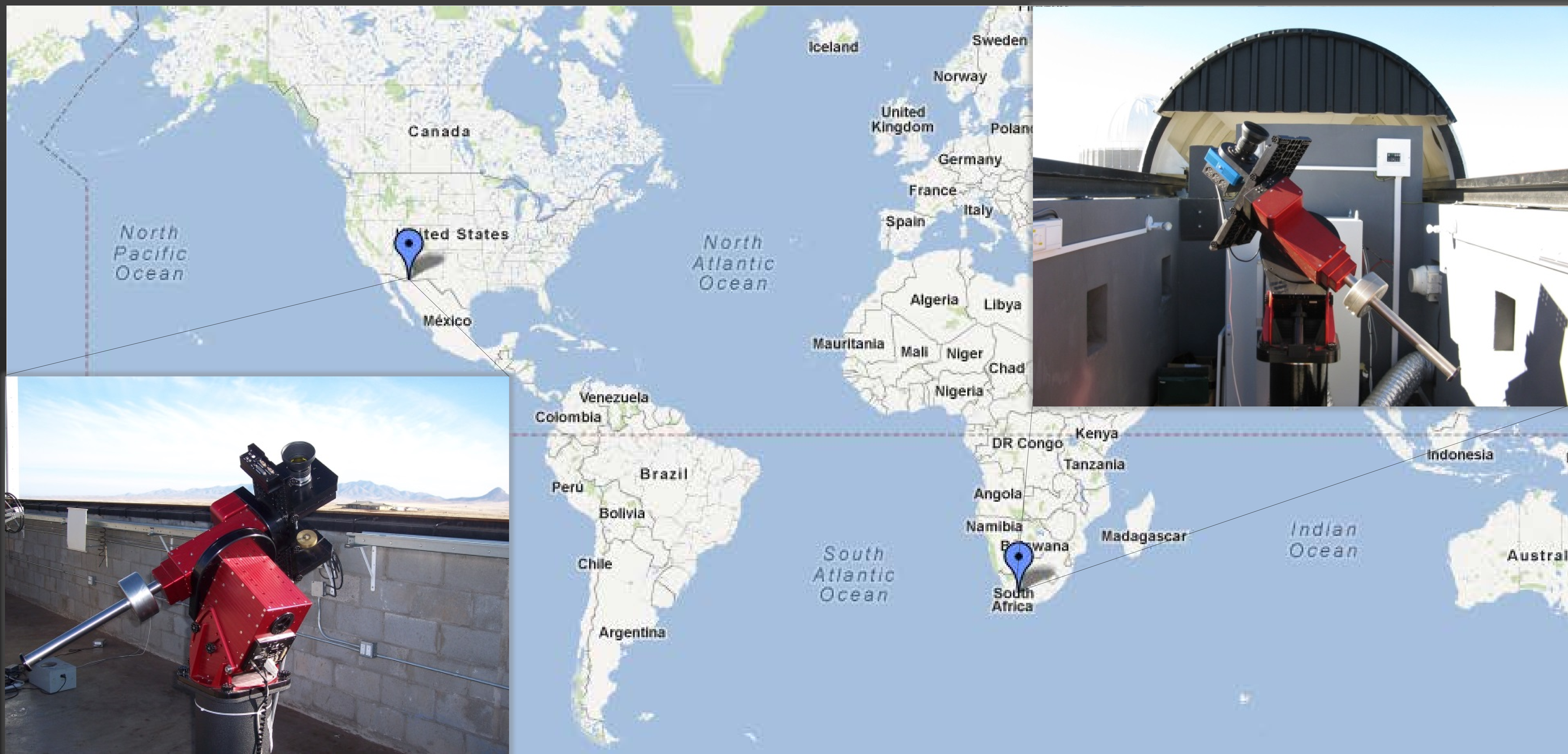
ADVANCED CCD PHOTOMETRY AND EXOPLANET TRANSIT PHOTOMETRY

By : Kenny A. Diaz Eguigure

KEL**T**: THE **K**ILODEGREE **E**XTREMELY **L**ITTLE **T**ELESCOPE



Robotic Survey for Transiting Exoplanets

KELT-North

Deployed 2005 to Winter Observatory, AZ

Operated by Lehigh, Ohio State and Vanderbilt

KELT-South

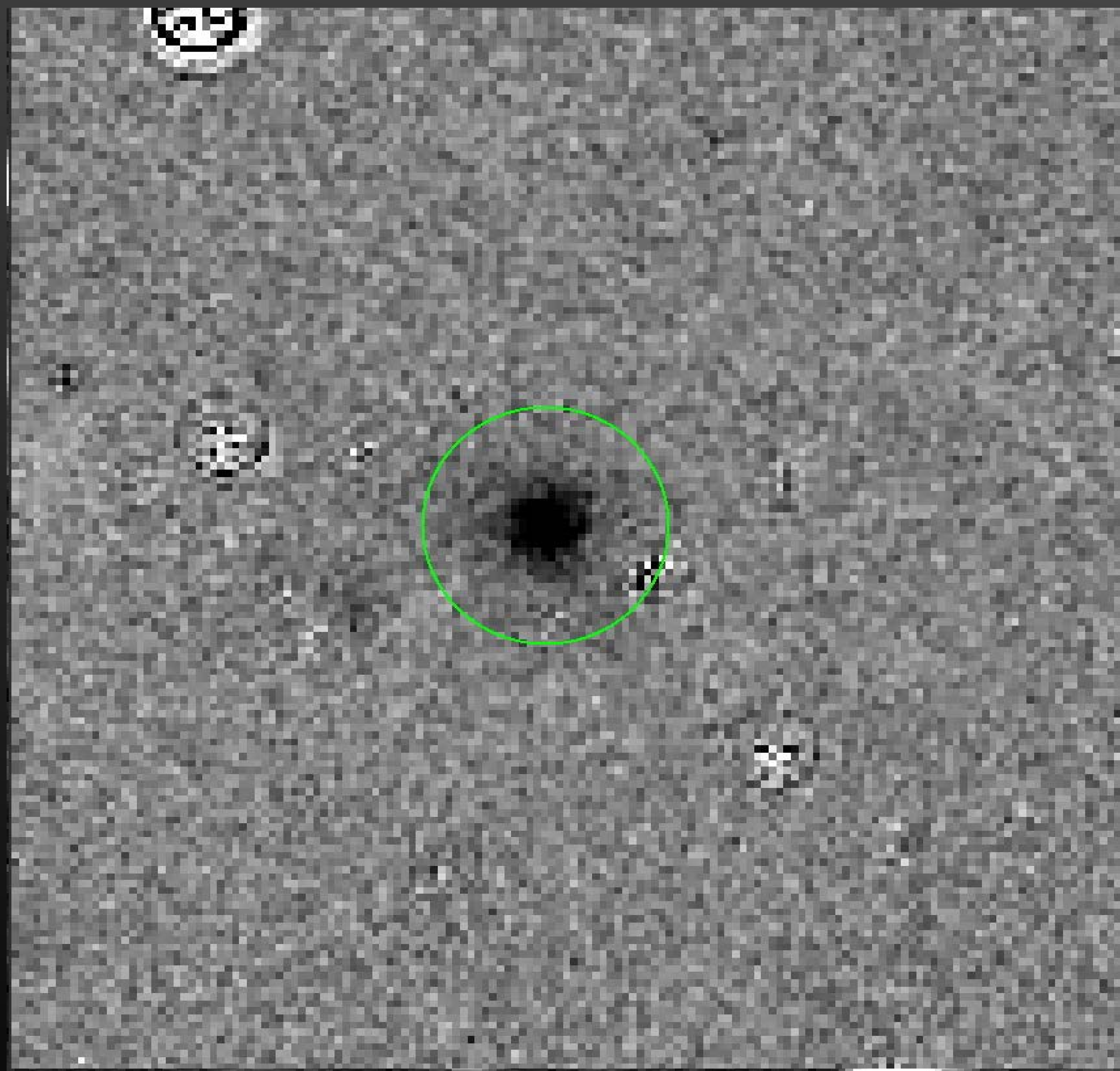
Deployed 2009 to Sutherland, South Africa

Operated by Lehigh, Vanderbilt, Fisk, and the University of Cape Town

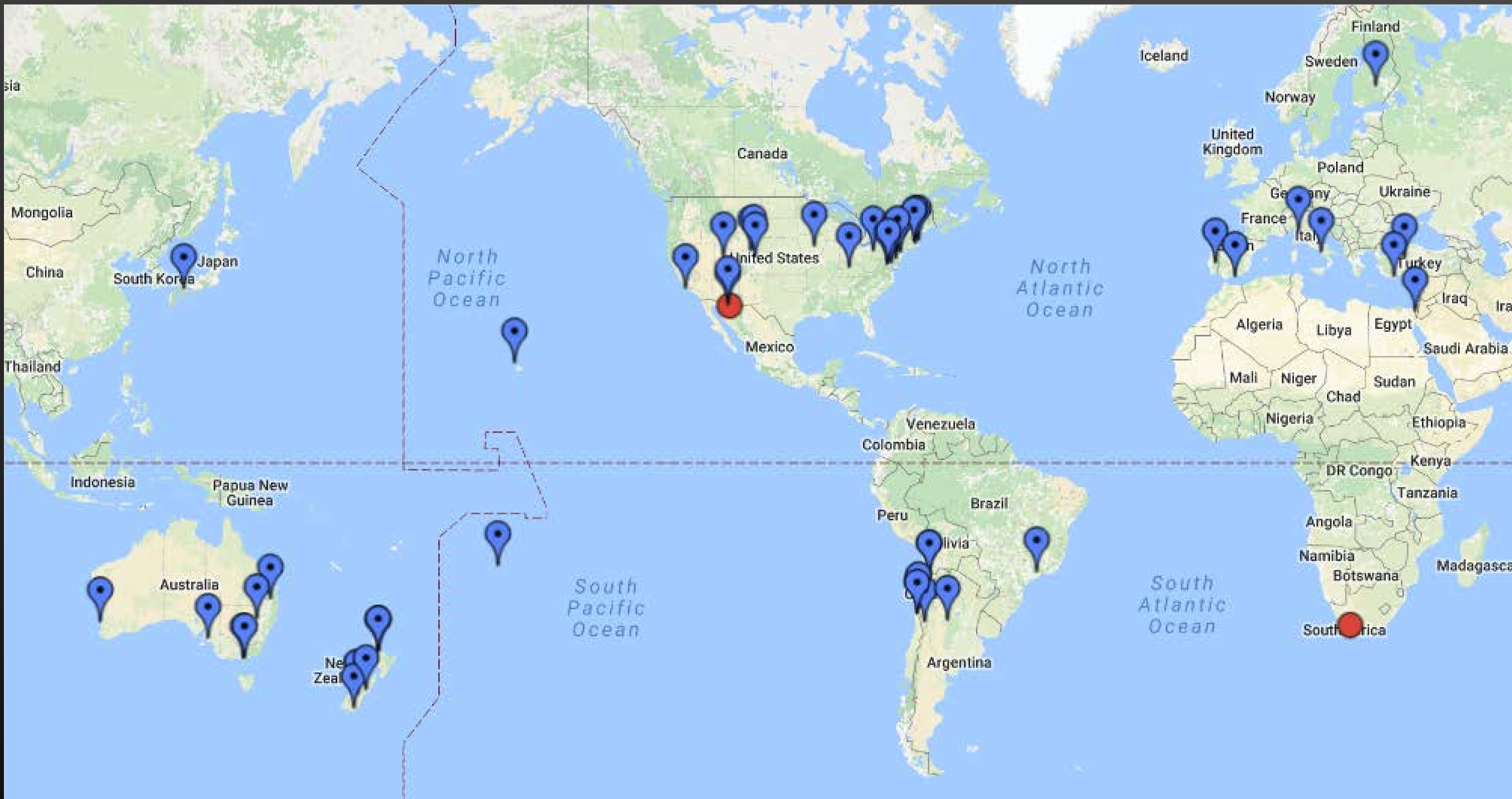
KELT: THE KILODEGREE EXTREMELY LITTLE TELESCOPE

- 2 Fully Robotic telescopes
- 4k x 4k CCD, 9 micron pixels
- 4.5 cm aperture
- 26 x 26 degree field of view
- $60,000 per telescope

DIFFERENCE IMAGE SUBTRACTION



KELT FOLLOW-UP COLLABORATORS

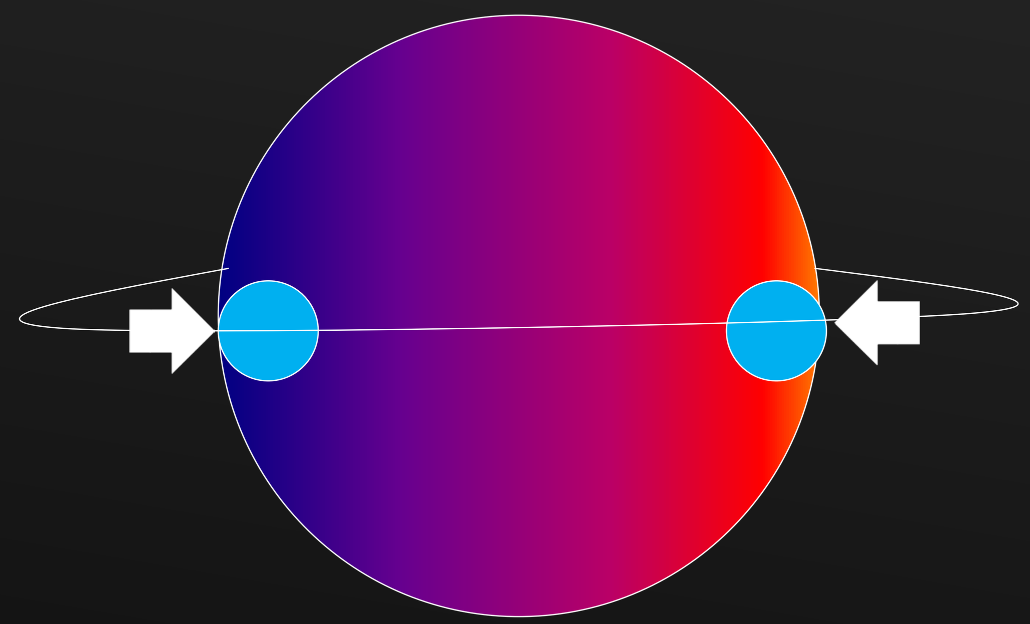


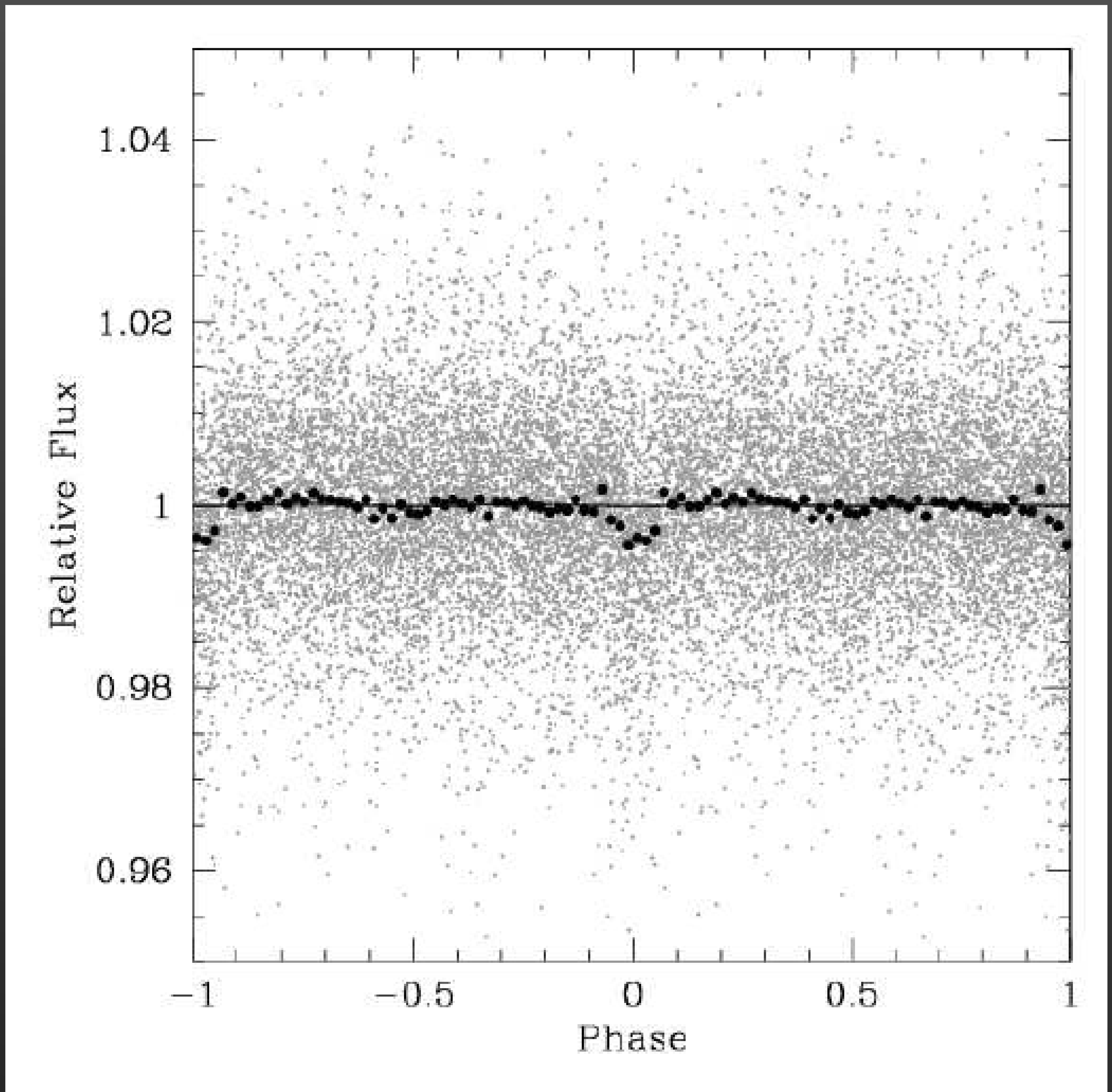
Small Colleges
Amateur Astronomers

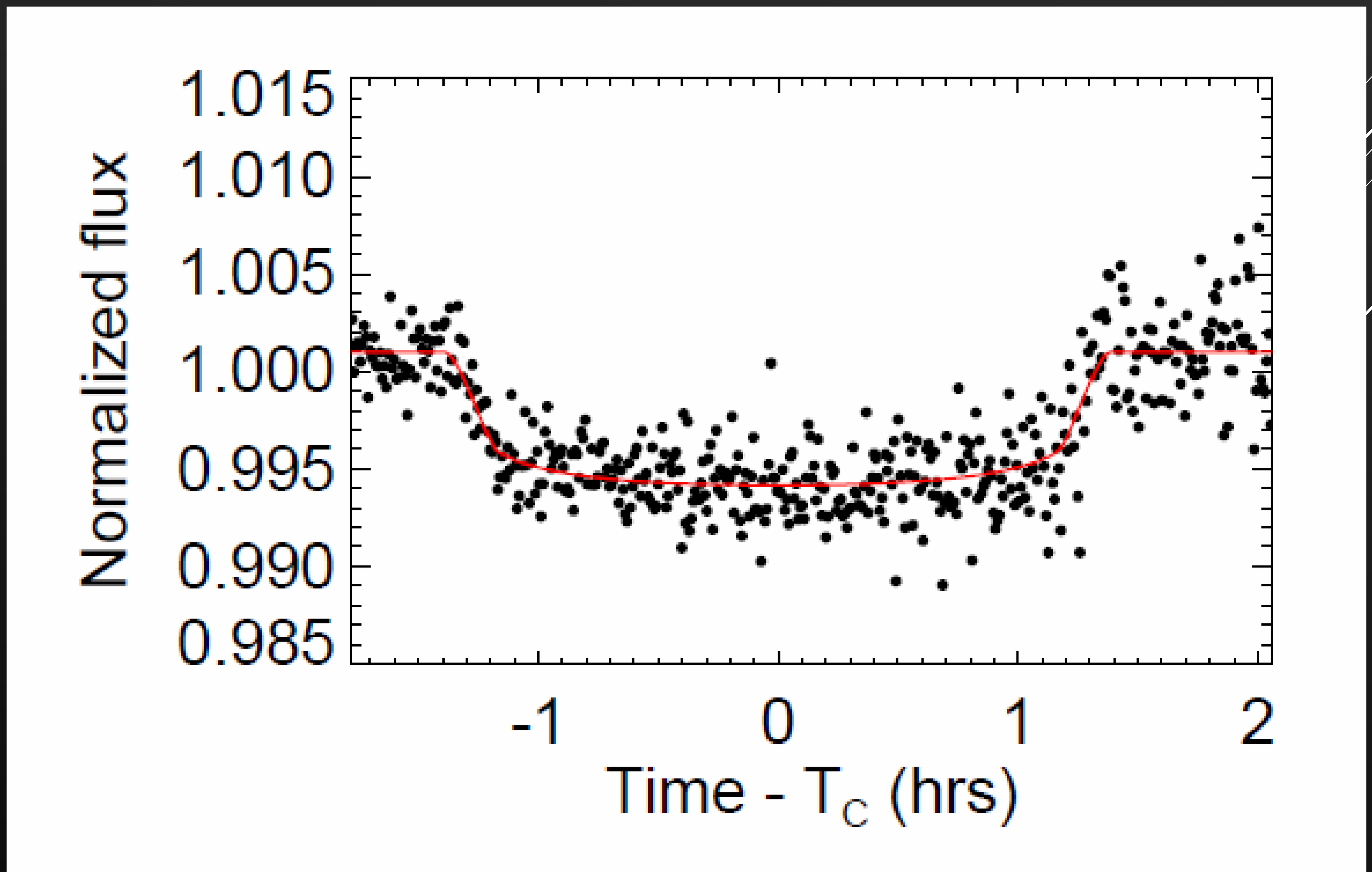
10-in to 32-in telescopes

KELT EXOPLANET DISCOVERIES

KELT-1b – A transiting brown dwarf

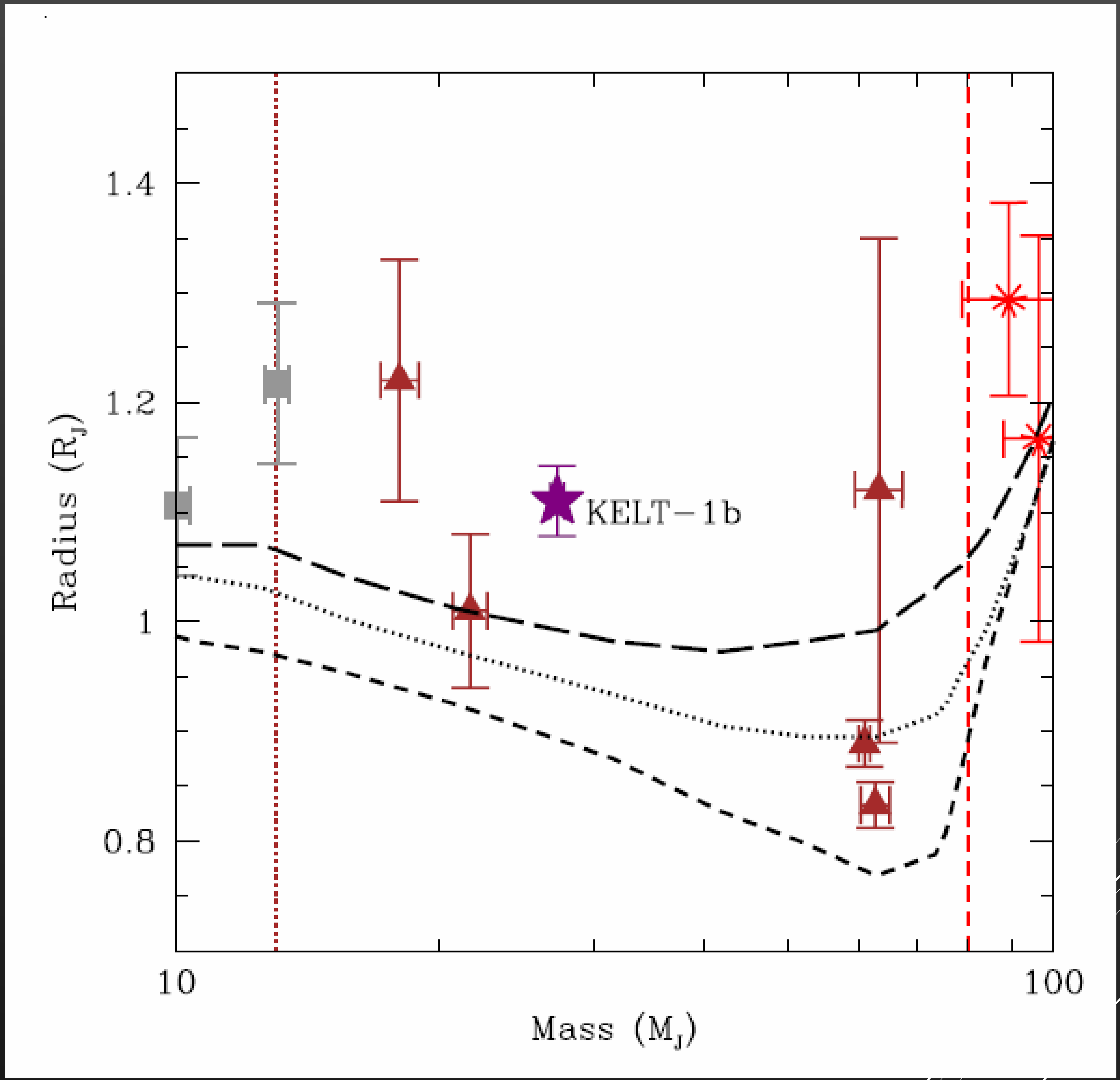






KELT-1b – A transiting brown dwarf

Host star – Bright (V=10.7) mid-F star
Brown Dwarf – 27 M_J companion in a 1.22-day orbit

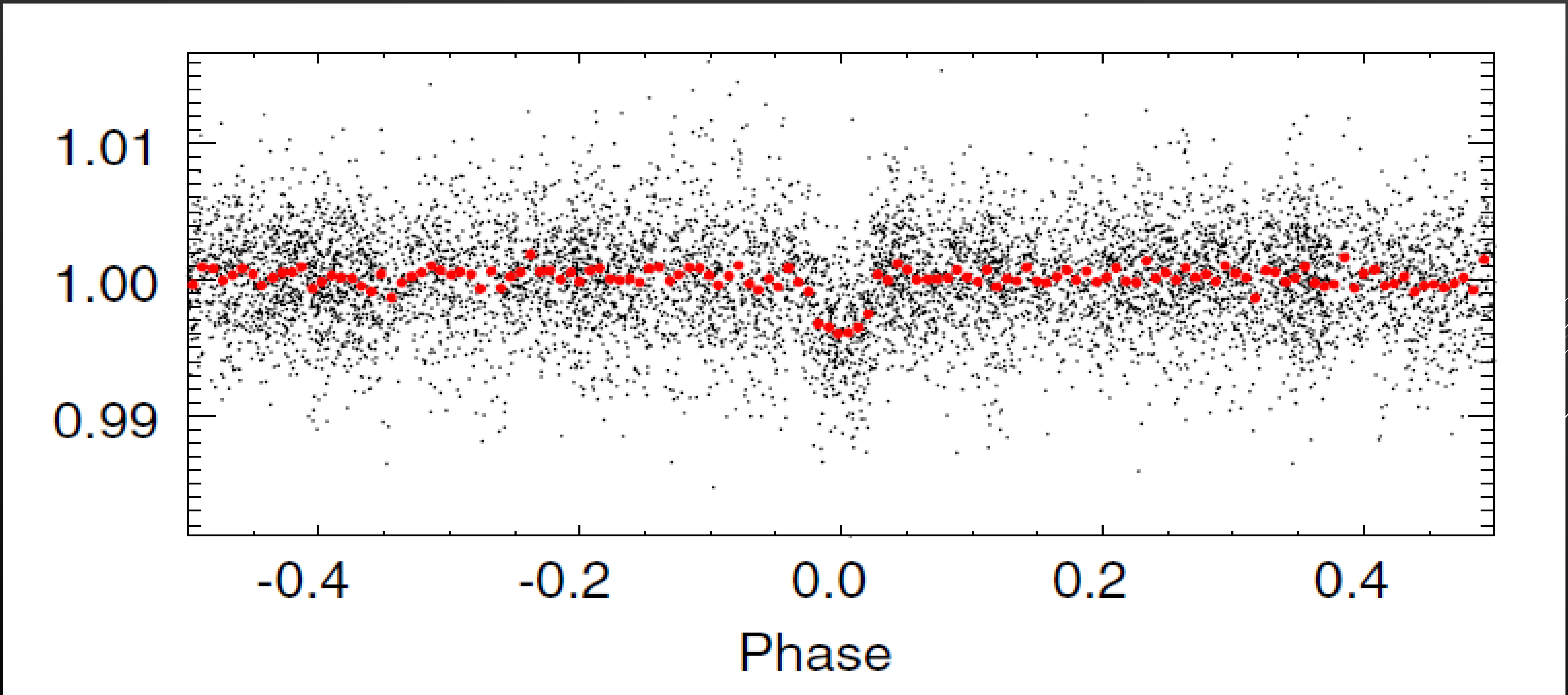


KELT-2Ab – A planet in a binary star system

Host star – V=8.77, late-F star

Planet – 1.52 M_J, 1.29 R_J in a 4.11-day orbit

Best age-dating for any extrasolar planet: age = 3.968 ± 0.010 Gyr



Precision CCD Photometry for Detection of Transiting Exoplanets

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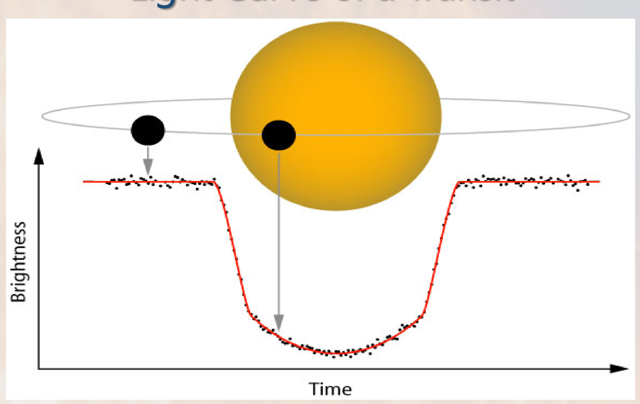
Introduction

Advanced CCD photometry[5] is a technique in modern astronomy that deals with the measurement of the change in luminous flux or the intensity of the electromagnetic radiation of an astronomical object. CCD photometry is one of the most fundamental techniques and innovative research tools used today by modern astronomers. It is also an area where valuable contributions can be made by students and amateur astronomers alike for the search for new exoplanets.

Light Curve of a Transit



This image shows a example of a light curve made from an exoplanet transit against brightness and time.

Purpose

- Develop advanced techniques of precision CCD photometry for a more accurate collection of stellar light data from an exoplanet transit.
- Integration of a precise auto-guidance system and guiding software.
- Collaborate with the Kilodegree Extremely Little Telescope (KELT) photometric survey for transiting exoplanets and the KELT Follow-Up team[4] on the search of new "Hot - Jupiter" on stars with an apparent visual magnitude of 8 to 11.

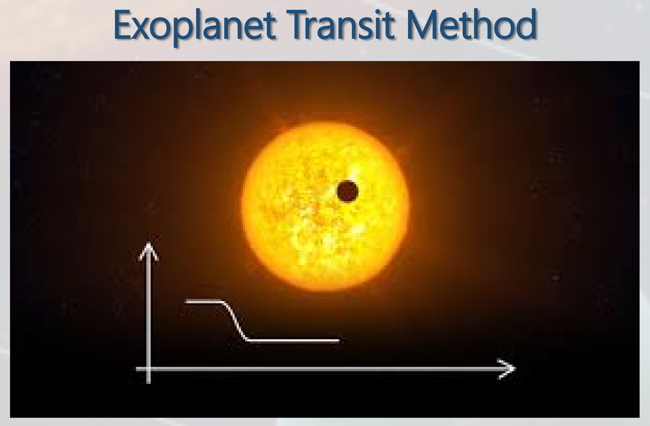
Analysis

During a three - month observation period (September - November 2016), all stellar light data collected from four KELT - Targets were calibrated and analyzed with AstroImagej[1] (AIJ). AIJ is an astronomical imaging software that brings a specific environment of astronomical tools for the reduction, analysis, detrending, modeling and plotting data. Although AIJ is a general purpose software, it is streamline for the time series of differential photometry, detrending and curve-fitting light.

Transit Method Photometry

The transit method[5] is based on the stellar light observation of a star's small drop in brightness that occurs when the orbit of one of the star's exoplanets passes ('transits') in front of the star
The amount of light lost (typically between 0.01% and 1%) depends on the sizes of the star and the exoplanet; and the duration of the transit depends on the exoplanet's distance from the star and the star's mass.

Exoplanet Transit Method

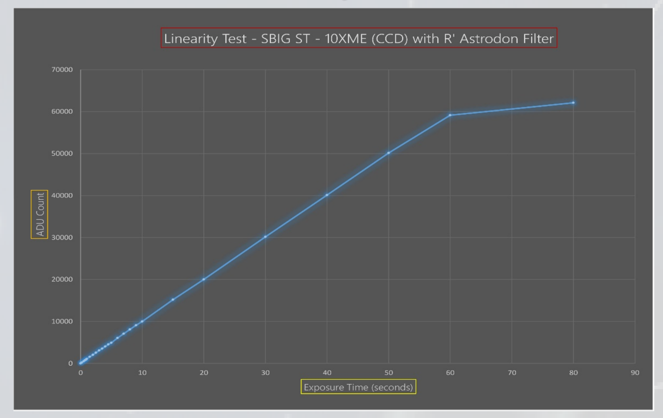


Animation by ESO.org
youtu.be/FLq8CJ5HQwE

Advanced CCD Photometry Techniques

Linearity Test: This graph shows the calibration test of the SBIG ST – 10XME CCD sensor through a Sloan r' filter. This test determines how the sensor responds to varying light levels. over. A CCD sensor should respond in a linear fashion all of the way up to the maximum well depth but does not. This test shows where the point of saturation and overexposure of an image begins to and allow us to plan exposure lengths accordingly.

Linearity Test

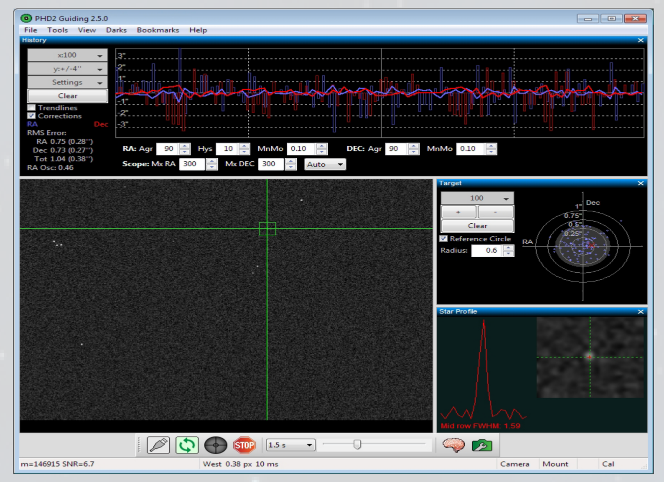


AAVSO Guide to CCD Photometry

Auto - Guiding System: This image shows how PHD2 telescope guiding software assists and simplifies the process of tracking a guide star, letting the observer concentrate on other aspects of deep-sky imaging or photometry.

- Software analyzes the tracking errors of the equatorial mount.
- Sends calibrated guide commands back to the mount to correct the Declination and Right Ascension tracking errors.
  - Keeps target centered which simplifies later processing.
  - Allows for longer exposures with no star trailing.

PHD2 Guiding Screen

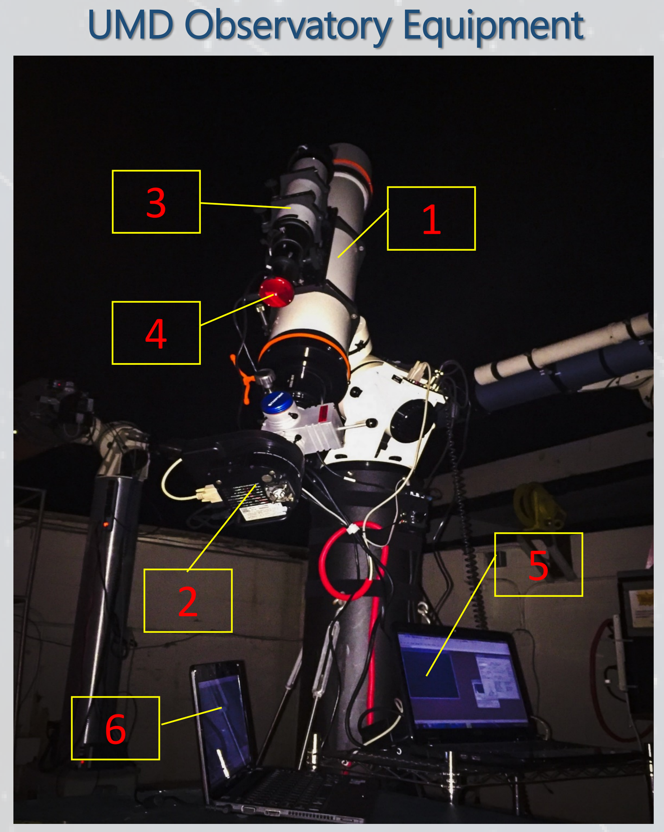


www.stark-labs.com/phdguiding.html

Optical Equipment:

1. 6" (152mm) Astro-Physics Refracting telescope.
2. SBIG ST – 10XME CCD camera with Sloan r' filter.
3. 80mm Stellarvue SV80/9D guide scope.
4. ZWO 120MM CMOS sensor guide camera.
5. Main computer with Maxlm DL imaging software.
6. Secondary computer with PHD2 guiding software.

UMD Observatory Equipment



www.astro.umd.edu/openhouse/

Acknowledgment

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- Elizabeth Warner, Principal Faculty Specialist and Observatory Director at Department of Astronomy, University of Maryland College Park.
- All members of the KELT Team.

Results of KEBC04C000694 (KELT Target)

From September - November 2016, three KELT targets (stars) were successfully observed. The data from those observations was calibrated and analyzed using AstroImageJ[1]. The results were submitted to and accepted by the KELT-North Team for further analysis in order to differentiate between Eclipsing Binary Star Systems and Exoplanets Transits. The following is a sample of the analyzed data from KEBC04C000694 sent to KELT - North Team.

Image A: This image shows a calibrated frame of KELT target KEBC04C000694 [T1] being analyzed against 9 comparison stars on a field of view of 8.1 arc-minutes on November 17, 2016.

Image B: This zoomed - in calibrated frame of KELT target KEBC04C000694 [T1] shows the object aperture and annulus rings (green circles). The brightness measurement is made by taking the brightness in the inner circle and subtracting the brightness in the outer rings.

Image A

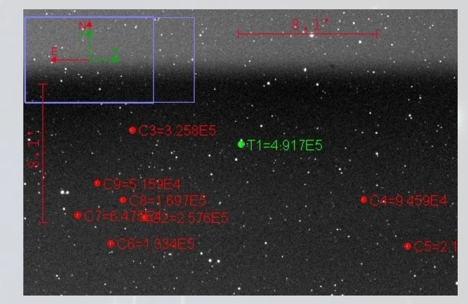
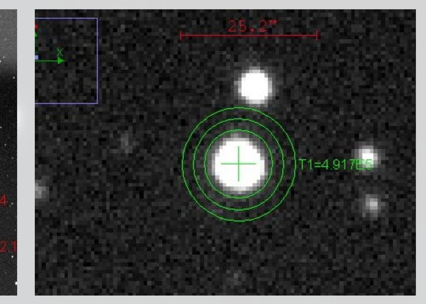


Image B



Graph:

- Shows a 1% drop in brightness of stellar light of KEBC04C000694 during its transit.
- Relative flux changed from 1.01 $Wm^{-2}m^{-1}$ to 0.98 $Wm^{-2}m^{-1}$ over a period of 5.00 hrs.
- Predicted 2.47 (days) period light curve (red) and a 3.00 (days) period light curve (green).
- Target [T1] star and comparison [C2 and C3] stars were AIRMASS detrended for differential photometry analysis.
- Graph displays 265 exposures at 45.0 (seconds) each.

Advanced Photometric Graph of KEBC04C000694

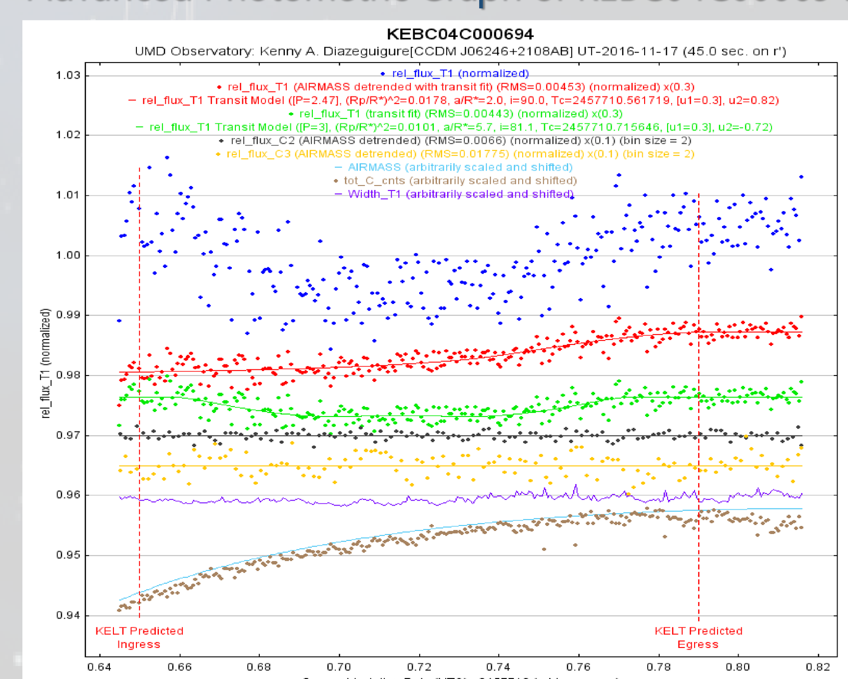
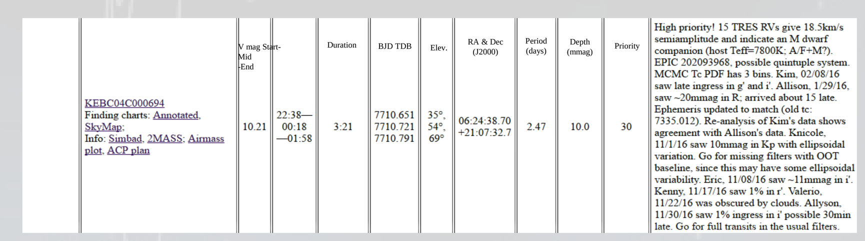


Image C: This image shows the results of observations made of KELT target KEBC04C000694 by the KELT follow-up team. Results were summarized in the comments section for the target on the website maintained by the KELT Team at the Department of Astronomy at Ohio State University.



		V mag	Start-Mid -End	Duration	BJD TDB	Elev.	RA & Dec (J2000)	Period (days)	Depth (mmag)	Priority	
	KEBC04C000694 Finding charts: Annotated, SkyMap; Info: Simbad, 2MASS; Airmass plot, ACP plan	10.21	22:38—00:18—01:58	3:21	7710.651 7710.721 7710.791	35°, 54°, 69°	06:24:38.70 +21:07:32.7	2.47	10.0	30	High priority! 15 TRES RVs give 18.5km/s semiamplitude and indicate an M dwarf companion (host Teff=7800K; A/F+M?). EPIC 202093968, possible quintuple system. MCMC Tc PDF has 3 bins. Kim, 02/08/16 saw late ingress in g' and i'. Allison, 1/29/16, saw ~20mmag in R; arrived about 15 late. Ephemeris updated to match (old tc: 7335.012). Re-analysis of Kim's data shows agreement with Allison's data. Knicole, 11/1/16 saw 10mmag in Kp with ellipsoidal variation. Go for missing filters with OOT baseline, since this may have some ellipsoidal variability. Eric, 11/08/16 saw ~11mmag in i'. Kenny, 11/17/16 saw 1% in r'. Valerio, 11/22/16 was obscured by clouds. Allyson, 11/30/16 saw 1% ingress in i' possible 30min late. Go for full transits in the usual filters.

Conclusion

- Precision transit photometry searches can operate on a massive scale from ground based telescopes.
- Auto guiding is crucial for this type of photometry.
- Understanding the hardware characteristics and the software functionality are critical to properly interpreting the results.

References

1. "AstroImageJ (AIJ) - ImageJ for astronomy." n.d. Web. 11 Aug. 2016.
2. "CCD Photometry guide." 9 Aug. 2014. Web. 11 Aug. 2016.
3. Conti, Dennis. Exoplanet observing. 2016. Web. 11 Aug. 2016.
4. "KELT-North transit survey." n.d. Web. 11 Aug. 2016.
5. "Transit Photometry." The Planetary Society Blog. N.p., n.d. Web. 11 Aug. 2016.

College of Computer, Mathematical, & Natural Sciences

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KELT North