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Detection of extrasolar planet WASP-10b by differential photometry using amateur optics

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Abstract

This study presents the detection and characterization of the exoplanet WASP-10b using differential photometry performed with amateur astronomical equipment. An overview of exoplanet properties, detection techniques, and the transit method is provided, followed by a description of the observational setup, recording procedures, calibration, and data processing workflow. More than one hundred CCD images were acquired using an 8-inch Schmidt–Cassegrain telescope and a monochrome Atik 383L+ camera, with additional calibration frames to correct instrumental noise and vignetting. Differential photometry was carried out using AstroImageJ, enabling precise extraction of the stellar flux of WASP-10 relative to nearby reference stars. The transit light curve was modeled using the Mandel & Agol analytic formalism, from which key planetary parameters were estimated. Results yield a planetary radius of approximately 1.12 RJ and an orbital inclination of 89°, both in good agreement with published values. The study demonstrates that high-precision exoplanet transit measurements are achievable with advanced amateur-level equipment, offering valuable scientific and educational contributions to exoplanetary research.

Keywords: Critical infrastructure; vulnerability analysis; defense of the country; event tree technique; Monte Carlo method, railway system

1. Introduction

Extrasolar planets (exoplanets) are planets that orbit outside the Solar System around a parent star. The number of extrasolar planets discovered increases every year due to the invention of new detection methods or the improvement of existing ones. The first extrasolar planets orbiting their parent stars were discovered only in the 1990s. The discovery of these planets also raised the very exciting question of the possible existence of life on them. From 1998 to December 2025, 6045 extrasolar planets were discovered.

The first planet that was discovered (in 1995) outside the solar system is 51 Pegasi b. The Kepler space telescope, using the transit method, discovered Kepler-47, the first double star to have planets: Kepler-47b and Kepler-47c. In 2016, the planet HD 131399Ab, a few million years old, was noticed in the constellation Centaur, which is located in a triple star system (HD 131399A, HD 131399B, and HD 131399C), and astronomers believe that multiple stars are too unstable for the long-term survival of planets.

HARPS (since 2004) has discovered about a hundred extrasolar planets, while the Kepler space telescope (since 2009) has discovered more than 2,000 extrasolar planets. About 20% of Sun-sized stars have Earth-sized planets in the habitable zone. Assuming there are 200 billion stars in the Milky Way, it is thought that there are at least 11 billion Earth-sized planets where life is possible. If planets orbiting red dwarfs are included in that number, that number rises to 40 billion.

Kepler-37b is one of the smallest exoplanets discovered, orbiting the star Kepler-37 in the constellation Lyra. It has a radius slightly larger than the radius of the Moon. Another low-mass planet discovered is Draugr (PSR B1257+12 A, PSR B1257+12 b, believed to orbit a pulsar), which is about twice the mass of the Moon. The most massive planet found on the NASA Exoplanet Archive is DENIS-P J082303.1-491201 b, and has a mass of about 29 Jupiters, although by some standards this planet can be classified as a brown dwarf. Kepler-70b (it orbits the star Kepler-70 in 5.76 hours) is one of the hottest exoplanets discovered, with a surface temperature of about 7140K. Its density is 5500 kg/m3.

Some planets are so close to their host stars that they take only a few hours to orbit them, while others take thousands of years to complete one rotation. Most of the planets that have been discovered are in the Milky Way, but there have been some potential detections of “extragalactic” planets. The closest extrasolar planet is Proxima Centauri b, 4.2 light-years (1.3 parsecs) from Earth, and orbits Proxima Centauri, the star closest to the Sun. There are indications that some form of life may be possible on Proxima Centauri b. One of the most distant exoplanets discovered is SWEEPS-11, which orbits the star SWEEPS J175902.67−291153.5 (in the constellation Sagittarius), and is approximately 27,710 light-years away.

In addition to extrasolar planets, there are also so-called "rogue planets" (e.g. WISE 0855−0714), planets that do not orbit any star. The potential number of such planets is measured in billions. The oldest known exoplanet is PSR B1620-26 b (also known as Methuselah), about 12,400 light-years away in the direction of the constellation Scorpius. The planet orbits two stars, a pulsar (PSR B1620-26) and a white dwarf (WD B1620-26) and is the first planet discovered orbiting two stars. It is believed to be 12.7 billion years old. The youngest exoplanet discovered is V830 Tau b, which orbits the T Tauri star V830 Tau, about 430 light-years away in the direction of the constellation Taurus. The planet is believed to be about 2 million years old.

One of the most studied extrasolar planets is a planet called HD 189733 b, which is about 63 light-years from Earth, in the direction of the constellation Vulpecula (The Fox). The planet orbits the star HD 189733 A, with an apparent magnitude of 7.6, and spectral type K1-2V. With a mass about 15% greater than that of Jupiter, the planet HD 189733 b rotates around its star in about 2.2 days, at an orbital speed of about 150 km/s. Carbon dioxide has been detected in its atmosphere.

In 2013, the color of the planet was discovered for the first time. By measuring the albedo, it was determined that the planet HD 189733b has a dark blue color. On the other hand, the planet GJ 504 b appears to be predominantly purple in color. Kappa Andromedae b, on the other hand, has a reddish color. One of the darkest known exoplanets is TrES-2b, a "hot Jupiter" planet that reflects less than 1% of the light from its parent star, meaning it is less reflective than charcoal or black acrylic paint. These "hot Jupiters" are expected to be so dark due to the sodium and potassium content of their atmospheres, but it is not known why TrES-2b is this way - perhaps due to some unknown chemical element.

The large surface temperature variations on the exoplanet 55 Cancri e have been attributed to possible volcanic activity, which releases large amounts of dust clouds that can blanket the planet and block thermal emissions. Some exoplanets (1SWASP J140747.93-394542.6, Fomalhaut b) are thought to have rings around them, similar to those of Saturn.

The atmospheres of several exoplanets have been detected so far. The first planet with an atmosphere (discovered in 2001) was HD 209458 b. KIC 12557548 b is a small, rocky exoplanet, very close to its parent star that is evidently evaporating and leaving behind a trail of clouds, something similar to a comet. Volcanic dust can be found in these dust clouds that can leave the planet due to low gravity, and in the cloud, there can also be vaporization of metals due to high temperatures (due to the proximity of the star).

Scientists are monitoring possible biological indicators on exoplanets. For example, molecular oxygen (0_2) in Earth's atmosphere is a result of photosynthesis by living plants and many types of microorganisms, so it can be used as an indicator of life on exoplanets [1], [2], [3], [4].

TOI-4600 c is one of the most intriguing long-period exoplanets discovered in recent years. Identified by NASA’s TESS mission and confirmed through ground-based follow-up observations, TOI-4600 c orbits its star roughly every 483 days, making it one of the longest-period planets ever detected by TESS. The planet is believed to be a cold gas giant, comparable in size to Saturn or Jupiter, likely located near or beyond the system's equivalent of the water-ice line. Its long orbital period and relatively moderate stellar flux make it especially valuable for studying atmospheric evolution and migration histories of outer gas giants. TOI-4600 c orbits a K-type star and forms part of a multi-planet system together with TOI-4600 b, enabling comparative studies of planetary system architecture and dynamical stability [33].

2. Detection of exoplanets by differential photometry

Extrasolar planets around stars similar to the Sun began to be found in large numbers only in the late nineties as a result of advanced telescope technology, but also CCD cameras and the possibility of computer image processing. Such advances enabled more accurate measurement of the luminous flux of stars, allowing astronomers to detect planets, not visually (the luminosity of the planets is too low for such detection), but by measuring variations in the luminous flux of the star as the planet passes in front of it (the so-called transit method or differential photometry method). The transit method is used by NASA's Kepler orbiting telescope. This method is also called the photometric or occultation method.

About 97% of all confirmed exoplanets have been discovered using indirect techniques, most commonly radial velocity measurements and differential photometry (tracking the transit of an exoplanet in front of a star). In addition to these two techniques, there are also direct imaging techniques, gravitational microlensing, polarimetry, astrometry, etc.

Photometry deals with measuring the flux or intensity of electromagnetic radiation from astronomical objects. The main task of differential photometry of exoplanets is to create a light curve that clearly shows the drop in the luminosity of a star due to the transit of a planet in front of it (Fig. 1). Each point on this curve (Fig. 1) represents the change in the magnitude of the parent star over a period of time. This means that when a planet passes in front of the star, a "dip" will appear in the light curve. This curve needs to be fitted so that the resulting function matches the experimental measurements as closely as possible.

Three important parameters for this curve (Fig. 1) are: the "depth" of the transit, the time of the start of the transit, and the time of the end of the transit. The transit curve, with the knowledge of the radius of the parent star (R*), allows us to estimate the following parameters [7]:

- The ratio of the radius of the exoplanet (Rp) to the radius of the parent star (R*).
- The ratio of the radius of the exoplanet's orbit (Rorb) to the radius of the parent star (R*).
- The central point of the transit tc and the duration of the transit t.
- The inclination of the exoplanet's orbit.

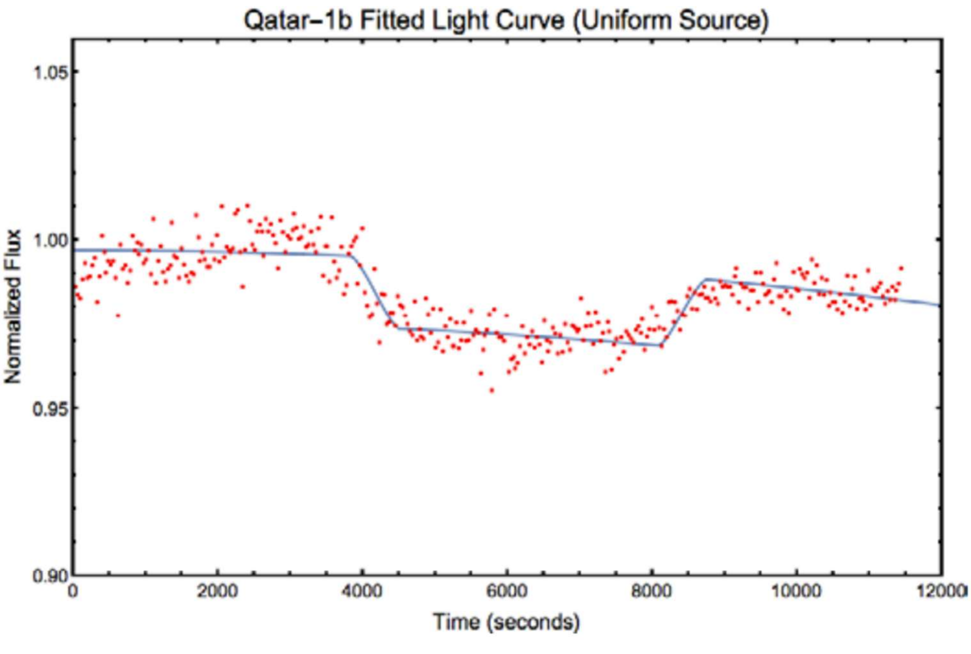

Fig. 1 Light Curve of the Exoplanet Qatar-1b [5]

How is this done in practice? Reference [6] provides a step-by-step tutorial on this procedure. In short, a large number of images are taken during the night, taking into account a nearby comparison star (whose magnitude we know). Exposures can be from 10s to 2 minutes for each image, and at least 4-5 hours of recording should be done. It is advisable to record 1 hour before and 1 hour after the start and end of the transit. Sometimes up to a thousand images are needed to record the entire transit.

A photometric program (e.g., Maxim dl, VPhot tool) is then used to determine the magnitude change of the host star using the technique of differential photometry. This means that the magnitude change of the exoplanet's host star is compared to the magnitude of a (non-variable) comparison star nearby.

The advantage of differential photometry is that only the difference in luminosity between the parent star and one or more comparison stars is important. In this way, the influence of factors such as light pollution, background sky glow, and passing clouds is eliminated. High precision of measurement requires the use of special astronomical CCD cameras on which the recording time can be set very precisely and whose sensors are much better for this purpose than, for example, CMOS sensors in DSLR cameras.

The detection of extrasolar planets using the transit method requires a fairly high measurement precision because the changes in the luminous flux of a star due to the transit of a planet are extremely small, and it is desirable that the orbital inclinations of extrasolar planets are close to an angle of 90°. The majority of extrasolar planets orbiting their host stars have an inclination of their orbits that is unfavorable for observation from Earth (<90°).

The magnitude of the change in the luminous flux of a star due to the transit of planets can best be described with a practical example. If, for example, if a planet the size of Jupiter were to pass in front of a star the size of the Sun, the change in light flux would amount to only 1.1%, while in the case of an extrasolar planet the size of Earth, that change in light flux would be approximately 0.84×10-4%. For a planet the size of Mars, the change in light flux intensity would amount to only about 0.3×10-5 %.

The atmosphere greatly affects the quality of astrophotographic images of stars. The most important of these are phase fluctuation and scintillation. Phase fluctuation is responsible for image shift (so-called cooking) and reduced visibility (so-called seeing), and is caused by the passage of light through different layers of the atmosphere, where the angle of arrival of the light rays changes, degrading the image. Scintillation is a second-order effect (causing the curvature of the wavefront) and results in a variation in light intensity over space and time. It is manifested by the twinkling of stars. Adaptive optics on telescopes can somewhat reduce the effects of these disturbances.

The advantage of the photometric method is that it can be used to identify a planet based on the light flux curve alone. This method, which is very important, can determine the approximate size of the planet being identified because the change in the intensity of the star's light flux during the transit of the planet is proportional to the ratio of the planet's radius to the star's. The star's radius is known in advance based on spectroscopy and is defined based on the star's luminosity and temperature values. In order to estimate the radius of an extrasolar planet very precisely, however, a telescope with a large objective diameter is required. Currently, this is done with telescopes of the 1m class and above, such as the TRAPPIST and LGOCT telescope systems. Also, with larger telescopes, the atmosphere of the transiting planet can be investigated. Namely, when a planet moves in front of the star, the light from the star itself passes through the upper layers of the planet's atmosphere.

By analyzing the spectrum of a given star (using spectroscopic equipment with higher resolution), chemical elements present in the atmosphere of a given planet can also be detected. The study of the atmosphere is of great scientific importance because it can provide a picture of the conditions prevailing on a planet – what gases it consists of, what the surface temperature is, whether there is liquid water on it, and even whether there is any form of life. For example, the presence of O2 or O3 molecules in the atmosphere of an exoplanet (detectable only by telescopes with an objective diameter of more than 2.5 m) can signal the existence of some form of life. In addition, perturbations in the transit times of extrasolar planets can be used to estimate the presence of other planets around the same central star [6].

3. Research methods for detecting exoplanets

The experimental research method involves systematic astrophotographic imaging of a selected candidate star, with the objective of detecting extrasolar planets through the transit method. This technique relies on measuring the slight reduction in the star's observed luminous flux when a planet passes in front of its disk, partially blocking the stellar light. In practice, this requires capturing a long sequence of calibrated images over several hours, ideally starting before the predicted transit and continuing after it has finished.

Throughout the analysis, a uniform surface brightness (luminous flux) across the stellar disk is assumed, allowing the observed decrease in flux to be attributed solely to the opaque silhouette of the transiting planet rather than intrinsic stellar variability or non-uniform emission. This assumption simplifies the mathematical interpretation of the light curve and enables the extraction of key planetary parameters such as radius ratio, orbital inclination, and transit duration.

Recording consists of the following procedures [7], [8], [9]:

- Setting up and verifying the assembly.
- Setting up the main telescope and auxiliary telescope.
- Setting up the camera to guide the telescope.
- Mounting the CCD camera on the main telescope.
- Placing a special filter in front of the CCD camera to eliminate the blue part of the star's spectrum, which is the most scattered in the Earth's atmosphere and contributes the most to measurement errors.
- Taking at least several hundred astrophotographic images of each candidate star, which will be used to analyze the brightness of the star for a certain time period (planet transit period).
- It is necessary to perform precise time synchronization on the camera (eg, Dimension 4 program).
- You need to know which time system is used:

  Julian Date/Universal Coordinated Time (JD_UTC),

  Heliocentric Julian Date/Universal Coordinated Time (HJD_UTC), or

  Barycentric Julian Date/Barycentric Dynamical Time (BJD_TDB).
- Software is used: eg Maxim DL for recording, and eg PHD2 program for telescope guidance.

The software recording procedure consists of the following [7], [8], [9]:

- Connecting the CCD camera with the Maxim DL program.
- Recording of monochrome images in FITS format.
- Depending on the resolution and the so-called seeing (atmosphere), brighter stars should be defocused min. 3 pixels in diameter, preferably 5-10 pixels.
- Shot exposures: generally 10-120 s.
- Shooting sensitivity ISO 100-200.

The differential photometry method involves the analysis of a large number of images, analyzing the intensity of the light flux from the observed star for the entire duration of the transit of an extrasolar planet. The shape of the light flux curve generally depends on the ratio of the radius of the planet to the central star, the latitude of the transit over the parent star, and the darkening of the edges of the stellar disk (so-called limb darkening).

In this work, the software Maxim DL was used, which enables very precise differential photometric measurements of the star for each measurement performed. Maxim DL also enables the export of the received data on the intensity of the light flux so that they can be processed in some of the software suitable for data analysis (e.g., MATLAB).

Reference stars used in photometry should have a magnitude as close as possible to that of the potential exoplanet host star, but it is also advisable to be of the same type of star. A good tool for selecting these stars is the AAVSO's Variable Star Plotter (VSP) utility [10].

Data processing and regression analysis methods used involve also the graphical representation of the change in the luminous flux for a candidate star in a certain time interval, based on a large number of calibrated astrophotographic images. Regression analysis of the obtained data defines the function of the change in the luminous flux intensity of a given star during the transit of an extrasolar planet. The curves are processed in software (e.g., MATLAB, Excel), which has a special tool (e.g., Curve Fitting Toolbox in MATLAB) for regression analysis.

Within the framework of mathematical methods, astrophysical equations allow for an approximate estimate of the radius of an extrasolar planet based on the precisely obtained change in the luminous flux for a candidate star and the size of the star (the star's radius is known in advance based on the known value of the star's luminosity and temperature, the so-called spectroscopic classification).

An example of work on the detection of exoplanets was like this [7], [8], [9].

Preparations involved the following (repeateble) procedures.

a. Collection of available data:

- Defining candidate extrasolar planets for analysis.
- Preparation for astrophotography of the candidate star (collection of data on the position (coordinates) and parameters of the star (type of star, mass, temperature, radius).
- Determining the date and exact time of the transit of an extrasolar planet (ephemeris for exoplanets).
- Example of an exoplanet search archive:
  - NASA Exoplanet Archive: http://exoplanetarchive.ipac.caltech.edu/cgi–bin/TransitView/nph-visibletbls?dataset=transits.
  - Exoplanet Transit Database (ETD) Website:http://var2.astro.cz/ETD/predictions.php.
  - Extrasolar Planet Transit Finder:http://jefflcoughlin.com/transit.html-
  - AAVSO's Variable Star Index (VSX),https://vsx.aavso.org/
  - Encyclopaedia of exoplanetary systems,https://exoplanet.eu/home/.

b. Recording the images:

- Going to the field (a place with less light pollution) and night shooting of candidate stars.
- Setting up the equatorial mount.
- Precise northing of the assembly to the northern sky.
- Setting up the main telescope and weights for proper mounting balance.
- Setting up an auxiliary telescope (finder) to guide the assembly (in recent times, astro cameras are used that have a special sensor inside the housing that is used for guidance).
- Placing an additional (e.g. planetary) camera on the auxiliary telescope, with the help of which the telescope will be positioned on one fixed star - guidance. In this way, it is possible to properly track (and cancel) the rotation of the Earth without star trails in images with longer exposures.
- Installing an astronomical CCD camera on the main telescope, which will record the brightness of the candidate star. Recording one star in just one night, if successful, takes at least 4-5 hours. In addition to the recording process, additional calibration images (dark, flat frames) are taken to reduce noise and vignetting in the images, as well as calibration images to reduce the overall measurement error.
- Care should be taken when a Meridian flip occurs (applies to all equatorial mounts). In the event of a flip, the shooting preparation process is repeated.

c. Data processing and analysis:

After the recording, data processing is initiated. The resulting images are processed using the software (differential photometry) by exactly determining the intensity of the candidate star's light flux in each of the images (several hundred images can be taken in one night). It is necessary to perform proper calibration of the images with dark, flat and bias frames using software. After estimating the intensity of the light flux for a given star, further data processing is performed using software, whereby a diagram of the change in the light flux of a given star for a certain time period (transit period) is defined. Based on the diagram of the candidate star's light flux, if the measurement was accurate, the existence of an extrasolar planet around the given star is confirmed.

The analysis of planet parameters is done using astrophysical models, where the size of the planet is determined, and if additional kinematic parameters for the star are available (e.g., radial velocity of the star), the inclination of the planet's path to the Sun, as seen from Earth, can also be determined. In case of failure of the recording for a particular night, after identifying the problem, the entire procedure should be repeated on another night, where it is important that it is clear and the atmosphere is as clean as possible. The aforementioned procedure is repeated every time a particular candidate star is recorded. Preparing the equipment for one recording takes 2-3 h. Most spring and summer days are used for recording. It is also necessary that the weather is clear, without the Moon in the night sky (or that it is not in its full phase), which further reduces the number of effective days for measurement. For additional details, we recommend following references [7], [8], [9].

4. Estimation of the parameters of the exoplanet WASP-10b

WASP (Wide Angle Search for Planets) is an international consortium of several academic organizations conducting an ultra-wide-angle search for exoplanets using the transit photometry method. An array of robotic telescopes aims to survey the entire sky, simultaneously observing thousands of stars of apparent magnitude 7-13. WASP is essentially an exoplanet discovery programme made up of the Isaac Newton Group, the IAC and six universities in the UK. Two continuously operating, robotic observatories cover the northern and southern hemispheres. SuperWASP-North is located at the Roque de los Muchachos Observatory on the mountain of the same name that dominates La Palma in the Canary Islands. WASP-South is located at the South African Astronomical Observatory, Sutherland in the arid Roggeveld Mountains of South Africa. They use eight wide-angle cameras that simultaneously scan the sky for planetary transit events and simultaneously allow the observation of millions of stars, allowing the detection of rare transit events.

4.1 The star WASP-10 and the planet WASP-10b

WASP-10 is a star in the direction of the constellation Pegasus. Figure 2 shows the currently known parameters of the star. Figure 3 shows the known parameters of exoplanet WASP-10b.

WASP-10

Observation data	
Epoch J2000	Equinox J2000
Constellation	Pegasus
Right ascension	$23^h\,15^m\,58.3005^s$ [1]
Declination	+31° 27′ 46.295″ [1]
Apparent magnitude (V)	12.7
Characteristics	
Spectral type	K5
Apparent magnitude (B)	~12.4 [2]
Apparent magnitude (R)	~12.03 [2]
Apparent magnitude (J)	10.603 ±0.026 [2]
Apparent magnitude (H)	10.117 ±0.029 [2]
Apparent magnitude (K)	9.983 ±0.018 [2]
Variable type	V*(1SWASP) [2]
Astrometry	
Proper motion (μ)	RA: 25.110 ±0.052 [1] mas/yr Dec.: −25.269 ±0.048 [1] mas/yr
Parallax (π)	7.0636 ± 0.0372 [1] mas
Distance	462 ± 2 ly (141.6 ± 0.7 pc)
Details	
Mass	0.71 −0.071+0.086 $M_\odot$
Radius	0.783 −0.043+0.035 $R_\odot$
Temperature	4675 ±100 K
Metallicity	0.03 ±0.2

Fig. 2 Parameters of star WASP-10 [10]

Parent star		
Star		WASP-10
Constellation		Pegasus
Right ascension	(α)	$23^h\,15^m\,58.3005^s$ [1]
Declination	(δ)	+31° 27′ 46.295″ [1]
Apparent magnitude	(m_V)	12.70
Distance		462 ±2 [1] ly (141.6 ±0.7 [1] pc)
Spectral type		K5
Orbital elements		
Semi-major axis	(a)	$0.0371^{+0.0014}_{-0.0013}$ AU
Eccentricity	(e)	$0.057^{+0.011}_{-0.005}$
Orbital period	(P)	$3.0927616^{+1.12E-5}_{-1.82E-5}$ d
Inclination	(i)	$86.8^{+0.6}_{-0.5}$°
Argument of periastron	(ω)	$2.737^{+0.194}_{-0.166}$°
Time of transit	(T_t)	$2454357.85803^{+0.00042}_{-0.0003}$ JD
Physical characteristics		
Mass	(m)	$3.06^{+0.23}_{-0.21}$ M_J
Radius	(r)	1.08 ± 0.02 R_J
Density	(ρ)	3220 kg m^{-3}
Surface gravity	(g)	6.93 g
Temperature	(T)	1300
Discovery information		
Discovery date		April 1, 2008
Discoverer(s)		Cameron et al. (SuperWASP)
Discovery method		Transit
Discovery site		SAAO
Discovery status		Published

Fig. 3 Parameters of exoplanet WASP-10b [11]

The star WASP-10 is about 22% smaller than the Sun, and has a mass about 30% less than the Sun's mass. It is classified as a K5 star, with a surface temperature of around 4675K - less than that of the Sun. It is about 460 light years away from us and cannot be seen with the naked eye because its magnitude is 12.7. It is about 270 million years old [12] and represents a relatively young star. It takes about 12 days for one revolution around its axis. The only confirmed planet around this star is WASP-10b, which was discovered in 2008.

The exoplanet WASP-10b is an extrasolar planet discovered in 2008 by SuperWASP using the transit photometry method. Additional radial velocity observations have shown that the planet is about three times more massive than Jupiter, while transit observations have shown that its radius is 8–28% larger than Jupiter's (1.08 to 1.28 Jupiter radii), relatively small for a hot Jupiter. The planet has a density similar to that of our Moon, and its surface temperature is about 1300 K. It takes about 3 days to orbit its star (compared to the 365 days it takes for the Earth to orbit the Sun). It is the only confirmed extrasolar planet in the WASP-10 planetary system, as the only other discovered planet in this planetary system, WASP-10c, is still unconfirmed [11].

Figure 4 shows the star WASP-10, in a field of view with an angular width of 15'x15′.

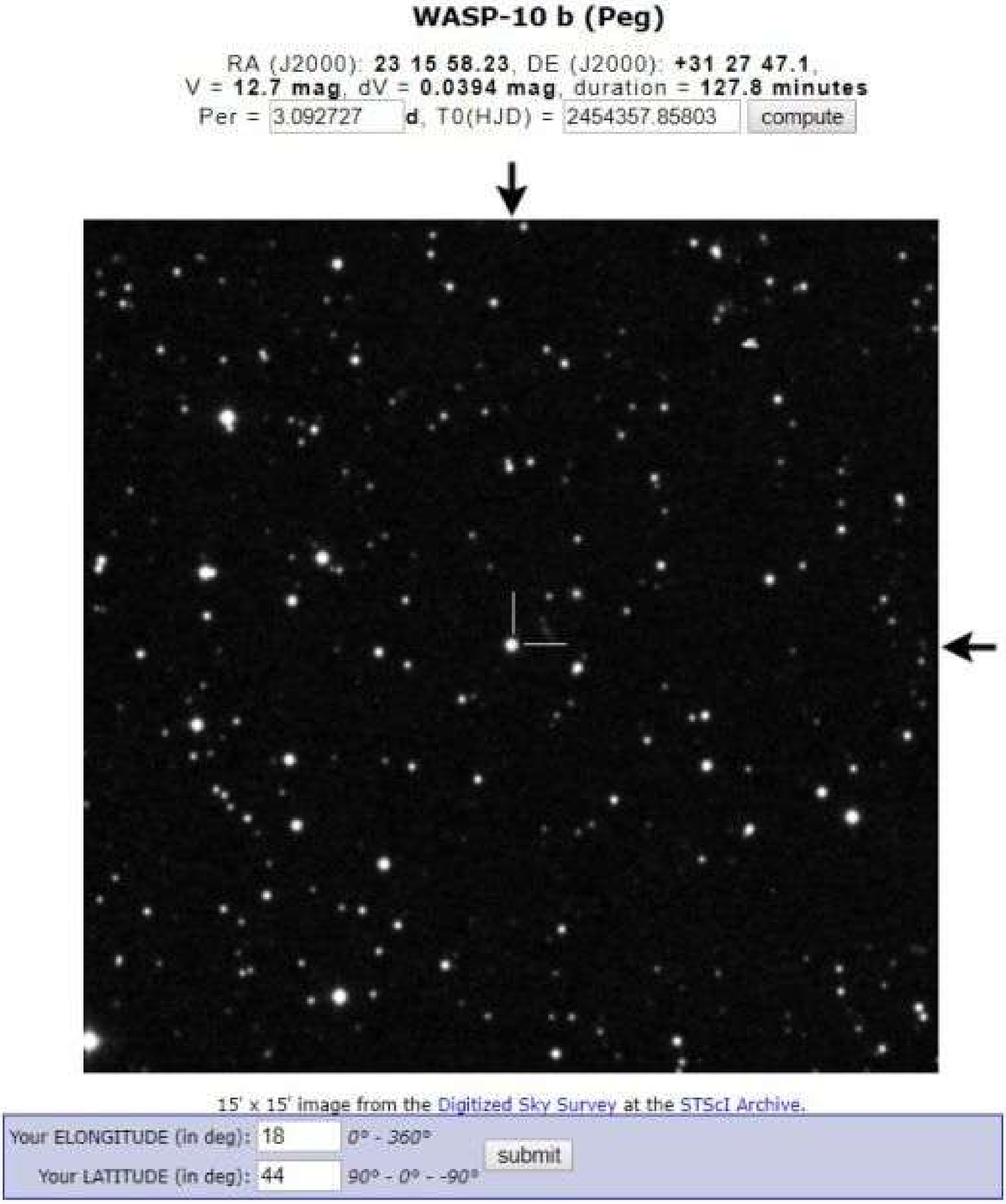

Fig. 4 Star WASP-10 in constellation Pegasus (Digitized Sky Survey, DSS)

Figure 5 shows the light curve determined by differential photometry for WASP-10b [13].

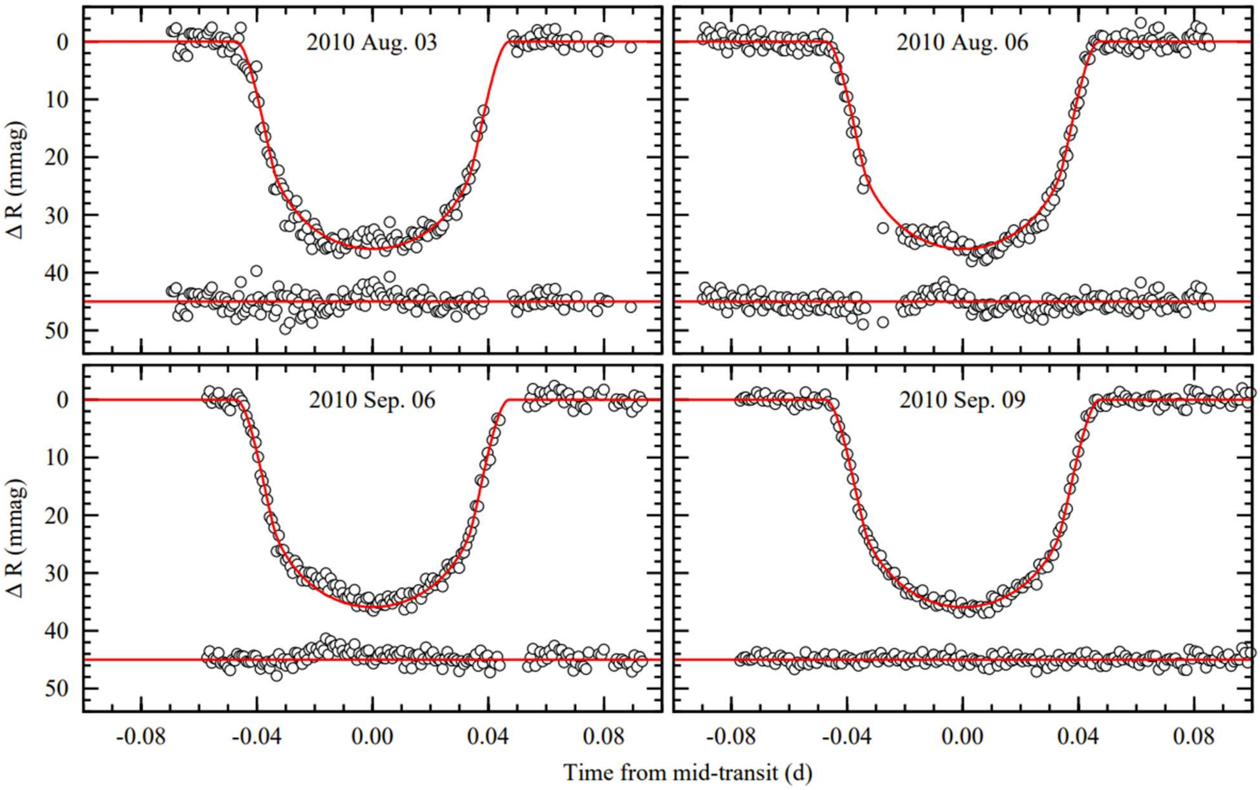

Fig. 5. Light curves for four transits of WASP-10 b with models based on the solution obtained for run 4 data and employing the quadratic limb darkening law. The residuals are shown in bottom plots. [13]

Table 1 gives the parameters of the planet WASp-10b (various authors), determined by modeling the light curve obtained by photometry.

Table 1. Physical properties of the WASP-10 system derived from light-curve modeling. Literature determinations are cited for comparison. [13]

Parameter	This work	Christian et al. (2009)	Johnson et al. (2009, 2010)	Krejcová et al. (2010)
Planet radius, R_b (R_J)	$1.03^{+0.07}_{-0.03}$	$1.28^{+0.077}_{-0.091}$	1.08 ± 0.02	1.22 ± 0.05
Planetary mean density, ρ_b (ρ_J)	$2.94^{+0.46}_{-0.25}$	$1.43^{+0.31}_{-0.29}$	2.35 ± 0.15	–
Planet gravitational acceleration, $\log g_b$ (cgs)	$3.88^{+0.04}_{-0.01}$	3.62 ± 0.06	3.828 ± 0.012	–
Equilibrium temperature, T'_{eq} (K)	950^{+30}_{-26}	1119^{+26}_{-28}	1370 ± 50	–
Orbital inclination, i (deg)	$89.5^{+0.4}_{-0.9}$	$86.9^{+0.6}_{-0.5}$	$88.49^{+0.22}_{-0.17}$	87.3 ± 0.1
Transit parameter, b (R_*)	$0.10^{+0.08}_{-0.18}$	$0.568^{+0.054}_{-0.084}$	$0.299^{+0.020}_{-0.043}$	–
Planet-to-star radius ratio, R_b/R_*	$0.1565^{+0.0033}_{-0.0022}$	0.170 ± 0.002	$0.15918^{+0.00050}_{-0.00115}$	0.168 ± 0.001
Star radius, R_* ($R_\odot$)	$0.67^{+0.03}_{-0.02}$	$0.775^{+0.043}_{-0.040}$	0.698 ± 0.012	0.75 ± 0.03
Scaled semi-major axis, a/R_*	$12.11^{+0.24}_{-0.15}$	$10.23^{+0.90}_{-0.92}$	$11.65^{+0.09}_{-0.13}$	10.64 ± 0.12
Mean star density, ρ_* ($\rho_\odot$)	$2.48^{+0.26}_{-0.17}$	$1.51^{+0.25}_{-0.20}$	2.20 ± 0.063	–
Star gravitational acceleration, $\log g_*$ (cgs)	$4.66^{+0.06}_{-0.04}$	$4.51^{+0.06}_{-0.05}$	$4.627^{+0.0101}_{-0.0093}$	–

Notes. The equilibrium temperature, T'_{eq}, was derived by assuming the effective temperature of the host star $T_{eff} = 4675 \pm 100$ K (Christian et al. 2009) and simplified relation $T'_{eq} = T_{eff}\sqrt{r_*/2}$ (Southworth 2010). Some quantities that were needed for calculations and could not be determined from the light curve analysis (e.g. planetary mass, semi-major axis) were taken from Johnson et al. (2009, 2010).

Researches focused on studying the exoplanet WASP-10b can be found in references [17-32].

Christian et al. [32] present the original discovery and characterization of WASP-10b, identifying it as a ~3 MJ gas giant transiting a late-type K star. The authors provide the first measurements of mass, radius, orbital parameters, and stellar properties.

The authors in [18] examine the role of tidal friction in driving orbital decay among ultra-short-period planets. By modeling tidal dissipation within both the star and planet, the study finds that frictional evolution significantly affects orbital stability, potentially leading to rapid inward migration and eventual planetary engulfment. Their results constrain the lifecycle of close-in exoplanet systems. The paper [19] evaluates how clouds increase atmospheric opacity and thereby affect the inferred metallicity of giant exoplanets. Through atmospheric modeling, the authors demonstrate that neglecting cloud opacity can lead to underestimation of heavy-element content. The study emphasizes the need for cloud-inclusive models when interpreting observational spectra. The work in [20] explores pulsating low-mass white dwarfs, mapping the instability strip of pre-ELM (extremely low-mass) white dwarfs. By coupling stellar evolution models with pulsation analyses, the authors identify regions in parameter space where pulsations occur, providing constraints on internal structure, mass loss, and binary evolution pathways.

The observational paper [21] presents transit photometry for five exoplanets (HAT-P-12b, HAT-P-13b, HAT-P-16b, HAT-P-23b, and WASP-10b) obtained at the Universidad de Monterrey Observatory. The study refines transit parameters such as depth, duration, and timing, demonstrating the capability of small-scale observatories to contribute precise exoplanet measurements. Basturk et al. [22] report on defocused transit observations using the 1-m T100 telescope at TÜBİTAK National Observatory. Defocusing reduces systematic noise and improves photometric precision. The study presents refined transit curves for selected exoplanets, validating the technique for high-accuracy ground-based photometry. Kammer et al. [23], using *Spitzer* infrared data analyzed secondary eclipses of five cool gas giant planets, deriving atmospheric emission properties. The authors identify empirical trends in thermal emission spectra, providing insights into atmospheric composition, temperature distributions, and radiative processes in cool giant exoplanets. Cruz et al. [24] report the detection of the secondary eclipse of WASP-10b in the Ks-band, offering one of the few ground-based measurements of thermal emission for this system. The results constrain the planet's dayside temperature and atmospheric properties. Maxted et al. [25] investigated WASP-1628+10, an EL CVn-type binary containing a very-low-mass stripped red giant. Through photometry and spectroscopy, the authors identify multi-periodic pulsations and model the evolutionary history of the system, informing the understanding of binary evolution and stellar stripping processes.

Barros et al. [26] examined transit timing variations (TTVs) in WASP-10b, exploring whether stellar activity can mimic TTV signals. The authors show that starspot occultations significantly influence timing measurements, emphasizing the need to correct for magnetic activity when interpreting TTVs. Husnoo et al. [27] provided observational constraints on tidal effects by analyzing the orbital eccentricities of exoplanet systems. The authors find correlations between eccentricity and tidal circularization timescales, contributing to understanding of tidal dissipation efficiencies in close-in planetary systems. Maciejewski et al. [28] studied transit timing variations and stellar activity in the WASP-10 system, presenting high-precision light curves and refined system parameters. The results suggest that starspots and magnetic activity significantly affect observed transit times, complicating interpretations of potential additional planets. Dittmann et al. [29] present transit observations of WASP-10b obtained with ground-based telescopes, yielding improved photometric precision. The authors refine physical parameters such as transit depth and orbital inclination, contributing to the early characterization of this planetary system.

Krejcova, Budaj & Krushevska [30] give a short observational report documenting photometric measurements of WASP-10b, confirming transit depth and duration. The paper supports previous detections and validates observational methods for small telescopes. Johnson et al. [31] in their study revised the radius of WASP-10b, showing it to be smaller than previously estimated based on improved light-curve analysis. The findings suggest a denser structure and prompt reevaluation of the planet's internal composition and formation history. The study [32] investigates how cloudy atmospheres influence the long-term thermal evolution of warm giant exoplanets. Using interior modeling, the authors show that clouds act as an additional insulating layer, altering cooling rates and modifying the planets' observable radii and luminosities. The work highlights the importance of atmospheric opacity in interpreting mass–radius relationships for giant planets.

4.2 Recording of WASP-10b and estimation of its parameters

The imaging and estimation of the parameters of the exoplanet WASP-10b within the framework of this work was carried out as follows, in accordance with the recommendations given in Chapter 3.

*Preparation***.** Collection of available data, namely:

- Defining an extrasolar planet (candidate) for analysis.
- Preparation for photometry of the candidate star (collection of data on the position (coordinates) and parameters of the star (star type, mass, temperature, radius).
- Determining the date and exact time of the transit of an extrasolar planet (ephemeris for exoplanets).
- Searching the online archives.

Recording. Astrophotographic recording of a candidate star, with the aim of detecting extrasolar planets around it using the transit method (reduction in the intensity of the light flux of the star when the planet passes in front of its disk). Surface uniform luminous flux of the observed star is assumed.

The recording consisted of the following procedures:

- Setting up and verifying the installation of SW EQ6.
- Setting up the main telescope, SCT 8″, and the auxiliary telescope (9x50mm) through which guidance was performed.
- Mounting the QHY-5LII guidance camera on the auxiliary telescope.
- Mounting the CCD Atik 383 L+ mono camera on the main telescope.
- Setting up the SGPro program for recording (finding a star using coordinates, setting the number and type of frames, setting camera and telescope parameters).
- Recording calibration frames (bias, dark, and flat frames) which are used to remove noise from images, hot pixels, and thermal signal, as well as vignetting of images.
- Lightly defocus the stars (preferably 5-10 pixels).
- Precise time synchronization on a laptop (e.g. with Dimension 4).
- Recording 120 images (monochrome images in FITS format) of the WASP-10 star, taking into account the beginning and end of the transit. It is also necessary to record at least half an hour before and after the transit. Based on the images of the candidate star, an analysis of the star's brightness for a certain time period (the planet's transit period) is performed. The exposures were 90 seconds (care should be taken that the star is not oversaturated ("burned out"), so the maximum ADU (Analog-to-Digital Unit) was at about 70% of the maximum.
- Care should be taken when the Meridian flip occurs (applies to all equatorial mounts). In the case of a flip, the images are inverted. This is corrected later when aligning the images.

Calibration (and star alignment) of recordings. Calibration of star images with bias, dark, and flat frames was performed in software. After that, the alignment of the stars was done so that all frames were exactly the same. Note that there is no vignetting in image (Fig. 6), which is very important in photometry.

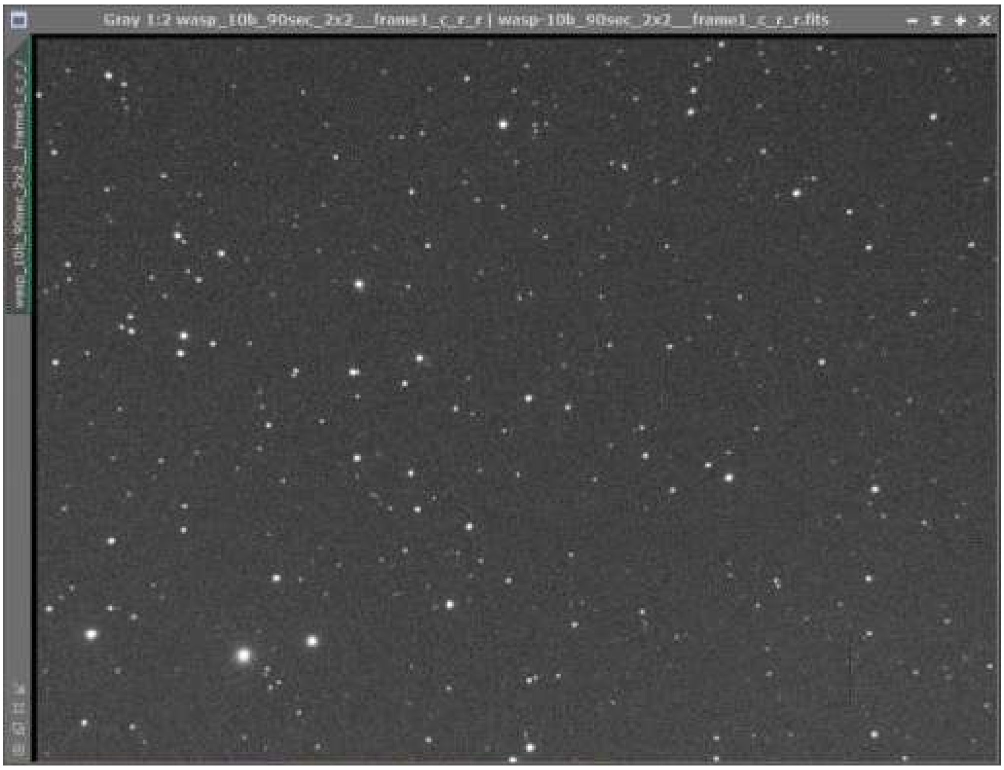

Fig. 6 Appearance of the calibrated and star-aligned image showing the star WASP-10 (in the center)

Differential photometry method. The method involves the analysis of all images, where the intensity of the luminous flux from the observed star is analyzed for the entire time of the transit of the extrasolar planet. The shape of the luminous flux curve generally depends on the ratio of the radius of the planet and the central star, the latitude of the transit over the parent star, and the darkening of the edges of the stellar disk (so-called limb darkening). The AstroimageJ software (Fig. 7) was used, which allows very precise differential photometric measurements of the star for each measurement performed. The program [16] also allows exporting the obtained data on the intensity of the luminous flux. Many scientific papers have been written using this program.

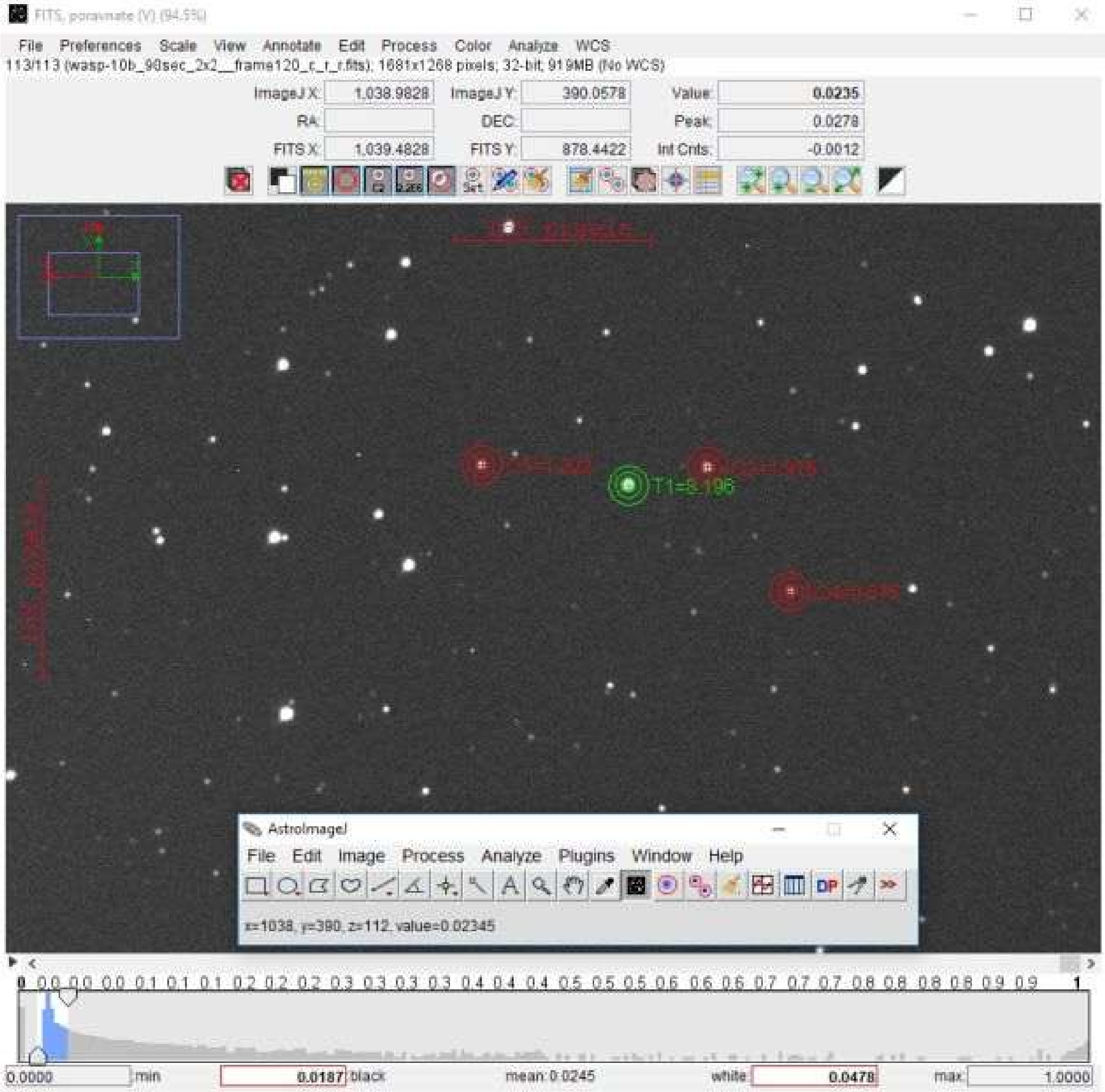

Fig. 7 The candidate star (green circle) and several nearby reference stars (red circles) in the AstroImageJ software.

If one wants to determine the magnitude of a candidate star, one must also define the magnitudes of the reference stars used in the photometry. A good tool for selecting these stars is the AAVSO's Variable Star Plotter (VSP) utility.

Data processing and regression analysis. These methods involve graphical representation and modeling of the change in the luminous flux for a candidate star in a certain time interval, based on the images. Regression analysis of the obtained data defines the function of the change in the luminous flux intensity of a given star during the transit of an extrasolar planet. The data were processed (modeled, fitted) in the AstroimageJ software (Fig. 8). In this, we had the help of Prof. Dr. John Kielkopf (Professor of Physics and Astronomy at the University of Louisville), one of the authors of the AstroimageJ program [14].

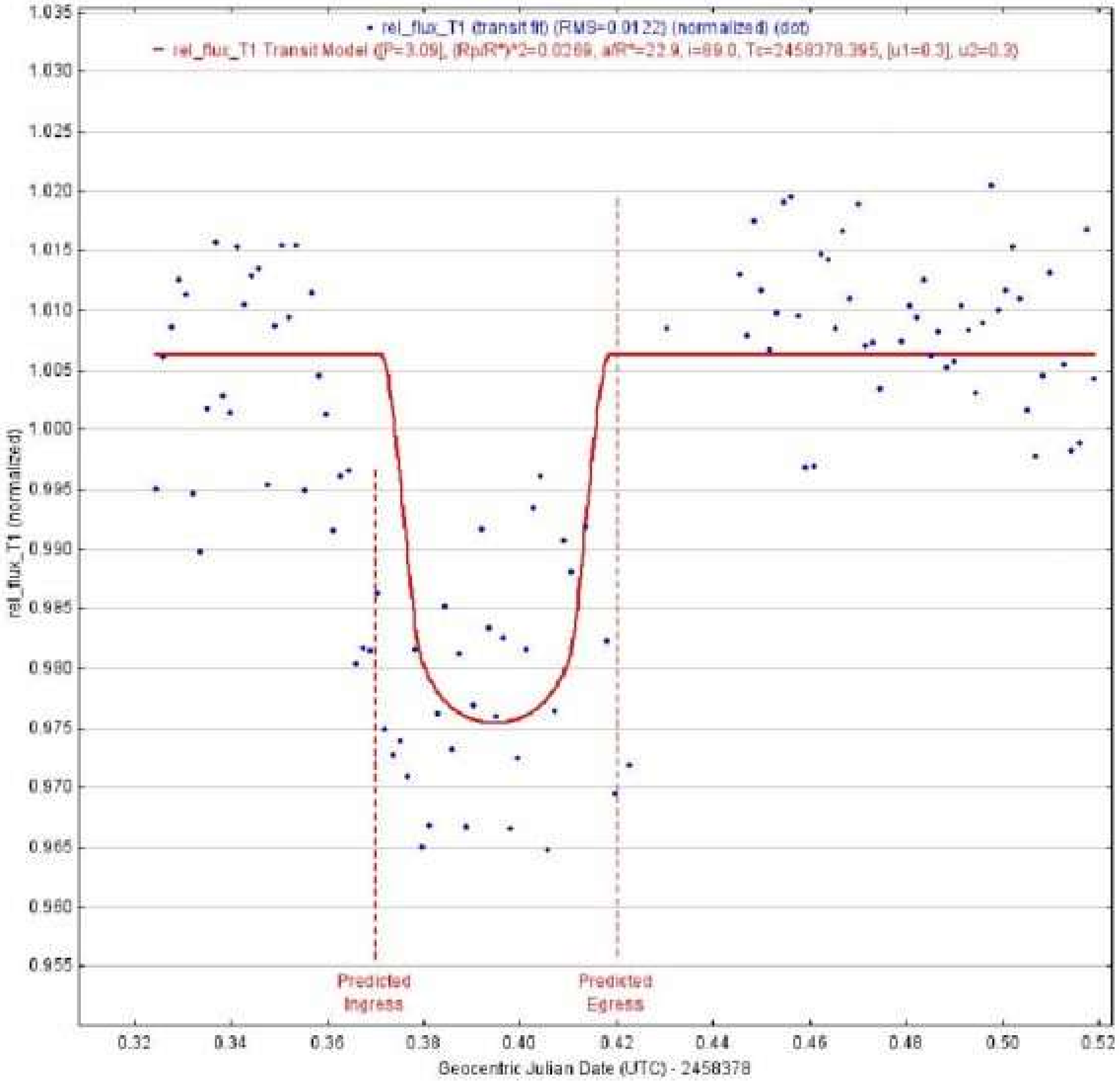

Fig. 8 Our modeling of the transit curve is based on the relative flux data (the candidate star's flux compared to the flux of the surrounding reference stars). Note that the drop in light intensity is only about 1%!

Mathematical methods. Astrophysical equations allow us to approximately estimate the radius of an extrasolar planet, as well as some other parameters of the planet, based on the precisely obtained change in the luminous flux for the candidate star and the size of the star (the star's radius is known in advance based on the known value of the star's luminosity and temperature, the so-called spectroscopic classification).

The exoplanet transit model used to estimate its parameters in the Astroimage J program is based on the model from the work of Mandel & Agol [15]. Here, the transit is modeled as an eclipse of a spherical star by a spherical planet with an opaque atmosphere.

The model is parameterized with several physical parameters (plus the light flux F_0), namely: the ratio of the planet's radius to the star's radius R_p/R^*, the ratio of the semi-axis of the planetary orbit to the star's radius a/R^*, the time of the middle of the transit T_c, the transit parameter would be the parameters u_1 and u_2 of the quadratic model of star edge obscuration. Based on these parameters, the inclination of the planet can also be determined.

In our case, we obtained an inclination of the planet of 89°, while the literature mentions a value of 86.8°-89.5°. We also obtained that the radius of the planet is 1.12 Jupiter's radius, which is a result of sufficient accuracy for amateur measurements, since in the literature this value ranges from 1.08 to 1.28 Jupiter's radius.

Also, based on our data and the model used [15], we obtained (Fig. 9) that the ratio of the semi-axis of the planetary orbit to the radius of the star a/R^* is equal to 22.6 (which means that the radius of the orbit of the planet WASp-10b is about 0.079 AU), and the value for this ratio circulating in the literature is 10.2 - 12.1 (the radius of the planet's orbit is about 0.041 AU).

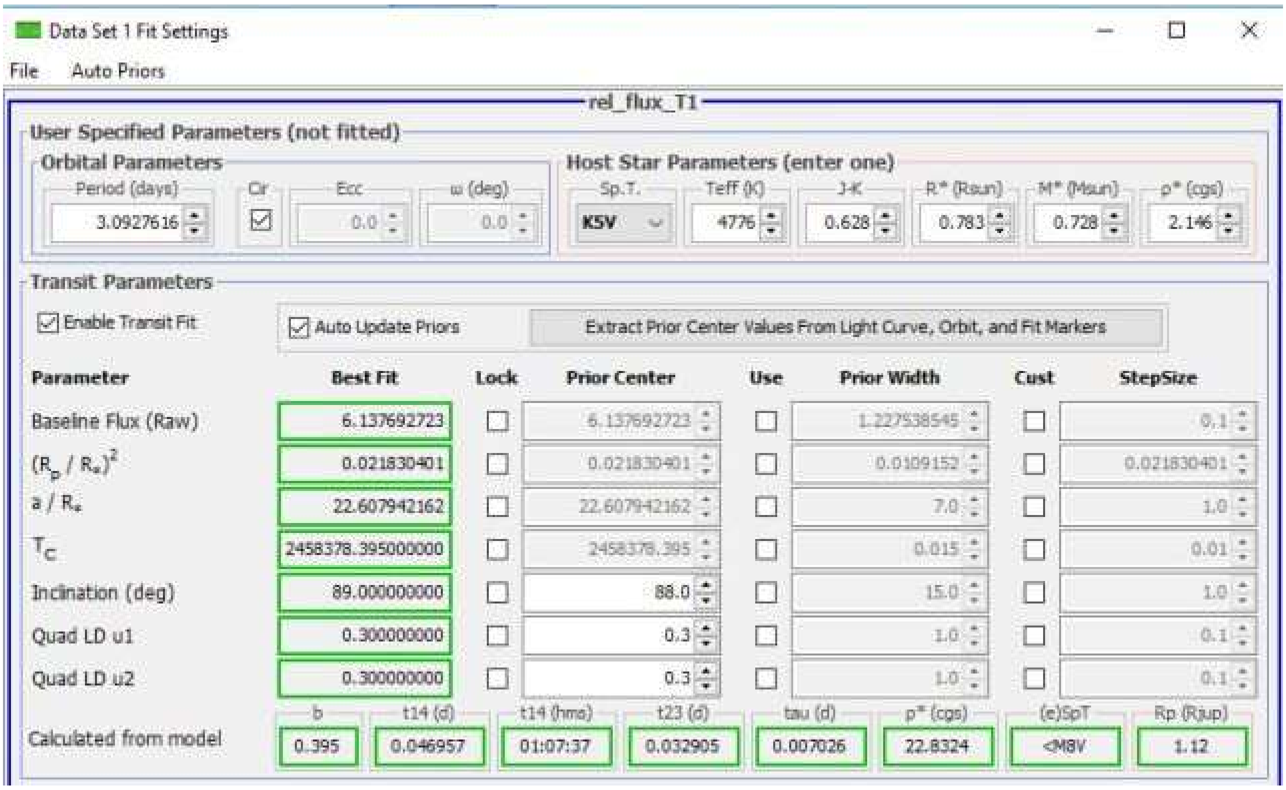

Fig. 9 Our application of the Mandel & Agol [15] model in AstroImageJ to determine the key parameters of the planet WASP-10b based on the obtained data.

In the upper part of fig. 9, it can be seen that the input parameters of the model, apart from the imaging data, are known data about the star WASP-10b. E.g., based on the mass of the star and its class, other parameters of the star can be determined (upper part of Figure 9). Also, the transit period (3.0927616 days) must be entered as input data.

Conclusions

The paper explains the method of differential photometry with the aim of determining the parameters of exoplanets. The introductory part describes the basics of exoplanets, with a review of some of the more interesting planets discovered so far. Also, the basics of practical amateur differential photometry are described, with a review of the necessary equipment and software.

The techniques used to estimate the main parameters of the exoplanet WASP-10b are described. Based on the imaging and data processing, the planet's inclination was obtained to be 89° (the literature mentions a value of 86.8°-89.5°). Also, the planet's radius was estimated to be 1.12 Jupiter radii (the literature mentions this value as 1.08 - 1.28 Jupiter radii). Based on our data and the model used [15], we obtained that the ratio of the planetary orbital semi-axis to the star's radius *a/R** is equal to 22.6 (which means that the orbital radius of the planet WASp-10b is about 0.079 AU), and the value for this ratio circulating in the literature is 10.2 - 12.1 (the planetary orbital radius is about 0.041 AU).

The described method is an interesting way for amateur astronomers to contribute to the astronomical community, but it is also a useful learning tool, especially for younger generations who are interested in the universe around us.

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