für Astronomie der Universität Heidelberg (ZAH) and International Space Science Institute (ISSI), Bern

Light Curve Anomalies

The first time an extrasolar planet (or exoplanet) was discovered with the method of gravitational microlensing was in 2004. In 2006, a cool planet of 5.5 Earth masses was discovered with this method (**Figure 1**, Beaulieu et al. 2006). Microlensing is a very sensitive technique for detecting exoplanets with (projected) distances between roughly 0.5 and 10 AU from their host stars and with masses between roughly Earth mass and 10 Jupiter masses. Very frequent photometric measurements with observation rates of about one frame per 15 minutes and visual photometric precision of about 20 mmag (millimagnitudes)[1] may in the future even allow to detect microlensing events caused by extrasolar moons (or exomoons). This means that not only the light curve of a microlensing host star and the deviation of this light curve caused by an exoplanet have to be considered, but also anomalies superimposed on the exoplanet's signal caused by its moon (or moons) have to be analysed. Simulations of convolved caustics and magnification patterns resulting from microlensing effects by exoplanets and exomoons suggest that massive extrasolar moons can in principle be detected. The detection of exomoons orbiting exoplanets of Earth-like masses in habitable zones would considerably enhance the probability for the discovery of extra-terrestrial life. The role and importance of our Moon for the origin of life on Earth was analysed by Benn (2001). He points out five possible criteria that may trigger and influence the evolution of life: (1) stabilisation of the planet's rotational axis, (2) elimination of primordial atmosphere, (3) generation of the planet's magnetic field, (4) generation of large tides, and (5) generation of longer-period tides. These aspects certainly support the conditions of life, so exomoons may play an essential role for the origin and evolution of life on their host exoplanets. This is why searching for microlensing effects through exomoons might be an important issue for the quest of extra-terrestrial life.

Figure 1 presents the observational data of the microlensing event OGLE-2005-BLG-390 – the discovery of a cool 5.5 Earth mass exoplanet (Beaulieu et al. 2006). The signal of the exoplanet is superimposed on the light curve produced by the host star, a small-amplitude blip at day 10; it is zoomed out in the extra diagram on the top right side of the diagram. This light curve illustrates the difficulty of the detection of exomoons. In order to be able to detect the much less significant microlensing effects caused by an exomoon, tiny deviations in the structure of the light curve need to be identified, which is only possible if the resolution in time and photometric magnitude is much higher than in this example (which was state of the art at the time).

Figure 1: The light curve of the OGLE-2005-BLG-390 microlensing event (differently coloured data points from different observatories) and best-fit model plotted as a function of time. (Credit: Beaulieu et al. 2006)



[1] The (visual) brightness of a star is measured in "magnitudes". By definition, 0 mag is the brightness of the star Vega (α Lyrae).

Classical Methods to Detect Extrasolar Planets

Let us briefly summarise the advantages and limits of the five classical methods to detect exoplanets, in particular with respect to the possibility of the detection of exomoons.

Direct Imaging

By about 2025 (hopefully) three new ground-based optical telescopes will become operational: The Giant Magellan Telescope (GMT), the Thirty Meter Telescope (TMT), and the European Extremely Large Telescope (ELT). Equipped with newest generation of advanced and dedicated technology in active and adaptive optics, it is expected that these telescopes will provide images in the optical and near infrared wavelength region with an angular resolution of more than ten times the resolution of the Hubble Space Telescope (HST). Although these instruments are designed to provide almost diffraction-limited images which allow for direct imaging of (some) exoplanets, their angular resolution will not be sufficient to separate exoplanet from exomoon images due to the close distance of such moons from their host planets and due to the immense contrast in brightness or magnitude between exoplanet and its host star. In addition, such telescopes are not intended to be scheduled for survey or monitoring observation campaigns.

Astrometry

The gravitational pulls of exoplanets acting upon their host star force the star to move on a Keplerian orbit around the barycentre of the exosystem. If only one exoplanet is present, the star's motion is quite regular and can be measured (at least with the Gaia satellite) if the exoplanet's mass is of the order of the mass of Jupiter. However, if more than two exoplanets are orbiting their host star, this motion can become quite complicated. Since the gravitational effect of an exomoon upon the host star is vanishingly small, there is no chance for this astrometric method to detect exomoons at all. The ratio between the masses of host star and exomoon is so large that the angular resolution needed to detect a variation in the host star's position would not be sufficient in any case. The strongest astrometric effects of exoplanets are expected for large distances from their host stars (which – on the other hand – means very long orbital periods).

Spectroscopy

The same argument concerning the effects of the gravitational force of an exomoon on the motion of a host star due the exomoon's motion around a (detectable) exoplanet applies to the spectroscopic method. Here (projected) radial velocities are extracted from Doppler shifted spectral lines of the order of a metre per second (or smaller). To be successful, the host star must be bright enough in order to produce a high enough flux for an extremely high resolution spectrum containing a sufficient number of spectral lines, so that the Doppler shifts can be analysed properly. Although this method was and still is very successfully used for the detection of exoplanets, it seems unimaginable that it will be able to detect exomoons: The effect of the barycentre motion of exoplanet plus exomoon cannot be disentangled into those two components. Radial velocity measurements are most sensitive for exoplanets with very small semi-major axes to their host stars because then their gravitational pull is strongest on the stars' velocity.

Transit

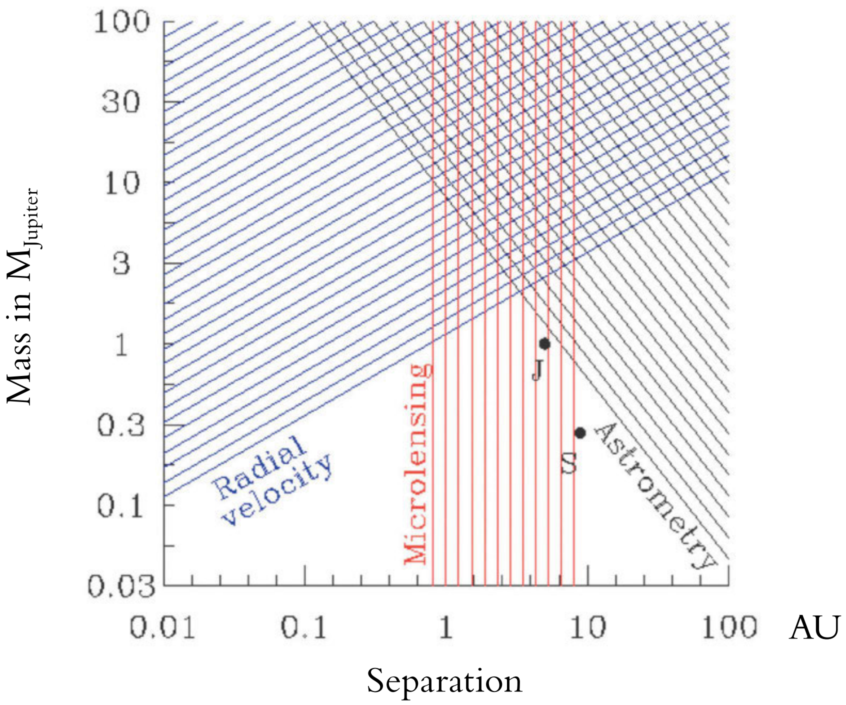
The transit method uses the simple geometric effect that – if we see the planetary system edge-on – the planet passes periodically in front of the host star and reduces its brightness slightly. That means transit observations are restricted to the rare cases where the line-of-sight coincides with the orbital plane of the exoplanet system, i.e., if the system is inclined by 90° w.r.t. the tangential plane to the celestial sphere. This means a serious limitation of the transit method in the sense that only about 1% or less of all planetary systems are detectable with this method. However, this can be corrected statistically. In addition to very frequent observations of the same field in the sky, highly accurate photometric measurements are required in order to detect small planets: the dip in the light curve is proportional to the square of the ratio of planet radius to stellar radius. The transit method, however, can potentially detect exomoons in two ways: the straightforward way is that occasionally a moon would be leading or tracing a planet transit and cause its one (very tiny) transit before or after the planet transit. Another way for (massive) exomoons to show up in the transit light curves is by modulating the exact periodicity of the transit: only the barycentre of the exoplanet-plus-exomoon system would pass regularly in front of the star, so a massive exomoon would affect the exact periodicity of the exoplanet transits and cause so-called transit timing variations (TTV). However, it will be certainly very challenging to detect exomoons with the transit method, even with satellites like CHEOPS, because many other phenomena could cause similar effects in the light curve, e.g., anomalies from other small exoplanets.

Gravitational (Micro-) Lensing

Gravitational microlensing is a method which also employs photometric measurements. It searches for the very rare occasion that a foreground star passes directly in front of a background star and focusses the light of the background star such that for a short time the background star brightens in a very characteristic way. The chance for this spatial coincidence to happen is very roughly one in a million. That means that a million stars have to be monitored regularly in order to detect one (stellar) microlensing event. And even if every star had a planet, this planet would be detected in only one out of one hundred stellar microlensing events. Exoplanets can be detected with microlensing when they are in a certain (projected) distance range to their host stars: If they are too close-in, the star-plus-planet system acts as a single-mass object with the combined mass. If the planet is very far away from its host star, the lensing system acts as two single lenses. Only if the planet is in a (projected) distance range between about 0.5 to 10 AU (cf. **Figure 2**), the star-plus-planet system acts as a binary lens system and the exoplanet might be detected. Interestingly, this distance range overlaps largely with the so-called habitable zone.

To first order, the lensing effect is independent of the mass of the exoplanet (cf. **Figure 2**), and it is also independent of the type of host star. In principle microlensing could also detect exoplanets around white dwarfs, neutron stars or black holes. And in particular for statistical analyses microlensing is well suited: Cassan et al. (2012) showed that on average every star has at least one planet.

Figure 2: Sensitivity of astrometry, spectroscopy, and microlensing for exoplanets (mass and separation).



Principles of Gravitational (Micro-)Lensing

According to Einstein's Theory of General Relativity, the mass distribution in the Universe tells space-time how to curve, and space-time tells the masses how to move. Curved space-time means, that light rays do not proceed along straight lines but follow so-called null-geodesics. Consequently, light rays **(Figure 3)** emitted by a source S and detected by an observer O are bent around a massive object L, which acts as a lens. The closer the light ray passes the lens, the more it is bent. With the observer situated in O, the source S is not visible, but rather two images, S_1 and S_2, at shifted positions. If the lens is a stellar mass object, the separation between the two images S_1 and S_2 is too small to be resolved with optical telescopes; however, the combined brightness of S_1 and S_2 is higher than the brightness of S because of the focussing effect. (This can be expressed differently: gravitational lensing changes the apparent solid angle of a source, it does not affect the surface brightness; the magnification is the ratio of the total solid angle of the images and the apparent solid angle of the unlensed source.) Since the three involved objects – observer O, lens L and source S – move relative to each other, this magnification is variable with time in a perfectly predetermined way (only depending on the impact parameter) so that microlensing events can be detected photometrically. The geometric relation between the positions of the lens, the source and the images is called "lens equation" (cf. **Figure 4**), it depends only on the mass of the lens, the distances observer-lens D_L, observer-source D_S and lens-source D_{LS} and the impact parameter ξ. The lens equation is thus a mapping from the lens plane to the source plane, it maps the images of a source star to its actual position in the source plane. Here we focus on the triple lens case with host star, exoplanet and exomoon. The triple-lens equation is a tenth-order polynomial equation in ξ.

One approach to solve the lens equation numerically, in particular if the number of lenses is higher than two, is to generate a magnification map in the source plane. This is a two-dimensional map of magnification as function of position. A one-dimensional cut through such a magnification pattern is a light curve of the source due to its motion relative to the lens. The method to produce a magnification pattern is known as inverse or backwards ray shooting: one "shoots" light rays from the observer to the lens plane and calculates the angle of deflection due to the individual objects acting as microlenses. Then these deflected light rays are followed until they hit the source plane. The rays are "collected" in the source plane in small squares. These "pixels" contain various numbers of rays (or photons); the number of rays per pixel is directly proportional to the magnification of a source with the size and shape of such a square. This two-dimensional density distribution of light rays can be easily visualised and is called "magnification pattern".

Figure 3: The bending of light rays emitted by a source S passing through curved space-time produced by lens L. (Credit: Wambsganss 1998)

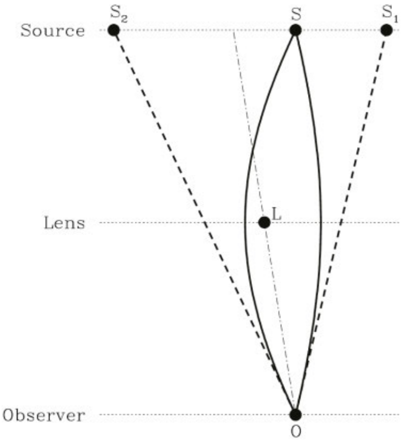
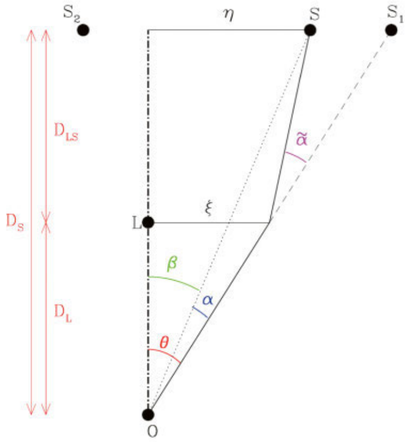


Figure 4: Parameters defining the lens equation in the case of gravitational (micro-)lensing. (Credit: Wambsganss 1998)



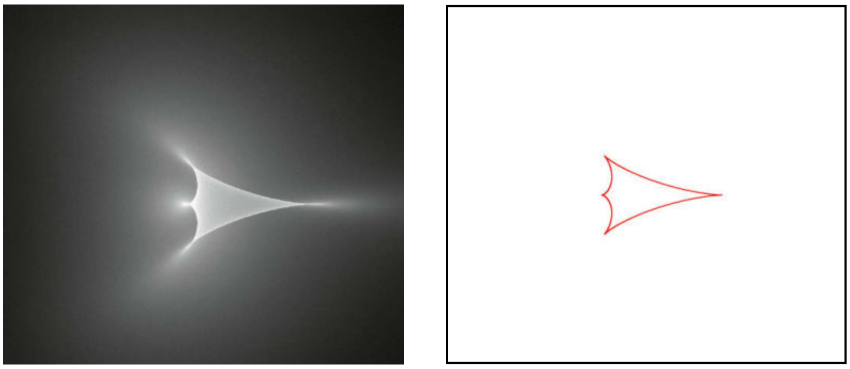


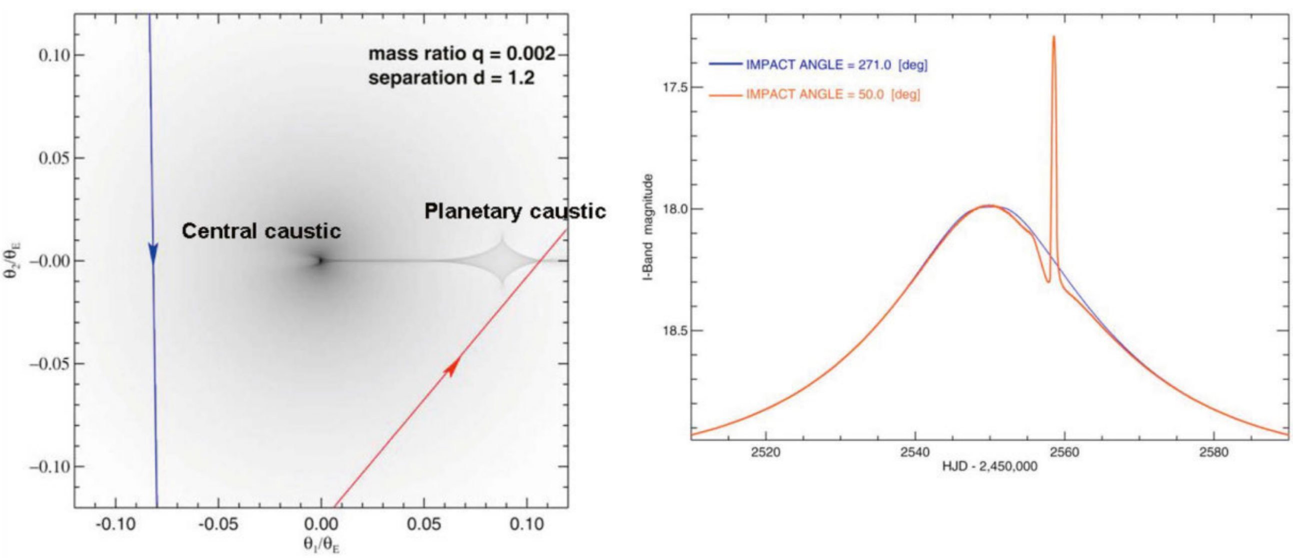
Figure 5: ***(Left)*** The magnification pattern of a two-body lens calculated by inverse ray shooting: The brighter the green scale, the higher the magnification. ***(Right)*** The corresponding caustic consisting of cusps and folds defining the positions where the lens equation becomes singular resulting in formally infinite magnification. (Credit: https://microlensing-source.org/)

An important feature of gravitational lensing is the occurrence of a "caustic". Caustics are well known in optics. In microlensing, the caustic corresponds to the positions of the source for which the solution of the lens equation results in infinite magnification, i.e., where the lens equation becomes singular. For a point lens, the caustic is degenerated to a single point: perfect alignment between source and observer results in an annulus shaped image, the so-called Einstein ring. For a two-body lens (such as a star plus exoplanet), the lens equation is more complex, but it remains true that there are solutions to this equation for which the magnification is infinite. In this case, the caustic is a closed curve, or set of closed curves, and at those curves the magnification diverges formally to infinity. An example magnification map and the corresponding caustic in this case are shown in **Figure 5.**

There are some general rules about caustics: (1) They are closed curves with an inside and an outside. (2) They have zero width. (3) The magnification diverges to infinity at the caustic. (4) The magnification inside of the caustic is always greater than the magnification outside of the caustic. (5) The caustic lines are called folds, the locations where curved folds connect are called cusps. The magnification pattern also depends on the mass ratio of the bodies defining

Figure 6: ***(Left)*** Magnification pattern of a two-body lens consisting of a host star (producing the central caustic) and its exoplanet (producing the planetary caustic).

(Right) Light curves resulting from the trajectories of the source for two cases depending on the impact angles represented by the blue and red straight lines.



the lens. The light curve depends on the path of the source relative to the lens and particularly relative to the caustics. A real situation is shown in **Figure 6.**

More complicated situations are drawn in **Figure 7,** where 8 (A), 4 (B), and 6 (C) exoplanets are situated at positions inside and outside the Einstein radius produced by the host star situated at the origin. **Figure 8** shows the caustics of a Saturn-mass planet (mass ratio 10^{-4}) with a projected separation close to one Einstein radius (so-called resonant lensing): the six panels from top to bottom show parts of the magnification patterns for separations of 1.105, 1.051, 1.025, 0.951 and 0.905 Einstein radii according to case C of **Figure 7. Figure 9** displays the typical (difference) light curves obtained from the second, fourth and sixth panel; time scales is in units of the Einstein time, the amplitude is given in magnitudes.

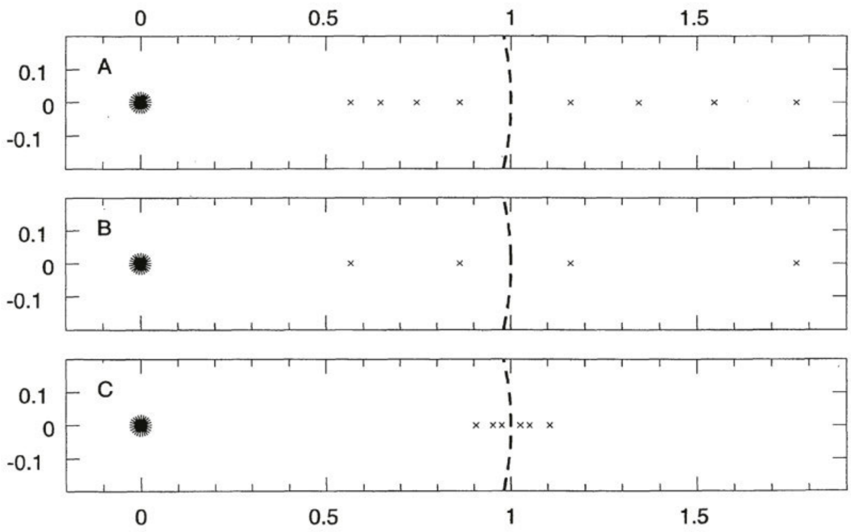


Figure 7: Geometry of three host star and exoplanet configurations A, B, and C with 8, 4, and 6 exoplanets, respectively. The star symbol at the origin of the coordinate system marks the position of the "main" lensing star. The crosses indicate the positions of the exoplanetary positions. The scale is in units of Einstein radii of the main lensing star. The dashed line shows the Einstein ring radius.

Figure 8: Resonant lensing represented by the caustic of a Saturn-mass exoplanet with a projected separation close to one Einstein radius corresponding to case C of **Figure 7.**

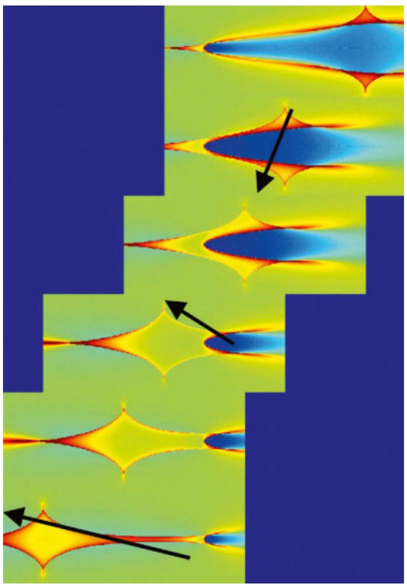
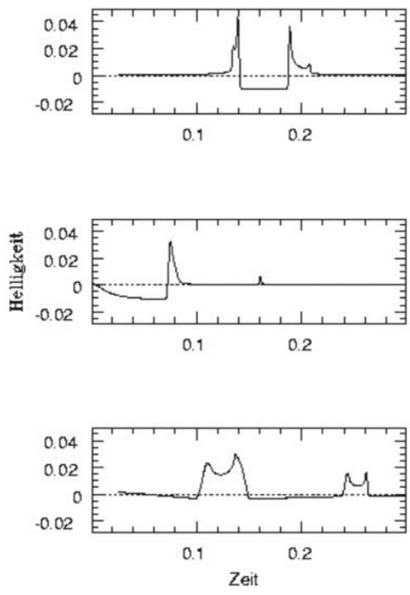


Figure 9: Microlensing light curves resulting from the three trajectories indicated by the arrows of **Figure 8.**



Detectability of Exoplanets and Exomoons by Microlensing

The idea to simulate the detectability not only of exoplanets, but mainly of exomoons, is simple: One calculates different magnification patterns resulting from different lens configurations (i.e., variations in parameter space where mass ratios, distances and angles are changed) and generates from them theoretical light curves representing different source paths and radii w.r.t. caustic or convolved situations (**Figures 10–12** and **Table 1**). Then one compares the simulated with measured light curves to identify possible exoplanets and exomoons. "Comparison" in this case means to subtract the light curve corresponding to a binary-lens magnification map and to test the significance of the deviation or residual light curve against statistical methods, e.g., χ^2-test.

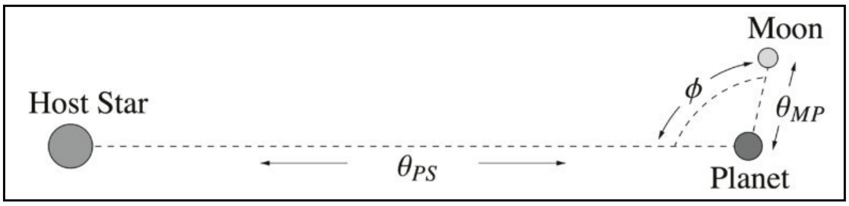
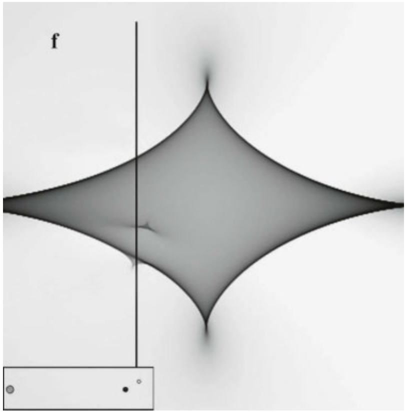


Figure 10: Triple lens configuration of a host star, an exoplanet and an exomoon. The mass ratios and geometric parameters are given in **Table 1.** (Credit: Liebig und Wambsganss 2010)

Table 1: Parameter values of a typical standard scenario. Parameters marked with an asterisk (*) are varied in order to evaluate their influence on the exomoon detection rate and to compare different triple-lens scenarios. The fixed parameters lead to values for the Einstein ring radius (1.9 AU in the lens plane). The lensed system is a Saturn-mass planet at a projected separation of 2.5 AU from its 0.3 solar mass M-dwarf host star. The Earth-mass exomoon orbits the exoplanet at 0.06 AU, i.e., in 0.01 mas angular separation.

	Parameter	Standard value	Comment
	D_S	8 kpc	distance to Galactic bulge
	D_L	6 kpc	
	M_{Star}	$0.3\ M_\odot$	most abundant type of star
	$\mu_\perp$	7 mas/year	$= v_\perp = 200$ km/s at $D_L = 6$ kpc
*	q_{PS}	10^{-3}	Jupiter/Sun mass ratio
*	θ_{PS}	$1.3\ \theta_E$	wide separation caustic
*	q_{MP}	10^{-2}	Moon/Earth mass ratio
*	θ_{MP}	$1.0\ \theta_E^P$	planetary Einstein radius
*	R_{Source}	$R_\odot$	brightness requirements vs. stellar abundance
*	f_{sampled}	$\simeq \frac{1\ \mathrm{frame}}{15\ \mathrm{minutes}}$	high-cadence observation
*	σ	20 *mmag*	typical value in past observations



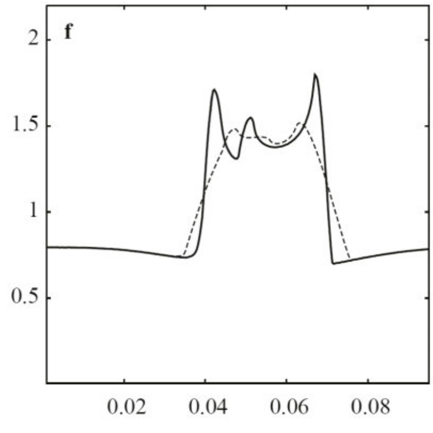


Figure 11: (Left) Magnification pattern computed for the lens configuration of Table 1. The relative positions of host star, exoplanet and exomoon are sketched in the lower left. A darker shade of grey corresponds to a higher magnification. The straight line marks the trajectory of the source.
(Right) Resulting light curves for two different source radii, one (thin) and three (dashed) solar radii. (Credit: Liebig und Wambsganss 2010)

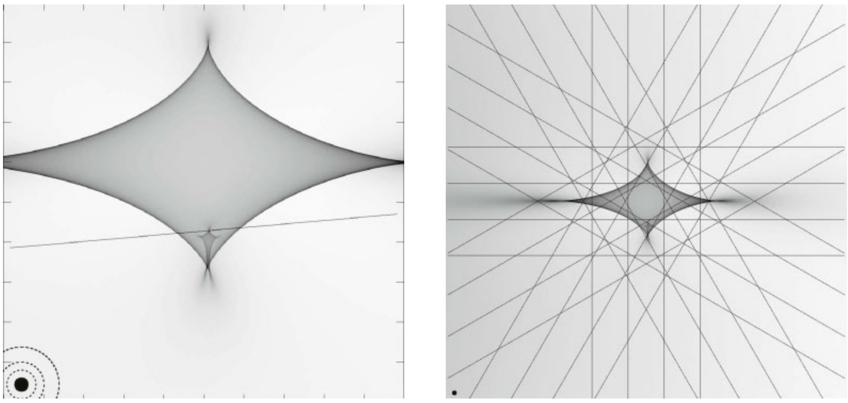
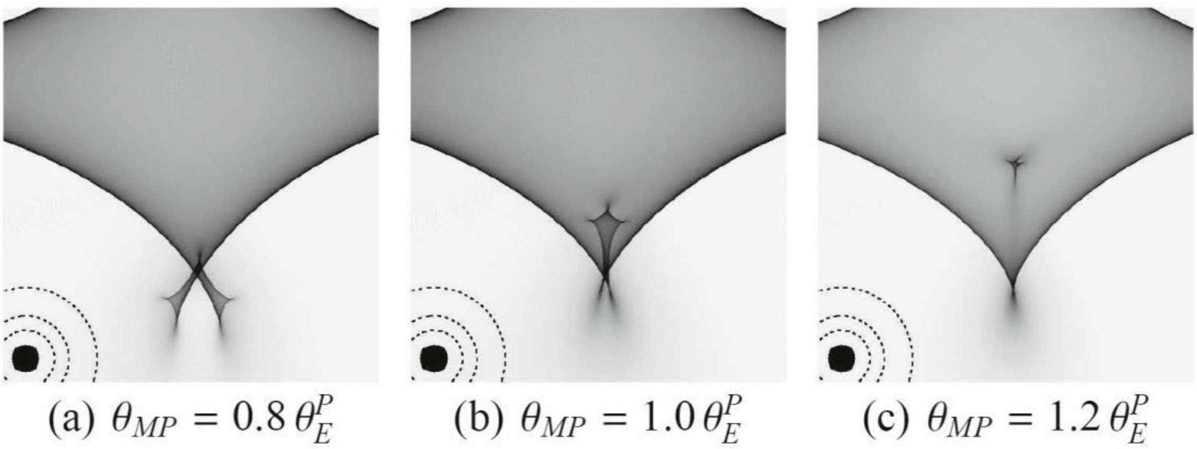


Figure 12: (Left) In the ideal case the trajectory or path of a source of reasonable size (indicated by the circles at the bottom left) will cross the magnification pattern through the caustics of both the exoplanet and the exomoon (seen at the lower cusp of the exoplanet caustic) as indicated by the straight line. ***(Right)*** However, the source trajectories have to be chosen independently of the (resonant) caustic features, though all light curves are required to pass through or close to the exoplanet caustic. This is realised through generating a grid of source trajectories that is only oriented at the exoplanet caustic. (Credit: Liebig und Wambsganss 2010)

To detect exomoons it is absolutely critical to have caustics by which the resulting light curves can clearly be discriminated from the exoplanet light curve. **Figures 13** and **14** show convolved magnification patterns of exoplanet and exomoon for different angular separations and different mass ratios, respectively.

In this way magnification patterns can be calculated for a whole orbit of the exomoon around its exoplanet. The result of such a simulation is shown in **Figures 15** and **16.** Actually, triple-lens magnification maps are generated, but only the caustics of the exoplanet and the exomoon are displayed for twelve orbital phases, i.e., in steps of 30°. Light curves resulting from caustic and source trajectory configuration as displayed in **Figure 16** are shown in **Figure 17.**

Figure 13: Exoplanet and exomoon magnification/caustic patterns for three different angular separations. (Credit: Liebig und Wambsganss 2010)



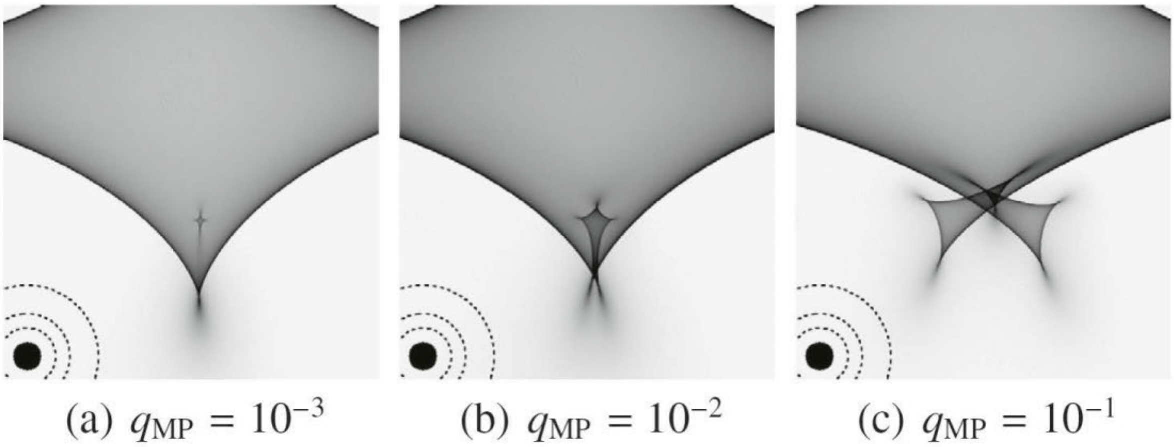


Figure 14: Same as **Figure 13** for three different mass ratios. (Credit: Liebig und Wambsganss 2010)

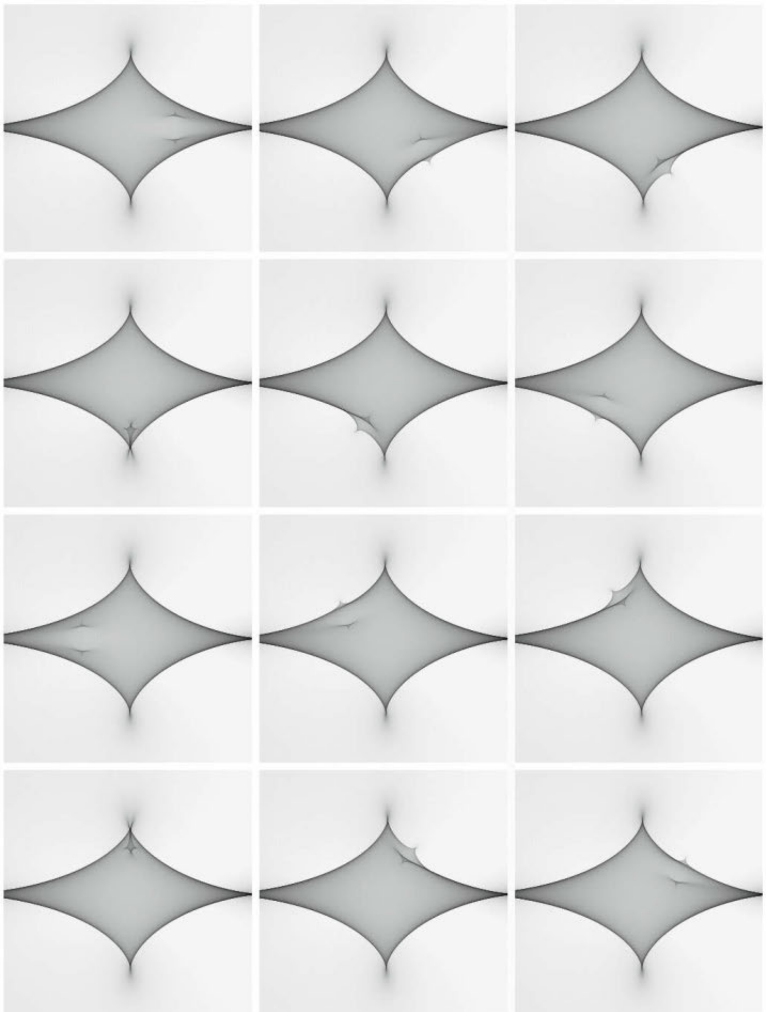


Figure 15: Set of calculated triple-lens magnification patterns including caustics of an exomoon orbiting an exoplanet in steps of 30°. (Credit: Liebig und Wambsganss 2010)

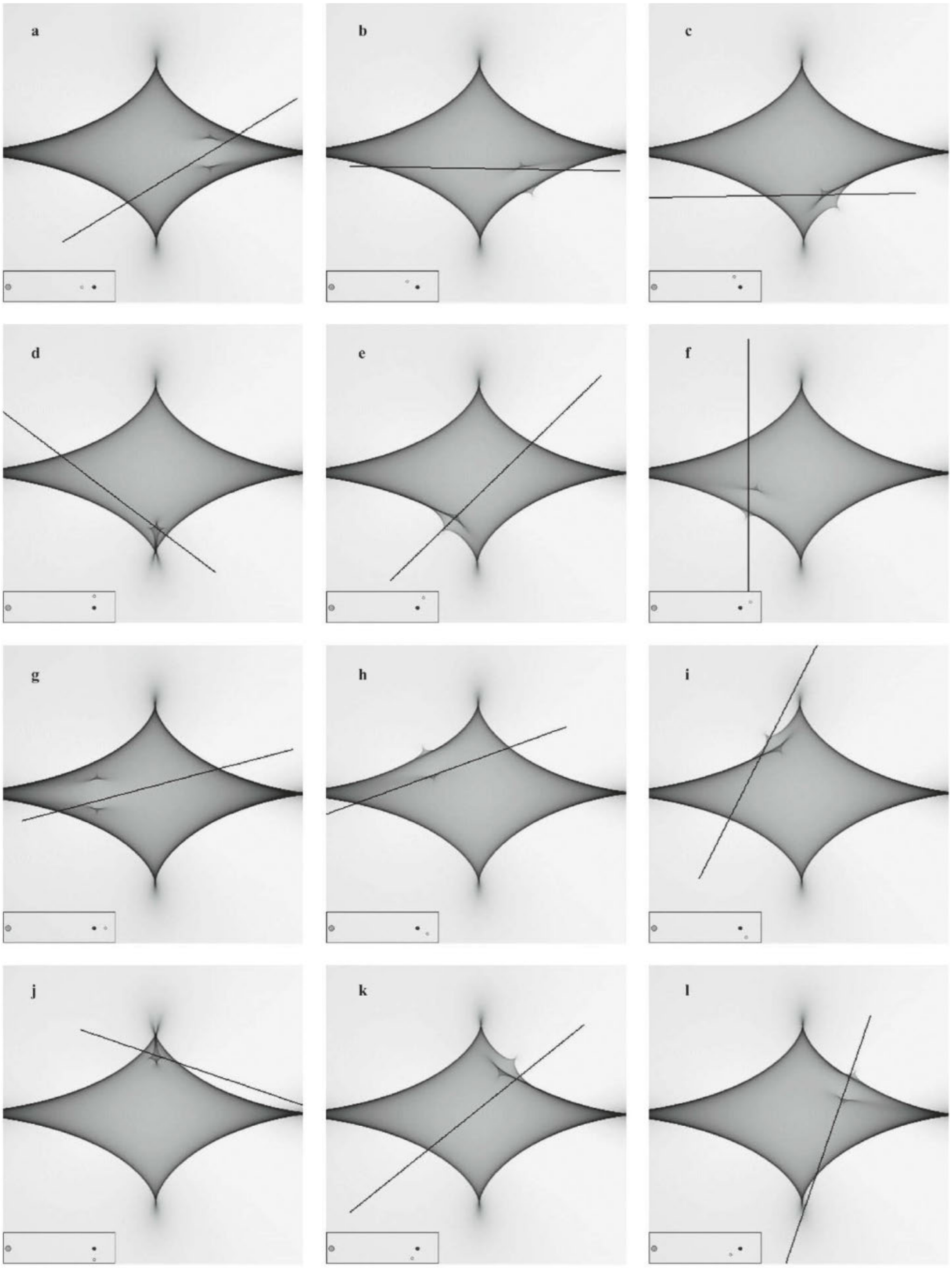


Figure 16: Triple-lens magnification maps for scenarios with mass ratios exoplanet/host star of 10^{-3} and exomoon/exoplanet of 10^{-2} and separation angle ratios exoplanet/host star of 1.3 and exomoon/exoplanet of 1.0 in units of Einstein radii (according to the standard scenario as summarised in **Table 1**). Displayed are the caustic configurations for twelve different exomoon positions completing a full circular orbit in steps of 30°. The relative positions of host star, exoplanet and exomoon are sketched in the lower left of each panel (not to scale). A darker shade of grey corresponds to a higher magnification. (Credit: Liebig und Wambsganss 2010)

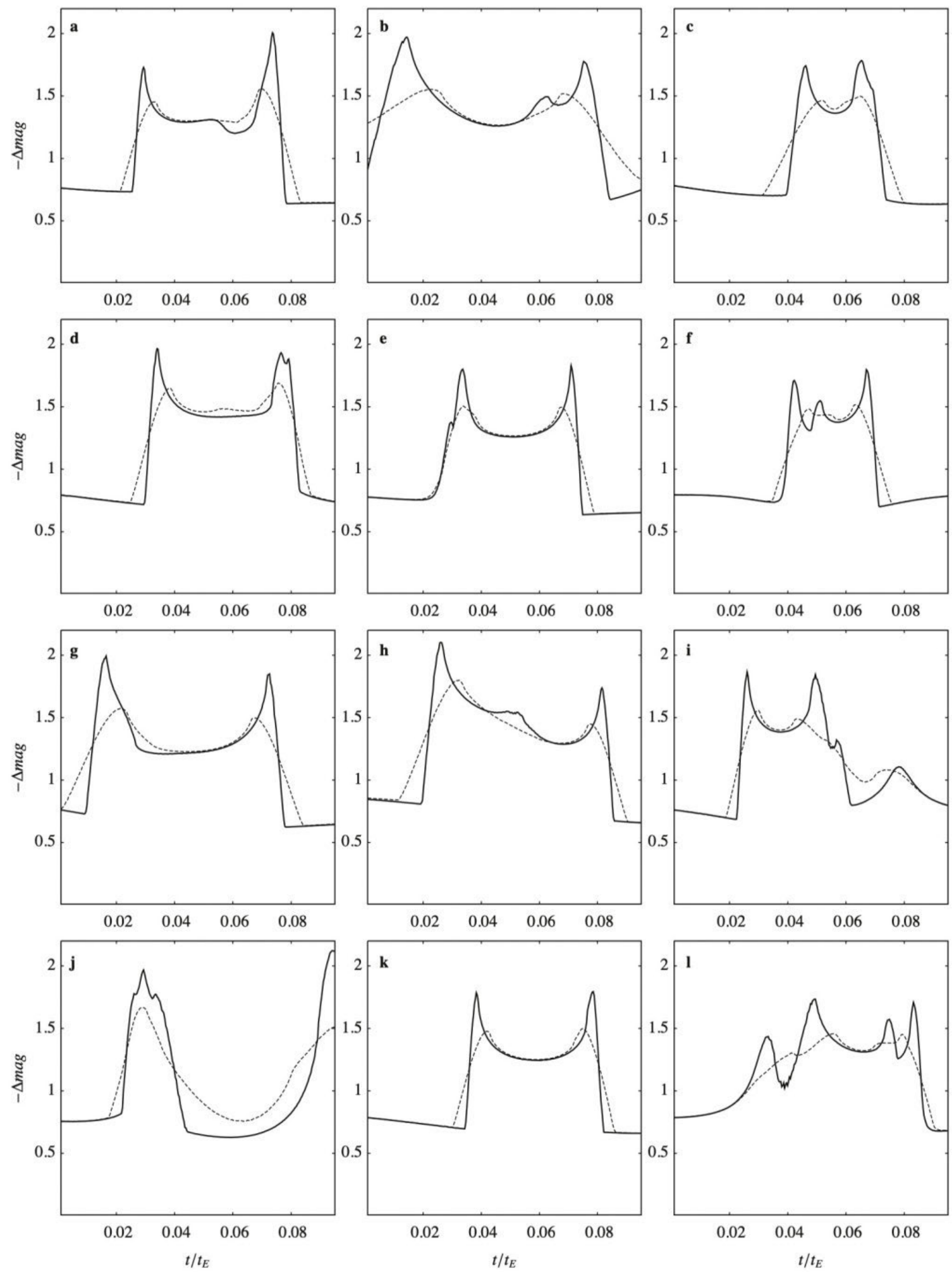


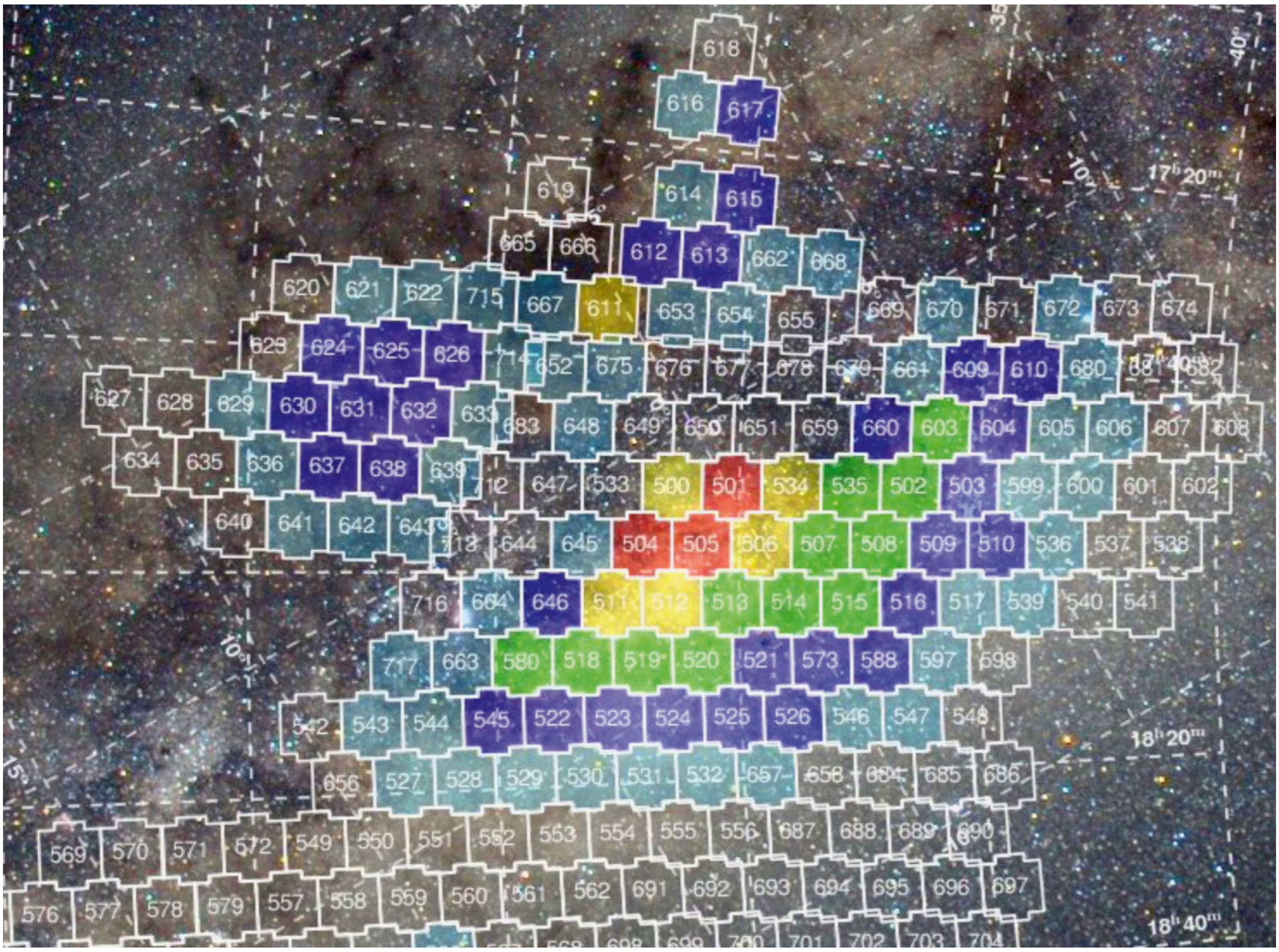
Figure 17: Sample of triple-lens light curves corresponding to the source trajectories as indicated in **Figure 16** by the straight lines crossing the caustics. The solid light curves were extracted with an assumed solar source size. The thin, dashed lines show the same light curves with source size of three solar radii. The magnification scale is given in negative magnitude difference, i.e., the unmagnified baseline flux of the source is 0. The time scale represents a uniform relative motion of source and lens. (Credit: Liebig und Wambsganss 2010)

Searching for Exoplanets and Exomoons with Microlensing Surveys

The search for microlensing events through exoplanets (and exomoons) is performed in a two-step strategy. The first step comprises the monitoring of more than 100 million stars in the galactic bulge several times per week. The CCD frames taken during this monitoring are then successively subtracted from each other (called "difference imaging"). In the case of a microlensing event, the difference images will contain residual light, and the community will be alerted. Two teams are responsible for this monitoring task: OGLE (Optical Gravitational Lens Experiment) monitors 170 million stars on a regular basis using a 1.3 metre telescope situated in Chile and can detect more than 2,000 alerts per observation season **(Figure 18).** MOA (Microlensing Observations in Astrophysics) follows a similar strategy by using a 1.8 metre telescope in New Zealand, and is typically alerting about 800 events per season.

In a second step, follow-up observations are taken from the alert

Figure 18: Search areas of the galactic bulge region scheduled for an OGLE-IV survey campaign. The observation cadence is colour coded: red (up to 30 frames/night), yellow (up to 10 frames/night), green (up to 3 frames/night), blue (1 frame/night), cyan (about 1 frame/2 nights). (Credit: Jan Skowron, OGLE Team)



events with high frequency (several times per hour) and high accuracy using the following networks: PLANET (Probing Lens Anomaly NETwork), equipped with five telescopes on the Southern Hemisphere; microFUN (Microlensing Follow-Up Network), using a main telescope (in Chile) plus many supplement telescopes around Earth, including amateur 0.25–1.8 metre telescopes; MiNDSTEp (Microlensing Network for the Detection of Small Terrestrial Exoplanets), consisting of a Danish 1.5 metre telescope (in La Silla) plus one Monet-North and one Monet-South; RoboNet (a microlensing search for cool planets), being part of the LCO (Las Cumbres Observatory Global Network), operating 1 metre and 2 metre robotic telescopes worldwide.

Conclusions

Gravitational Microlensing is a powerful method for the detection of extrasolar planets. One of its strengths is its possibility to determine the abundance of exoplanets: Cassan et al. (2012) have shown that on average every star in the Milky Way is surrounded by at least one planet of Neptun mass. Another strength is the sensitivity to low masses, i.e., Earth-like exoplanets. In the future gravitational microlensing has the potential to even detect exomoons around exoplanets around distant stars. The possible detection of exomoons requires extremely high photometric measuring precision of the order of milli-magnitudes and sampling rates of ideally one frame every few minutes, applied to many 100 million stars. In parallel, numerical simulations of many three-lens configurations and robust modelling codes need to be developed. It sounds very ambitious, but all this is within reach of current or near future possibilities.

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https://microlensing-source.org/

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His research concerns the search for extrasolar planets, quasars, galaxy clusters and gamma-ray bursts, strong gravitational lensing (multiple quasars, giant luminous arcs and microlensing), extragalactic astrophysics and cosmology (dark matter, Hubble constant), the simulation, modelling, observation and analysis of astronomical data (e-science, virtual observatory, data storage, open data and open access).