The Role of Amateur Astronomers in Exoplanet Research

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Overview

• Contributions To-Date
• Technical Capabilities and Techniques Used
• HST Collaboration
• Lessons Learned
• Direct Exoplanet Detection and Imaging
• What the Future Holds
Background

• Amateur astronomers primarily use the transit method

• Some successful attempts at RV measurements (to 50m/sec) and microlensing observations

• Direct imaging currently not possible due to seeing and diffraction limiting factors

• Observations also include other “exo-objects” – e.g., disintegrating planetesimals (WD-1145)
Contributions To-Date

• Confirm new exoplanets – the KELT program

• Refine the ephemeris of known exoplanets – an HST collaboration

• Help extend the baseline of tertiary eclipse models by conducting Eclipse Timing Variations (ETVs)

• Conduct private surveys
Capabilities
Observations

• Transit depths detectable to 2 mmag (>10 mmag more typical)

• Alternating use of filters to distinguish eclipsing binaries from exoplanets

• Simultaneous observations can better refine ephemeris

• Same equipment used for deep sky imaging can easily be adapted to exoplanet observing
World-Wide Network of Observers
Typical Setup
Location: Suburban Annapolis, MD
Techniques

• High precision, differential photometry employed

• Demands uniform flat-fielding, precise guiding, and accurate timing

• All-in-one software (AstroImageJ) can be used for calibration, differential photometry and transit modeling
WASP-12b on UT2016-01-06

Conti (V, 45 sec)

- rel_flux_T1 (normalized)
  - rel_flux_T1 Transit Model (P=1.09, (R_p/R*)^2=0.0127, a/R*=3.2, i=90.0, T_c=2457393.601228, [u1=0.39], [u2=0.3])
  - rel_flux_T1 Residuals (RMS=0.00397) (chi^2/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)
- top_C_cnts (arbitrarily scaled and shifted)

Barycentric Julian Date (TDB) - 2457393 (mid-exposure)
WD-1145+017 Observations

Courtesy of Mario Motta
HST Collaboration

• Purpose of HST program #14260:

“Using the water molecule as a probe, we will investigate the degree to which planetary envelopes are enriched in heavy elements as a function of planetary mass, and how that enrichment might be affected by mass loss.

We will define the degree to which clouds occur in exoplanetary atmospheres, over a wide range in temperature, surface gravity, and stellar irradiation.”

• Drake Deming is PI, along with several co-investigator’s

• 15 exoplanets being observed, some multiple times

• HST’s WFC3/IR camera used
Status

- HST has completed 20 of 23 visits
- Role of amateur astronomers is to help refine ephemeris
- Over 60 high-quality, ground-based observations have been made to-date
- A “Practical Guide to Exoplanet Observing” developed—provides best practices and a tutorial on AstroImageJ
Pipeline

• An updated, prioritized list of targets is regularly posted

• Observers post light curves and initial modeling results

• Promising observations are re-reduced in a standard way, using the original images, and a transit model fit is performed; $\text{BJD}_{\text{TDB}}$ time base used

• If the re-reduction looks good, results are scheduled for inclusion in a global fit

• A global fit, with best detrend parameters, is conducted for both circular and eccentric orbits
Sample Global Fit Output

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### TABLE 3

**Median values and 68% confidence interval** for the physical and orbital parameters of the WASP-76b system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Adopted Value (Torres circular)</th>
<th>Value (Torres eccentric)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stellar Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_*$</td>
<td>Mass ($M_\odot$)</td>
<td>$1.370^{+0.072}_{-0.067}$</td>
<td>$1.389^{+0.069}_{-0.069}$</td>
</tr>
<tr>
<td>$R_*$</td>
<td>Radius ($R_\odot$)</td>
<td>$1.693^{+0.33}_{-0.31}$</td>
<td>$1.682^{+0.30}_{-0.30}$</td>
</tr>
<tr>
<td>$L_*$</td>
<td>Luminosity ($L_\odot$)</td>
<td>$4.10^{+0.32}_{-0.31}$</td>
<td>$4.03^{+0.33}_{-0.33}$</td>
</tr>
<tr>
<td>$\rho_*$</td>
<td>Density (cgs)</td>
<td>$0.3998^{+0.043}_{-0.042}$</td>
<td>$0.406^{+0.046}_{-0.046}$</td>
</tr>
<tr>
<td>log $g_*$</td>
<td>Surface gravity (cgs)</td>
<td>$4.117^{+0.099}_{-0.098}$</td>
<td>$4.129^{+0.096}_{-0.096}$</td>
</tr>
<tr>
<td>$T_{\text{eff}}$</td>
<td>Effective temperature (K)</td>
<td>$6315^{+194}_{-94}$</td>
<td>$6313^{+93}_{-93}$</td>
</tr>
<tr>
<td>[Fe/H]</td>
<td>Metallicity</td>
<td>$0.202^{+0.056}_{-0.056}$</td>
<td>$0.206^{+0.056}_{-0.056}$</td>
</tr>
<tr>
<td><strong>Planet Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e$</td>
<td>Eccentricity</td>
<td>$0.0124^{+0.013}_{-0.0086}$</td>
<td>$0.0154^{+0.013}_{-0.0086}$</td>
</tr>
<tr>
<td>$\omega_*$</td>
<td>Argument of periastron (degrees)</td>
<td>$-51^{+1}_{-72}$</td>
<td>$-51^{+1}_{-72}$</td>
</tr>
<tr>
<td>$P_*$</td>
<td>Period (days)</td>
<td>$1.80988211^{+0.000000069}_{-0.000000069}$</td>
<td>$1.80988245^{+0.000000068}_{-0.000000068}$</td>
</tr>
<tr>
<td>$a_*$</td>
<td>Semi-major axis (AU)</td>
<td>$0.0328^{+0.0055}_{-0.0055}$</td>
<td>$0.0329^{+0.0054}_{-0.0054}$</td>
</tr>
<tr>
<td>$M_P$</td>
<td>Mass ($M_\oplus$)</td>
<td>$0.873^{+0.038}_{-0.038}$</td>
<td>$0.893^{+0.034}_{-0.034}$</td>
</tr>
<tr>
<td>$R_P$</td>
<td>Radius ($R_\oplus$)</td>
<td>$1.669^{+0.033}_{-0.033}$</td>
<td>$1.656^{+0.040}_{-0.040}$</td>
</tr>
<tr>
<td>$\rho_P$</td>
<td>Density (cgs)</td>
<td>$0.233^{+0.009}_{-0.009}$</td>
<td>$0.244^{+0.016}_{-0.016}$</td>
</tr>
<tr>
<td>log $g_P$</td>
<td>Surface gravity</td>
<td>$2.890^{+0.013}_{-0.013}$</td>
<td>$2.906^{+0.016}_{-0.016}$</td>
</tr>
<tr>
<td>$T_{eq}$</td>
<td>Equilibrium temperature (K)</td>
<td>$2205^{+33}_{-32}$</td>
<td>$2197^{+35}_{-35}$</td>
</tr>
<tr>
<td>$\Theta_*$</td>
<td>Safronov number</td>
<td>$0.02463^{+0.00075}_{-0.00075}$</td>
<td>$0.02539^{+0.00078}_{-0.00078}$</td>
</tr>
<tr>
<td>$(F)$</td>
<td>Incident flux ($10^9$ erg s$^{-1}$ cm$^{-2}$)</td>
<td>$5.36^{+0.31}_{-0.31}$</td>
<td>$5.29^{+0.33}_{-0.33}$</td>
</tr>
<tr>
<td><strong>RV Parameters</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_C$</td>
<td>Time of inferior conjunction (BJD$_{TDB}$)</td>
<td>$2457059.85251^{+0.00026}_{-0.00026}$</td>
<td>$2457059.85240^{+0.00027}_{-0.00027}$</td>
</tr>
<tr>
<td>$T_P$</td>
<td>Time of periastron (BJD$_{TDB}$)</td>
<td>$111.0^{+2.8}_{-2.8}$</td>
<td>$120.7^{+2.1}_{-2.1}$</td>
</tr>
<tr>
<td>$K$</td>
<td>RV semi-amplitude (m/s)</td>
<td>$0.872^{+0.038}_{-0.038}$</td>
<td>$0.892^{+0.035}_{-0.035}$</td>
</tr>
<tr>
<td>$M_P \sin i$</td>
<td>Minimum mass ($M_\oplus$)</td>
<td>$0.000608^{+0.000018}_{-0.000018}$</td>
<td>$0.000629^{+0.000018}_{-0.000018}$</td>
</tr>
<tr>
<td>$w$</td>
<td>RM linear limb darkening</td>
<td>$-1074^{+29}_{-29}$</td>
<td>$-1081^{+13}_{-13}$</td>
</tr>
<tr>
<td>$\gamma_{CORALIE}$</td>
<td>m/s</td>
<td>$-1047^{+38}_{-38}$</td>
<td>$-1057^{+17}_{-17}$</td>
</tr>
<tr>
<td>$\gamma_{SPHIE}$</td>
<td>m/s</td>
<td>$0.021^{+0.032}_{-0.032}$</td>
<td>$0.013^{+0.014}_{-0.014}$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td></td>
<td>$0.0038^{+0.010}_{-0.010}$</td>
<td>$0.0039^{+0.010}_{-0.010}$</td>
</tr>
<tr>
<td>Linear Ephemeris from Follow-up</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P_{\text{Trans}}$</td>
<td>Period (days)</td>
<td>$1.8098821^{+0.0000007}_{-0.0000007}$</td>
<td>$1.8098821^{+0.0000007}_{-0.0000007}$</td>
</tr>
<tr>
<td>$T_0$</td>
<td>Linear ephemeris from transits (BJD$_{TDB}$)</td>
<td>$2457059.85259^{+0.000267}_{-0.000267}$</td>
<td>$2457059.85259^{+0.000267}_{-0.000267}$</td>
</tr>
</tbody>
</table>

(cont’d)
Key Lessons Learned

• Need way to scale initial qualification and follow-up reduction to support large scale future surveys (e.g., TESS, JWST)

• Need better training tools to push quality closer to original observers

• Need a database to store and later retrieve light curve data
Direct Detection and Imaging: Challenges and Potential Solutions
Will Amateur Astronomers be able to directly detect exoplanets?

Proxima Centauri
(4.2 ly’s)

1 AU

0.77 arcseconds

Earth
Challenges

• Seeing limitations: atmospheric turbulence makes it difficult to differentiate both sources
  - (typical amateur astronomer seeing: 2-3 arcseconds)

• Diffraction limitations: the wave nature of light produces an Airy disc pattern for both point sources
  - (Rayleigh criterion for a 14” aperture: 0.46 arcseconds)

• Differential magnitude limitations: the extreme differences in magnitude between both objects makes it difficult to collect photons for the reflected light from the planet
Possible Solutions

• Seeing limitations: speckle interferometry

• Diffraction limitations: shaped aperture masks

• Differential magnitude limitations: charge injection devices
The Future

• The need for follow-up observations will continue to grow with upcoming space-based surveys (TESS, JWST)

• Contribute to TTV timings of hot Jupiters with close-in companions (see Becker, et al., 2015)

• The AAVSO is developing a repository for amateur astronomer exoplanet observations

• Amateur astronomers continue to explore techniques for direct exoplanet imaging/detection

• Observatories at educational institutions offer another source of exoplanet observations: just need training and coordination
Summary

• A network of amateur astronomers is available to the professional community for conducting transit observations

• Benefits:
  – the global network maximizes temporal and sky coverage
  – different campaigns can be quickly supported
  – simultaneous observations of a given target can be scheduled – mitigates weather issues and allows for comparative observations with different filters
  – observing time is economical (free!)

• Amateur astronomers are available to test new direct imaging and detection techniques
Links

• www.astrodennis.com
  – “A Practical Guide to Exoplanet Observing”

• www.aavso.org/exoplanet-section