Exoplanet Observing by Amateur Astronomers

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by

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Q: Which stars host one or more planets?
A: Most of them!
...and one in five are believed to host an Earth-sized planet that could support life!
Background

• Exoplanet (Extrasolar Planet) – a planet orbiting a distant “host star”

• First exoplanet was discovered in 1992

• Both space-based (e.g., Kepler) and ground-based observatories have been used to detect exoplanets
Detection Methods:
3,264 Confirmed Exoplanets

- Direct Observation: 41
- Microlensing: 36
- Other: 36
- Radial Velocity: 582
- Transit Method: 2,569
The Transit Method

• Measures dip and length of light curve
The Radial Velocity Method

• Measures the Doppler shift of the host star’s spectrum as an orbiting planet causes it to wobble around their common center of gravity (“orbital reflex motion”)

• Can even be used to determine the orientation and direction of the planet’s orbit (the Rossiter McLaughlin Effect)
The Rossiter-McLaughlin Effect

In the Rossiter-McLaughlin Effect, the apparent rotation of a binary star system is affected by the gravitational influence of the secondary component. The effect is characterized by differences in the observed rotation rate of the system, which can be quantified using the orbital elements of the binary. The diagrams illustrate the effect for different values of the inclination angle (λ) and the mass ratio (b) of the binary system.
The Microlensing Method

- Measures the change in magnification of a background star as a planet orbits the foreground "lensing" star.
Direct Imaging

- The “Holy Grail” of methods to determine habitable planets (see October 2015 S&T article)

Image credit: J. Rameau, University of Montreal / C. Marois, Herzberg Institute of Astrophysics.
Until now, we are mostly looking in our immediate neighborhood!
Painting by Jon Lomberg, Kepler mission diagram added by NASA
What can we learn from the Light Curve?

- Exoplanet radius
- Exoplanet orbital radius
- Exoplanet orbit inclination to our line-of-sight

Assumes knowledge of host star’s radius and exoplanet’s orbital period
Creating the Light Curve

• Differential Photometry is used to calculate the relative change in flux between the Host star and one or more comparison stars

• The flux of the Host and comparison stars are first adjusted for background sky noise (due to light pollution, sky glow, moon light, etc.)

• A data point on the light curve = the relative change in flux of the Host star

• A best fit of the model of a transit is made based on these data points
Suspected Star Spot

Image Courtesy of Robert Trudel
Amateur Astronomers Can Detect Exoplanets!

...using the transit method to determine a light curve
...using the same equipment used for deep sky imaging
...even in light polluted skies
...with >90% accuracy
...and their observations are providing valuable science data!
Exoplanet Pro/Am Collaborations

- Space-based Observatories
- Ground-based Observatories
- Amateur Astronomers
Current Collaborations

• Confirmation of exoplanet candidates
  – KELT Follow-up Project

• Refinement of ephemeris of confirmed exoplanets
  – Hubble Study of Exoplanet Atmospheres

• Study of anomalous activity
  – Characterization of orbiting “planetesimals”
  – Example: WD-1145+017b – a suspected disintegrating asteroid orbiting a white dwarf
Hubble Exoplanet Pro/Am Project

• An approved Hubble Space Telescope (HST) survey of 15 exoplanets is taking place throughout 2016

• The survey’s purpose is to obtain key science data regarding the atmosphere of these 15 exoplanets prior to the James Webb Space Telescope (JWST)

• The project’s Principal Investigator is noted planetary scientist Dr. Drake Deming

• Approach:
  – Hubble’s Wide Field Camera 3 is using spatial scanning and a grating prism (grism) to obtain spectroscopy measurements in the 1.4 micron band
  – Each exoplanet is being visited one or more times
Hubble Pro/Am Collaboration

• Objectives:
  – provide refined ephemeris of the target exoplanets to the HST team
  – determine any unusual activity such as star spots or flares on the target planet’s host star
  – develop a framework and a world-wide network of advanced amateur astronomers for other such collaborations

• Status:
  – observations have been made of 9 of the 15 exoplanet targets
  – follow-up observations will be made of these and the remaining 6 targets through the end of 2016
Location of Participating Observation Sites
Detection of Other “Exo-Objects” (e.g., Disintegrating Planetesimals) by Amateur Astronomers!
WD1145 UT2016-03-30
MarioMotta (clear)-60sec

Courtesy of Mario Motta
Courtesy of Mario Motta
 Courtesy of Mario Motta
WD1145 UT2016-03-30

MarioMotta (clear)-60sec

32” scope 1 min exp

11” scope: 8 min exp.

WD1145 UT2016-03-30
Conti (Clear, 240 sec)

rel_flux_T1 (RMS=0.13844) (normalized)
The Future
Exoplanet Missions

Courtesy NASA
Summary

- Detection by amateur astronomers of exoplanets is possible, even in light-polluted areas

- Detection of other “exo-objects” also has now been demonstrated

- If properly coordinated, amateur astronomers can and are providing valuable information to professional exoplanet investigators

- Exoplanet detection is challenging, but extremely rewarding

The thrill of seeing a light curve develop of a transiting distant planet can be as satisfying as seeing the result of a pretty deep-sky picture!
Resources


3. Exoplanet Observing for Amateurs, Second Edition (Plus), Bruce L. Gary

4. The Exoplanet Handbook, Michael Perryman

5. The Handbook of Astronomical Image Processing, Richard Berry and James Burnell (comes with AIP4WIN photometry software)


Case Study
The Night Sky

WASP-12
Case Study: Detection of WASP-12b

Date/Time: January 5-6, 2016

Site: Suburban Annapolis, MD

Image scale= 0.63 arc-sec/pixel

FOV=14x11 arc-min.

Filter: V

Exposures: 337@45 seconds each
Observatory Setup
Location: Suburban Annapolis, MD
Four Phases to Exoplanet Observing

• Preparation Phase

• Image Capture Phase

• Calibration Phase

• Post-Processing and Modelling Phase
Preparation Phase

- Collect preliminary information
- Select an exoplanet target
- Predict potential meridian flips for GEMs
- Choose appropriate exposure times: important that host and comparison stars do not reach saturation during imaging session!
- Setup file directories
- Acclimate CCD camera to appropriate temperature
- Generate flat files if twilight flats are used
- Setup autoguiding system
- Synchronize image capture computer to USNO atomic clock
Image Capture Phase

• Begin imaging session 1 hour before predicted ingress time and end 1 hour after egress time

• Handle a meridian flip as expeditiously as possible

• After capturing raw images, capture darks and biases, as well as flats if an electroluminescence panel is used
The Importance of Uniform Flats

Post-flip:
Star lands on a “dust mote!”
Post-Processing and Modelling

• Use AstroImageJ freeware to conduct this last phase

• Calibrate raw images using bias, darks, flats

• Update FITS headers of calibrated files with AIRMMASS and BJD_{TDB} times (Barycentric Julian Date/Barycentric Dynamical Time)

• Conduct differential photometry on calibrated files
The Key Tools of Differential Photometry: the Aperture and Annulus
Selection of Comparison Stars around WASP-12
Conduct Model Fit

• Enter into AstroImageJ:
  – Orbital period
  – Predicted ingress/egress times
  – Limb darkening coefficients
  – Optionally, mass of Host star

• Add appropriate detrend parameters

• Select and adjust placement of light curve plots

• Deselect any comparison stars that are not linear
WASP-12b on UT2016-01-06

Conti (V, 45 sec)

- rel_flux_T1 (normalized)
- rel_flux_T1 (AIRMASS detrended with transit fit) (RMS=0.00397) (normalized)
- rel_flux_T1 Transit Model ([P=1.97], (Rp/R*)²=0.0127, a/R*²=3.2, i=90.0, Tc=2457393.601228, [u1=0.39], [u2=0.3])
- rel_flux_T1 Residuals (RMS=0.00397) (chi²/dof=2.09)
- rel_flux_C2 (AIRMASS detrended) (RMS=0.00366) (normalized) x(0.5) (bin size = 2)
- rel_flux_C3 (AIRMASS detrended) (RMS=0.00343) (normalized) x(0.5) (bin size = 2)
- rel_flux_C4 (AIRMASS detrended) (RMS=0.00428) (normalized) x(0.5) (bin size = 2)
- AIRMASS (arbitrarily scaled and shifted)
- tot_C_cnts (arbitrarily scaled and shifted)
## Accuracy of Model Fit Results for the Case Study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model Fit</th>
<th>Published</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit depth</td>
<td>0.0127</td>
<td>0.0138</td>
<td>92.0%</td>
</tr>
<tr>
<td>Transit duration</td>
<td>176.7 min.</td>
<td>175.7 min</td>
<td>99.4%</td>
</tr>
<tr>
<td>Orbit radius</td>
<td>0.024 au</td>
<td>0.023 au</td>
<td>95.7%</td>
</tr>
<tr>
<td>Orbit inclination</td>
<td>90 °</td>
<td>82.5 °</td>
<td>90.9%</td>
</tr>
<tr>
<td>Planet radius</td>
<td>$1.79_{\text{Jup}}$</td>
<td>$1.79_{\text{Jup}}$</td>
<td>100%</td>
</tr>
</tbody>
</table>
Light Curve with Effects of Meridian Flip Detrended
Exoplanet Observing vs. Deep Sky Imaging

• Where Exoplanet Observing is more stringent:
  o Calibration (with darks, flats) a necessity
  o Consideration for atmospheric extinction
  o Accurate polar alignment and guiding
  o Appropriate image scale (i.e., arc-seconds/pixel)
  o Choice of filter
  o Necessity to stay within CCD linearity (to avoid saturation of Host Star)
  o Choice of aperture and annulus radii

• Where Exoplanet Observing is less stringent:
  o Less sensitive to light pollution, moon light, and scintillation
  o In some cases, out-of-focus stars may be desirable
Science Contributions from Amateur Exoplanet Observations

• Can help confirm candidate planets (e.g., there are currently 3,704 unconfirmed Kepler candidates)

• Can refine transit times and depths of confirmed planets

• Can help determine Transit Time Variations that could indicate multi-planetary systems

• Can detect occurrences of host star events (e.g., “star spots”)

• Can collaborate with professional astronomers on specific exoplanet studies
Derivation of Exoplanet Properties Using Transit Method

From Transit Method Light Curves

Star Radius ($R_{AU}$)  Star Mass ($M_*$)  Transit Depth ($d_{flux}$)  Exoplanet Orbital Period ($p_{days}$)  Transit Duration ($t$)

Exoplanet Radius ($r_{au} = R_{au} \times d_{flux}$)

Exoplanet Orbital Radius

Kepler's Third Law

\[ a_{au} = \sqrt[3]{M_\ast \frac{p_{days}^2}{365^2}} \]

Angular displacement of transit

Distance of transit across star surface

Exoplanet Orbit Inclination ($i$)
Derivation of Additional Exoplanet Properties Using Radial Velocity Method

Radial Velocity Method

- Measure Radial Velocity ($V_{m/s}$)
- Exoplanet Orbital Period ($p_{days}$)
- Exoplanet Mass (see Notes)

From Transit Method:

- Exoplanet Orbit Inclination ($i$)
- Exoplanet Radius ($r_{au}$)

**Exoplanet Mass (see Notes)**
$$m_p = V_{m/s} p_{days}^{1/3} M_\star^{2/3} / (28.4 \sin(i))$$

**Notes:** Assumes $m_p \ll M_\star$ and orbit is circular; $m_p$ is in units relative to $M_{\text{jupiter}}$

**Exoplanet Density**
$$\rho = m_p / r_{au}$$