The O’Connell Effect in Eclipsing Binary Stars

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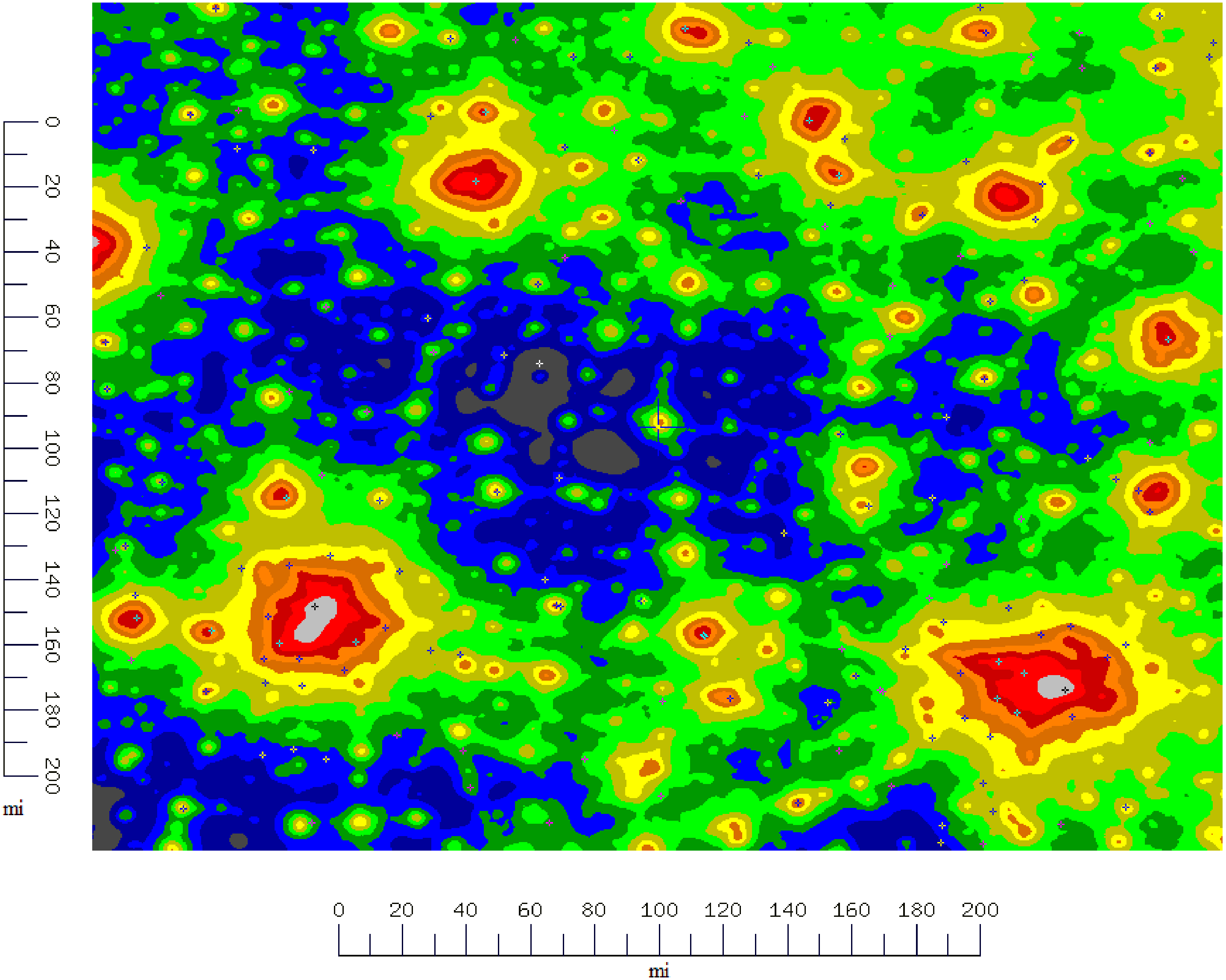
Truman State University

Outline of Talk

- Kirksville and Truman State University
- Astronomy & Astrophysics Research at Truman State
- Variable stars and eclipsing binary stars
- Differential Photometry
- Light Curve analysis and the O'Connell effect
- Opportunities presented by **survey missions** like Kepler
- DSLR Photometry
- **How you can contribute**

Truman State University
Kirksville, Missouri: “Missouri’s North Star”

Light Pollution Map



Color	Artificial / Natural Sky Brightness	Sky Brightness mags / sq arcsec V Band	Bortle Scale approx
	< 0.01	22.00 to 21.99	1
	0.01 to 0.06	21.99 to 21.93	2
	0.06 to 0.11	21.93 to 21.89	2
	0.11 to 0.19	21.89 to 21.81	3
	0.19 to 0.33	21.81 to 21.69	3
	0.33 to 0.58	21.69 to 21.51	4
	0.58 to 1.00	21.51 to 21.25	4
	1.00 to 1.73	21.25 to 20.91	4.5
	1.73 to 3.00	20.91 to 20.49	4.5
	3.00 to 5.20	20.49 to 20.02	5
	5.20 to 9.00	20.02 to 19.50	5

Image Credit: David Lorens (University of Wisconsin-Madison)

http://www.cleardarksky.com/

Truman State University

- Public liberal arts and science institution
- Undergraduate student population of about 6000
- Physics department has 7 permanent faculty members
- Around 10-15 physics graduates every year
- Our program offers BS and BA in physics and a physics minor.
  - <u>Astronomy minor</u> introduced last year (9 minors in two years + 6 enrolled)
  - <u>Astrobiology minor</u> to be introduced in Fall 2017

The Truman Observatory

- Three CCD cameras
- Several smaller 6 and 8 inch scopes
- Upgrade to 17-inch Planewave and Paramount (Summer 2016)
- NURO – 31 inch scope @ Lowell

14-inch Meade LX200GPS telescope

ST-8300 SBIG CCD camera

Astronomy & Astrophysics Research @ Truman State

Undergraduate Students

- Tyler Gardner, Gage Hahs (Phys): **Eclipsing Binary Stars**
- Charlyn Ortmann (Phys): **Astrobiology, EB stars**
- Nathan Scott, Nicole Fiore (Bio): **Astrobiology**
- Ingrid Roettgen (Comm), Steve Pankey (Phys), Eric Hilker (Bio): **Light Pollution**
- Kaila Lorenzen (MACC): **Light Pollution**

Funding: Missouri Space Grant Consortium (MOSGC), Missouri EPSCoR
Office of Student Research (OSR), Truman State University

Astronomy & Astrophysics

Research @ Truman State

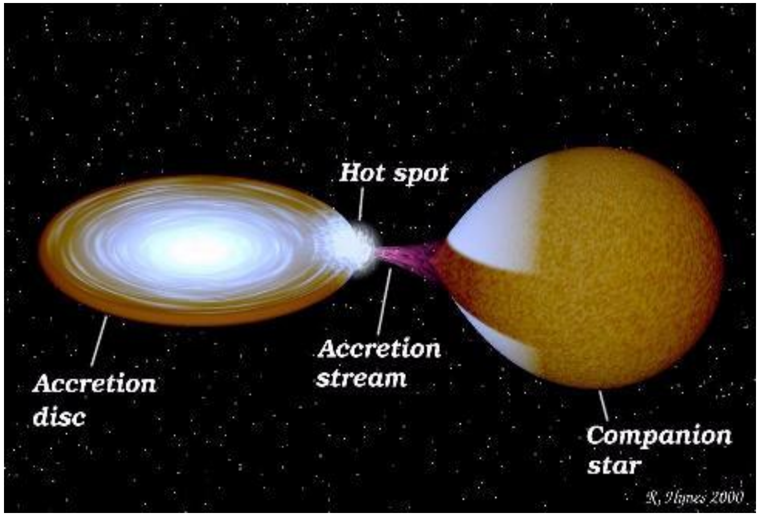
- Variable Stars
  - Eclipsing Binaries
  - δ-Scuti variables
- Exoplanet transits
- Light Pollution
- **DSLR Photometry**
- Binary Star Evolution
- Habitable Zones around Stars
- Astrobiology

Outreach

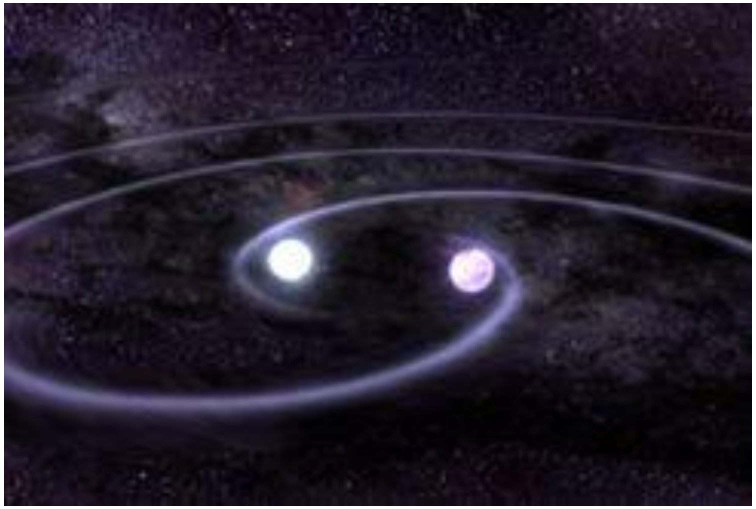
- ‘Stargazers’ student astronomy club
- 5-6 ‘open houses’ and special events per semester

Binary Stars: Why study them?

- Around 50% of stars in the Galaxy are thought to be part of a binary system.
- Determine masses of components
  - Radii can be determined for stars in eclipsing binaries
- Test the theory of stellar structure and stellar evolution
- Mass Transfer and accretion disks
- Study of compact objects
- **Star spots**



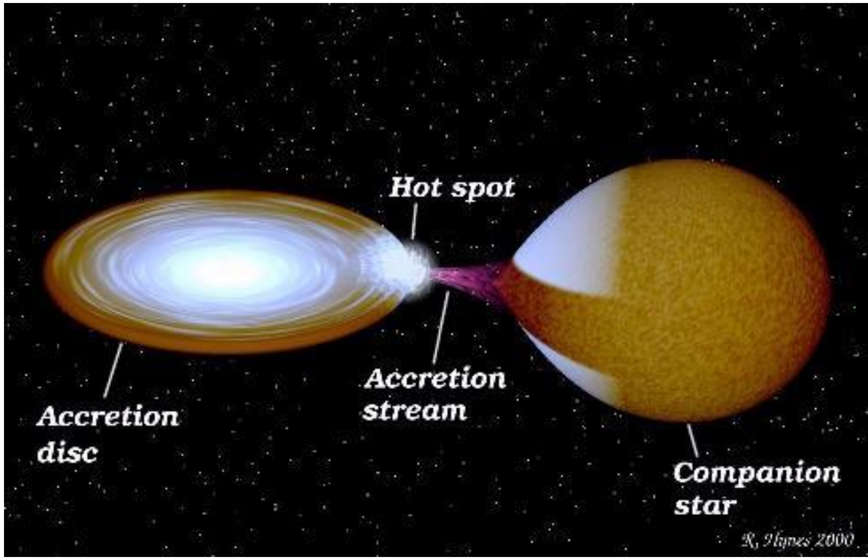
Picture Credit: Rob Hynes



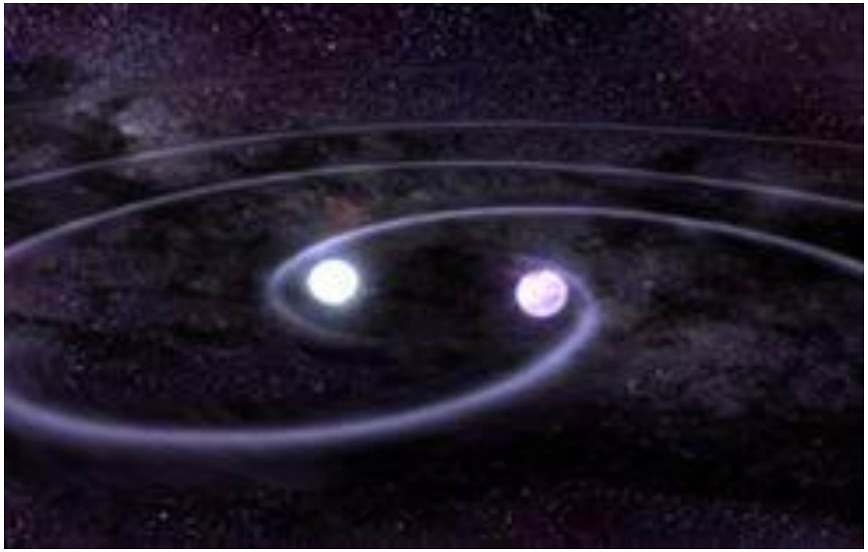
Picture Credit: Gavin Ramsay

Binary Stars: Why study them?

- Relatively easy way to introduce undergraduate majors and motivated high-school students to astronomy research.
- Relatively easy for amateur astronomers to meaningfully contribute to our collective scientific knowledge base.

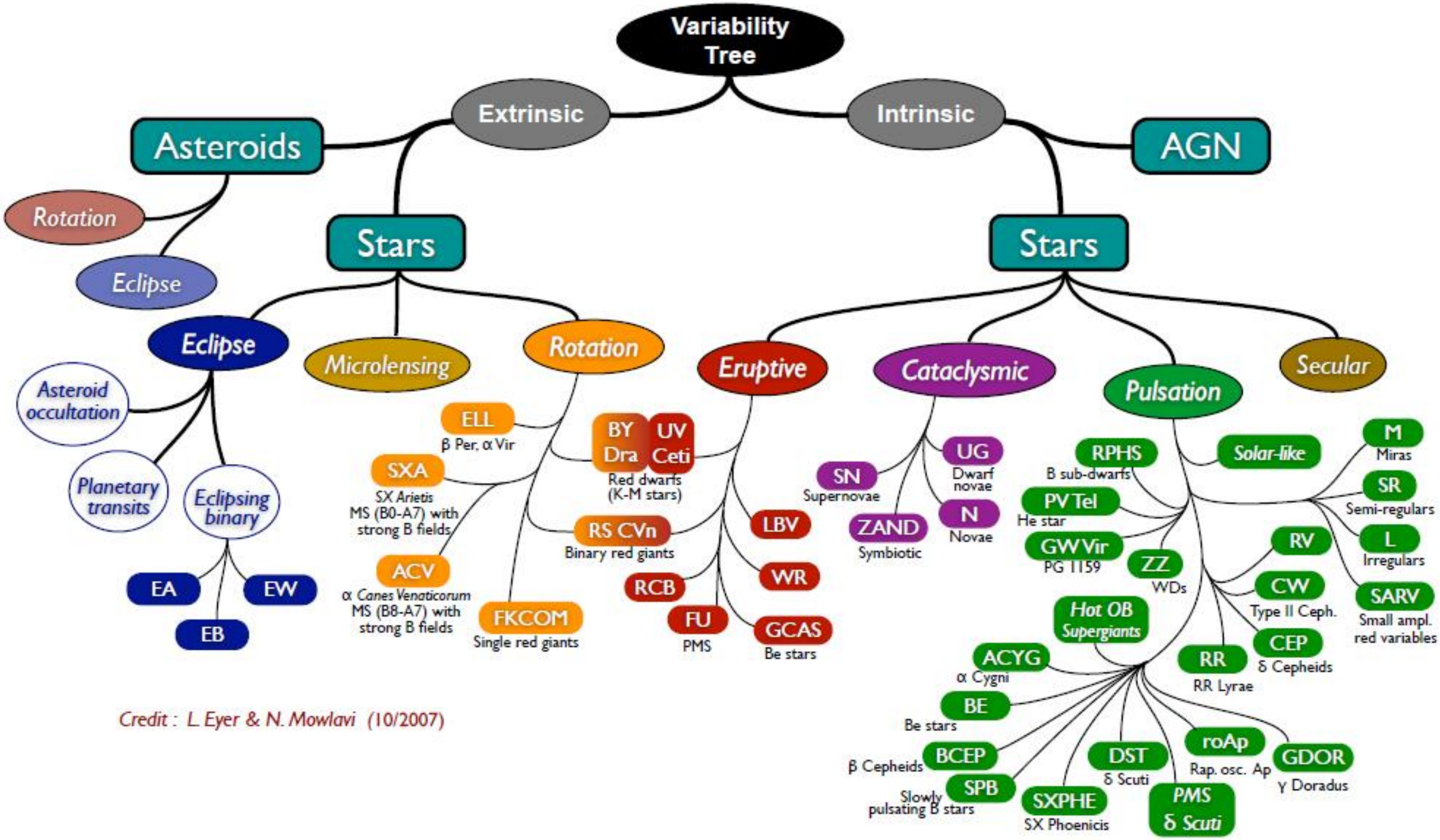


Picture Credit: Rob Hynes



Picture Credit: Gavin Ramsay

Variable Stars



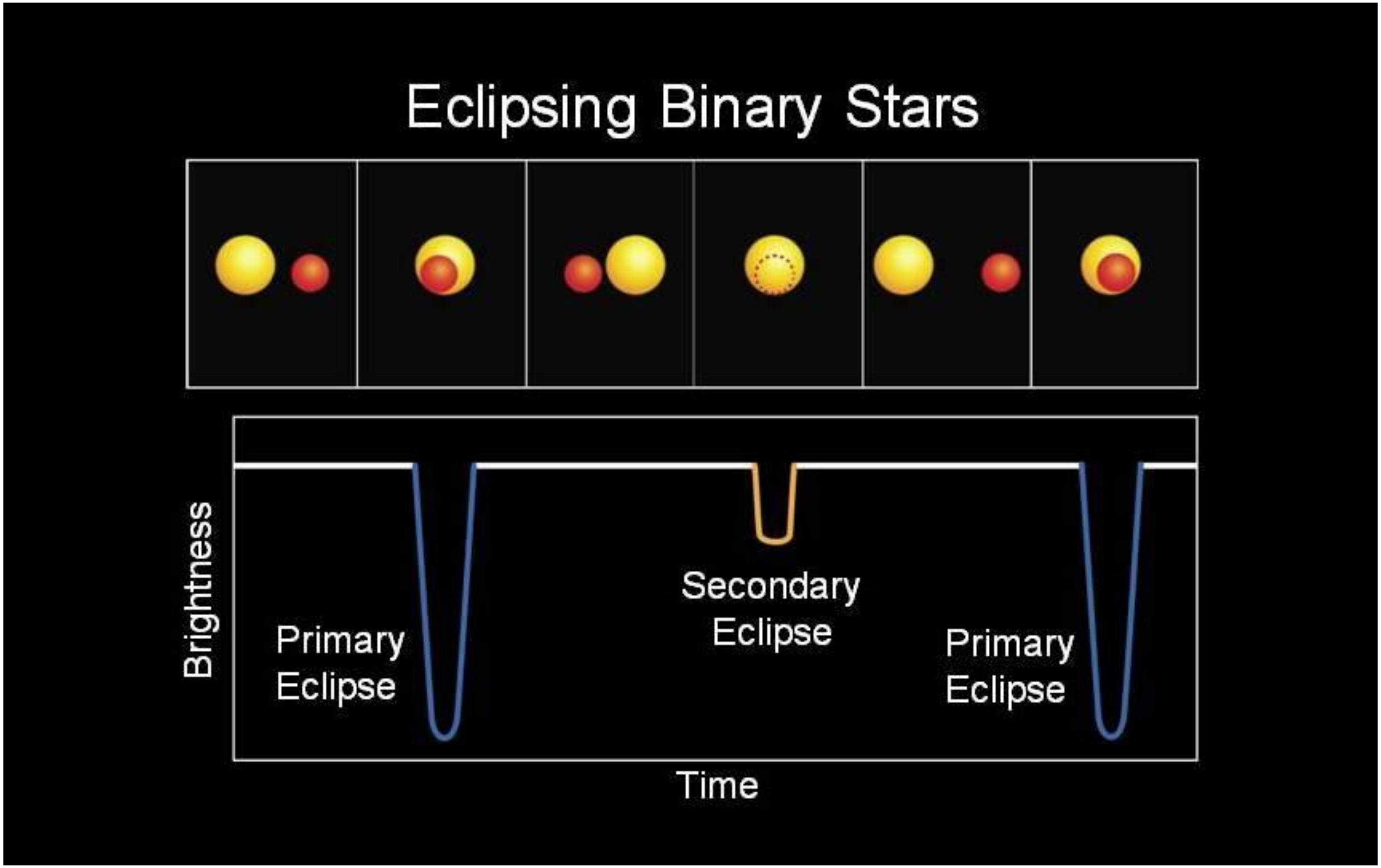
Credit : L Eyer & N. Mowlavi (10/2007)

Variable Stars: Types

- There are different ways to classify variable stars.
- One way is to classify them based on the reason for variability:
  - geometric variables,
  - pulsating variables and,
  - eruptive variables
- For our purposes the 'geometric variables' are Eclipsing Binary (**EB**) systems, though exoplanets and systems containing a disk or dust would also fall under this category.

http://astro.unl.edu/naap/ebs/animations/ebs.html

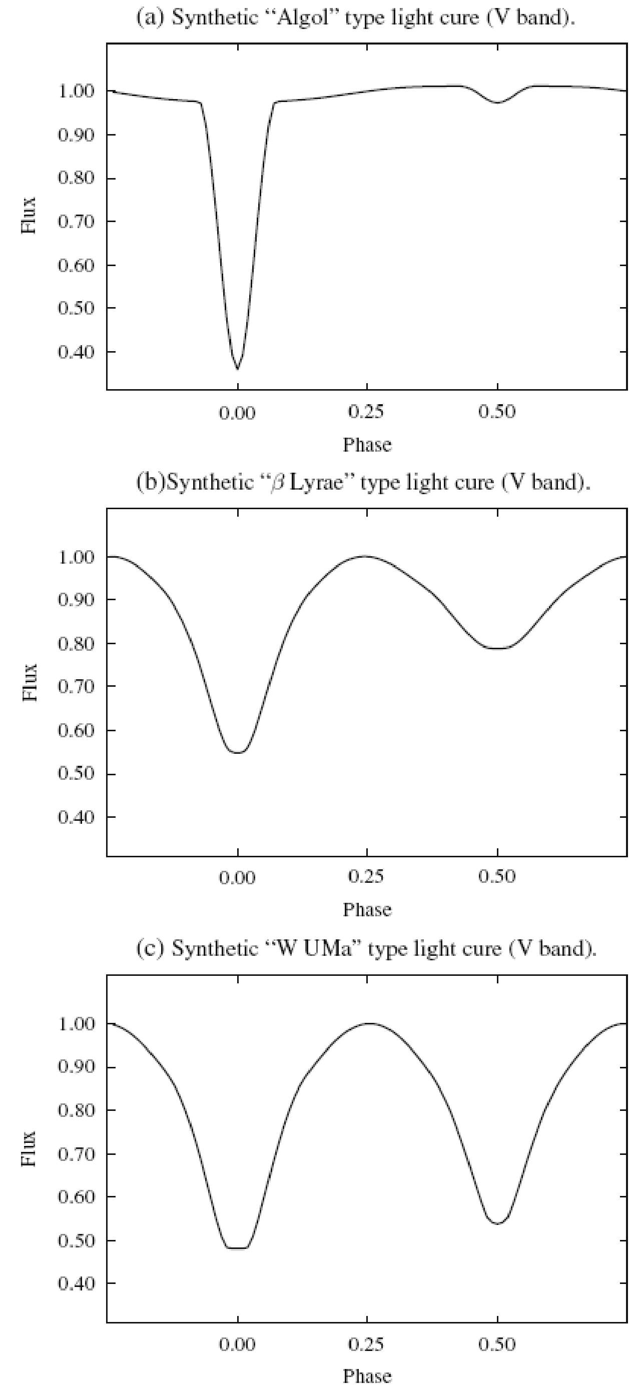
Eclipsing Binary Stars: What are they?



http://kepler.nasa.gov/

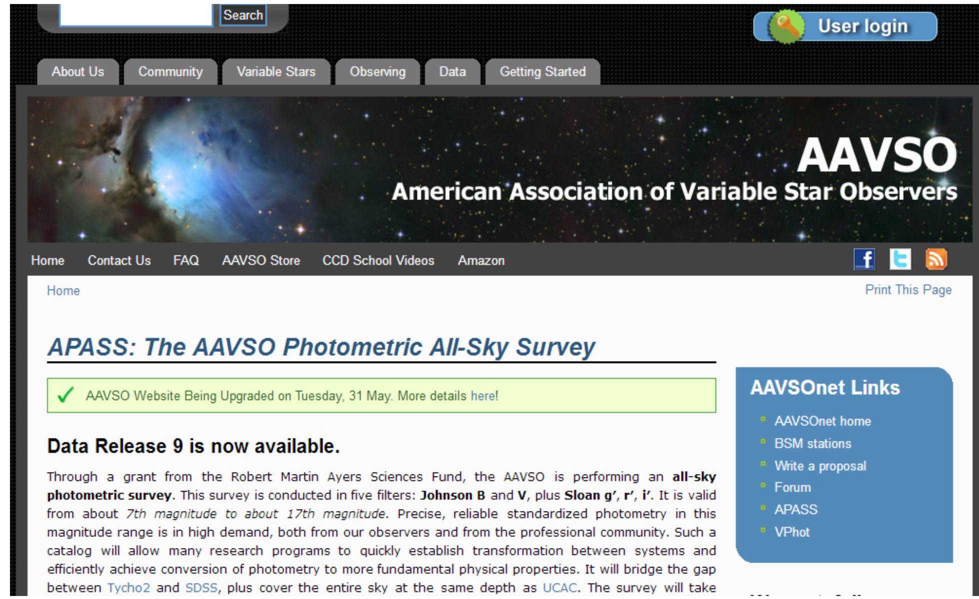
Types of EBs

- EA: Algol type variables
  - Clearly defined eclipses with a definite start and end point
- EB: β-Lyrae type variables
  - Clearly defined eclipses, but may show variations outside eclipse; mainly due to non-spherical nature of components
  - Depth of minima are significantly different
- EW: WUMa type variables
  - A continuously varying light curve with unclear ‘start’ and ‘end’ point for eclipses.
  - Both components are severely distorted from spherical shape.
  - Depth of minima are comparable



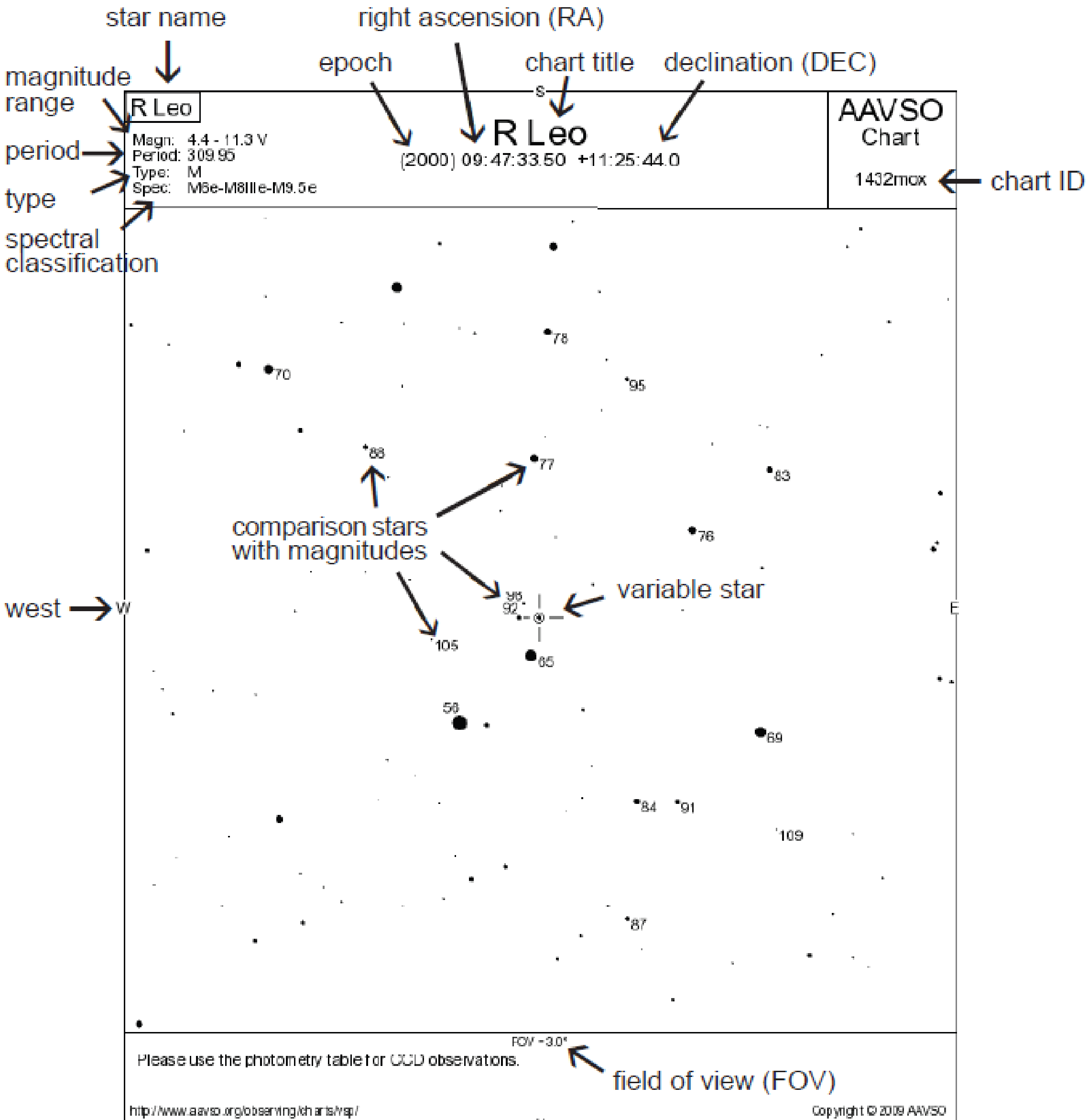
Eclipsing Binary Stars: Resources

- AAVSO *(aavso.org)*
  - VSP [Star Charts]
  - VPHOT [Photometry tool]
  - VSTAR [Light Curve plots]
  - APASS [Standard stars]



- University of Krakow EB Ephimeris *(http://www.as.up.krakow.pl/ephem/)*

Figure 2.2 — *Sample AAVSO star chart*



The Image taking process

- Telescope
  - Point to object
  - Track object with minimal drift
  - Focus object on focal plane
  - Collect photons
- CCD
  - Convert light into electric signal by releasing electrons
  - Proportionality between amount of current generated and incident light
  - Option for using different filters
  - CCD cooled to minimize thermal noise
- Computer/Software
  - Control telescope and CCD
  - Store images in an automated fashion
  - Image calibration and data analysis

Differential Photometry

Steps involved in Differential Photometry:

1. Check your images
2. Calibrate images (dark subtraction & flat fielding)
3. Identify the stars
4. Set the aperture
5. Choose check and comparison stars
6. Measure the magnitudes
7. Determine the uncertainty
8. Run photometry on time-series images
9. Generate Light Curves

Identifying Target (CoRoT 1b)

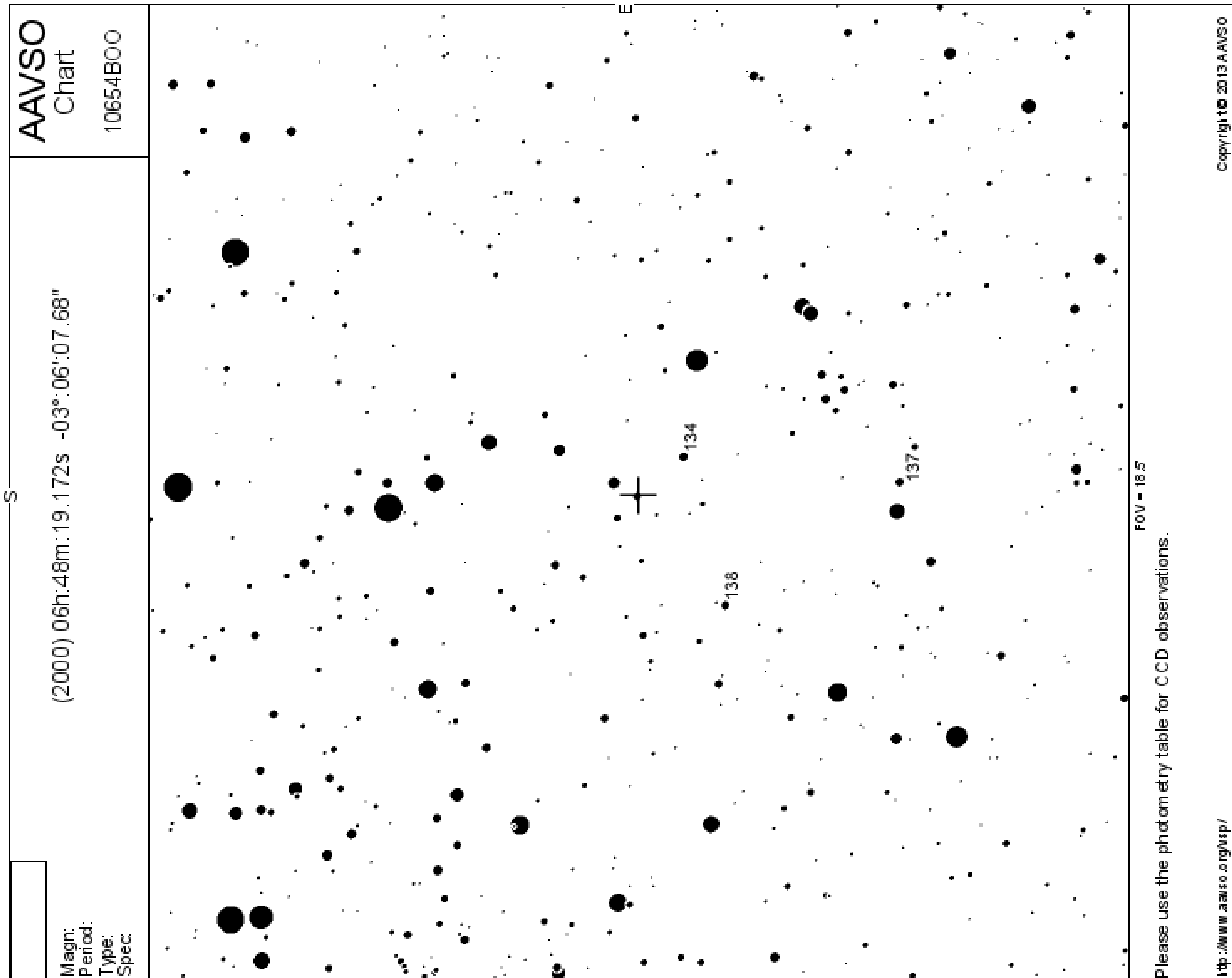
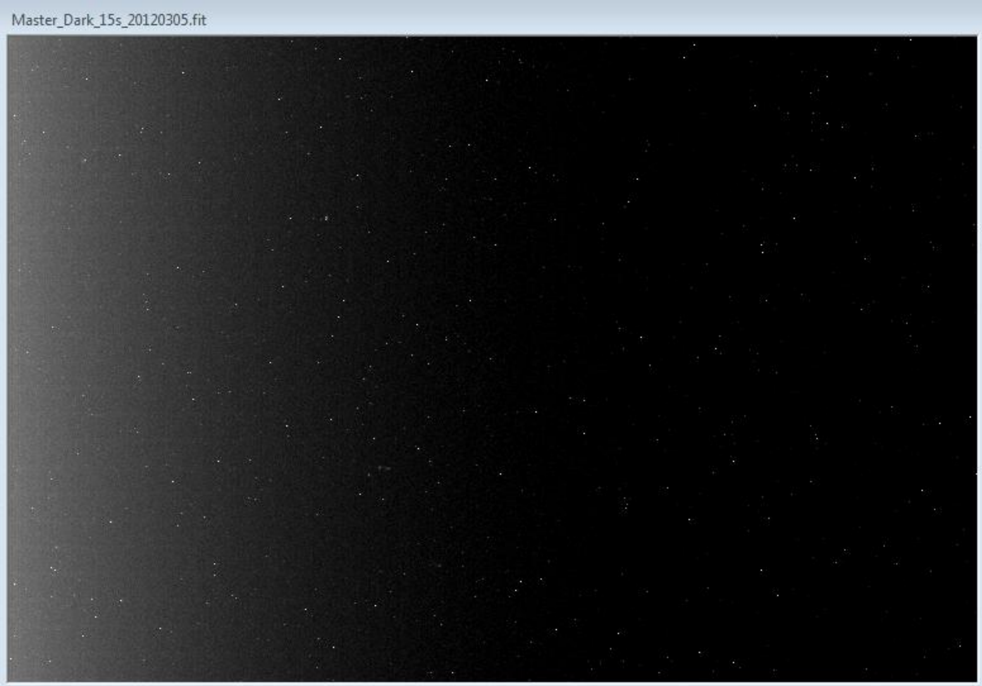


Image Processing

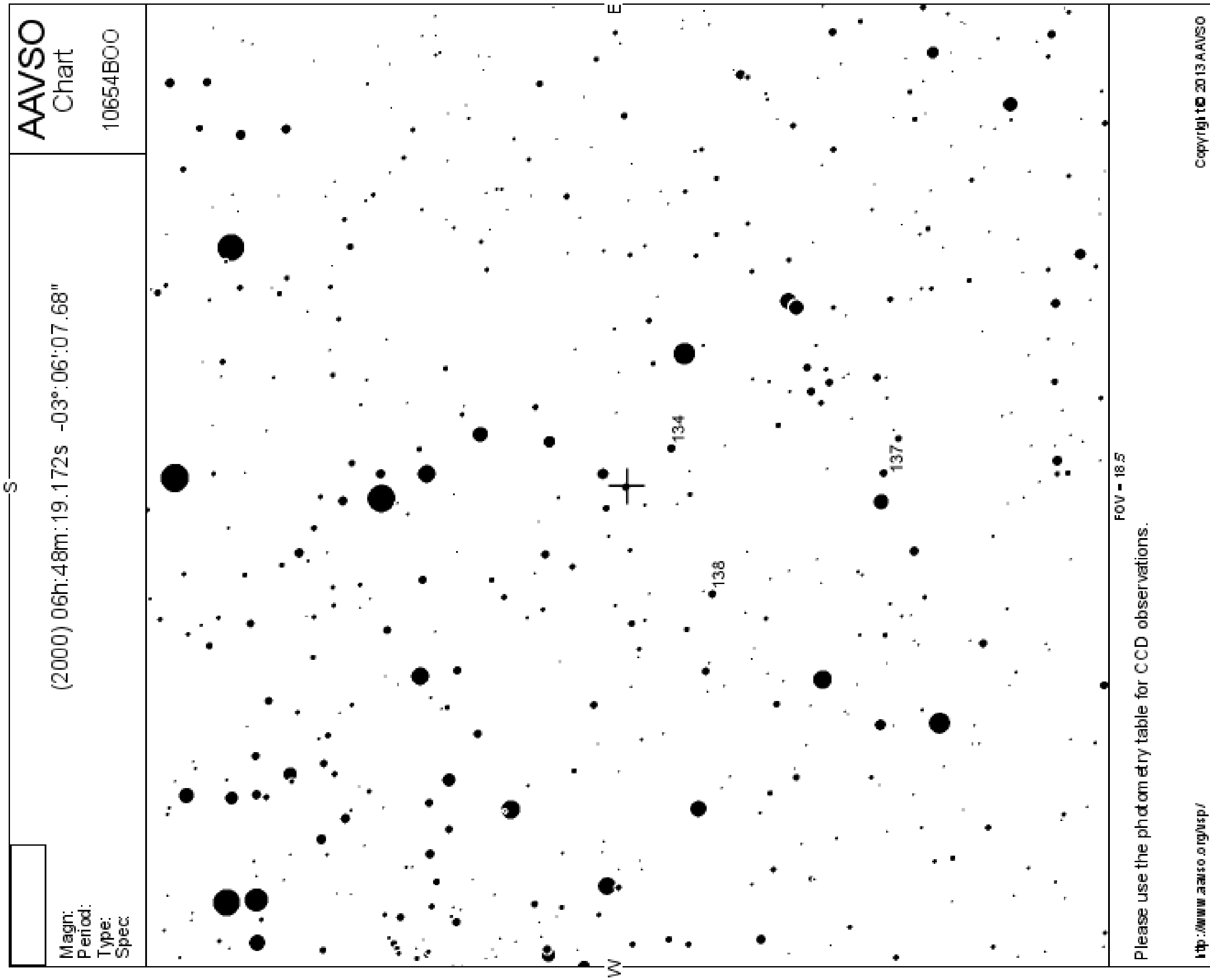


Dark Frame: Same exposure time as image

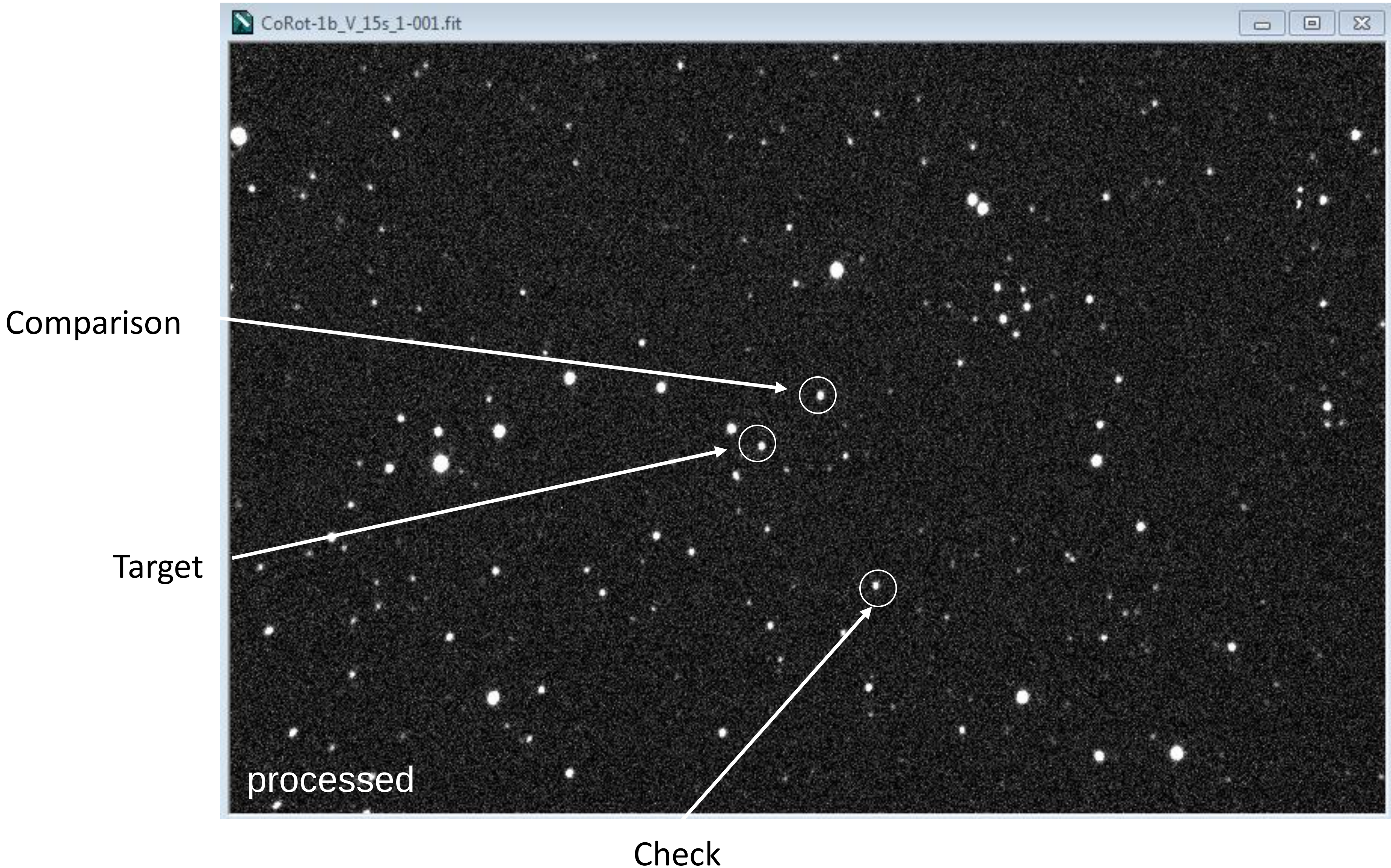
Flat Frame: Uniform illumination

Dark Subtraction & Flat Fielding

Identifying Target (CoRoT 1b)



Identifying Target



Target Stars (Gardner, Hahs, Gokhale, 2015)

Table 2. Target, comparison, and check star coordinates and comparison star B and V magnitudes.

Star Designation	*Position* R. A. (2000) *h m s*	Dec. (2000) *° ′ ″*	*V*	*B*
		Target Stars		
ASAS J105855+1722.2	10 58 55.05	+17 22 12.1	—	—
NSVS 5066754	13 20 57.77	+47 29 29.3	—	—
NSVS 9091101	00 22 43.44	+08 50 05.9	—	—
		Comparison Stars		
TYC 1429-165-1	10 58 57.953	+17 25 35.26	12.47	12.30
—	13 20 20.77	+47 33 42.2	12.541	13.388
—	00 22 16.12	+08 47 06.7	13.084	14.179
		Check Stars		
—	10 59 01	+17 18 39.97	—	—
—	13 20 51	+47 25 46	—	—
—	00 22 45.9	+08 52 15.43	—	—

Binary Stars: Light Curves

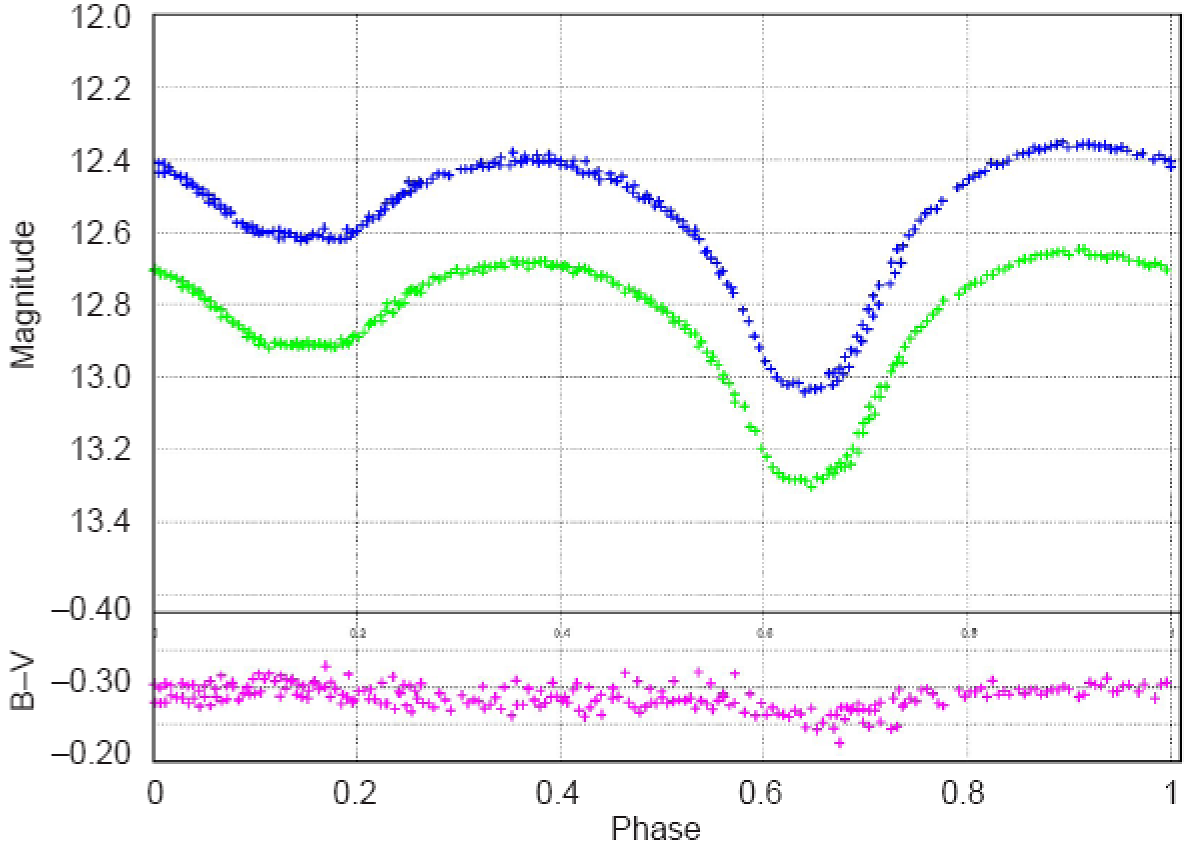


Figure 1. Light curve for ASAS J105855+1722.2, along with the B–V color versus orbital phase. The two colors denote Bessell B and V filters. Note the difference in depth of the two eclipses and the smoothly varying light curve. Also note the difference in the primary and secondary maxima (O'Connell effect).

Binary Stars: Light Curves

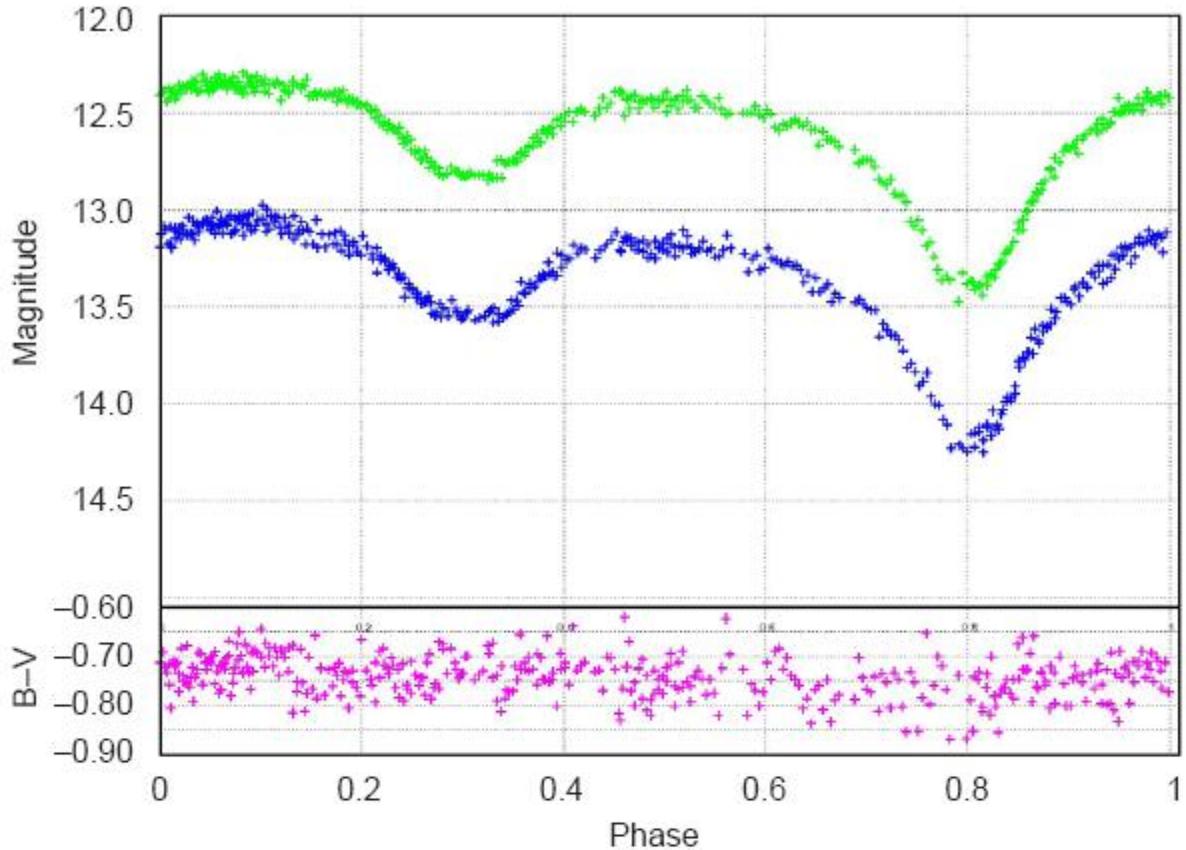


Figure 2. Light curve for NSVS 5066754 in Baader Blue and Green filters and the B–V color versus orbital phase. Note the difference in depth of the two eclipses and the smoothly varying light curve. Also note the difference in the primary and secondary maxima (O'Connell effect).

Binary Stars: Light Curves

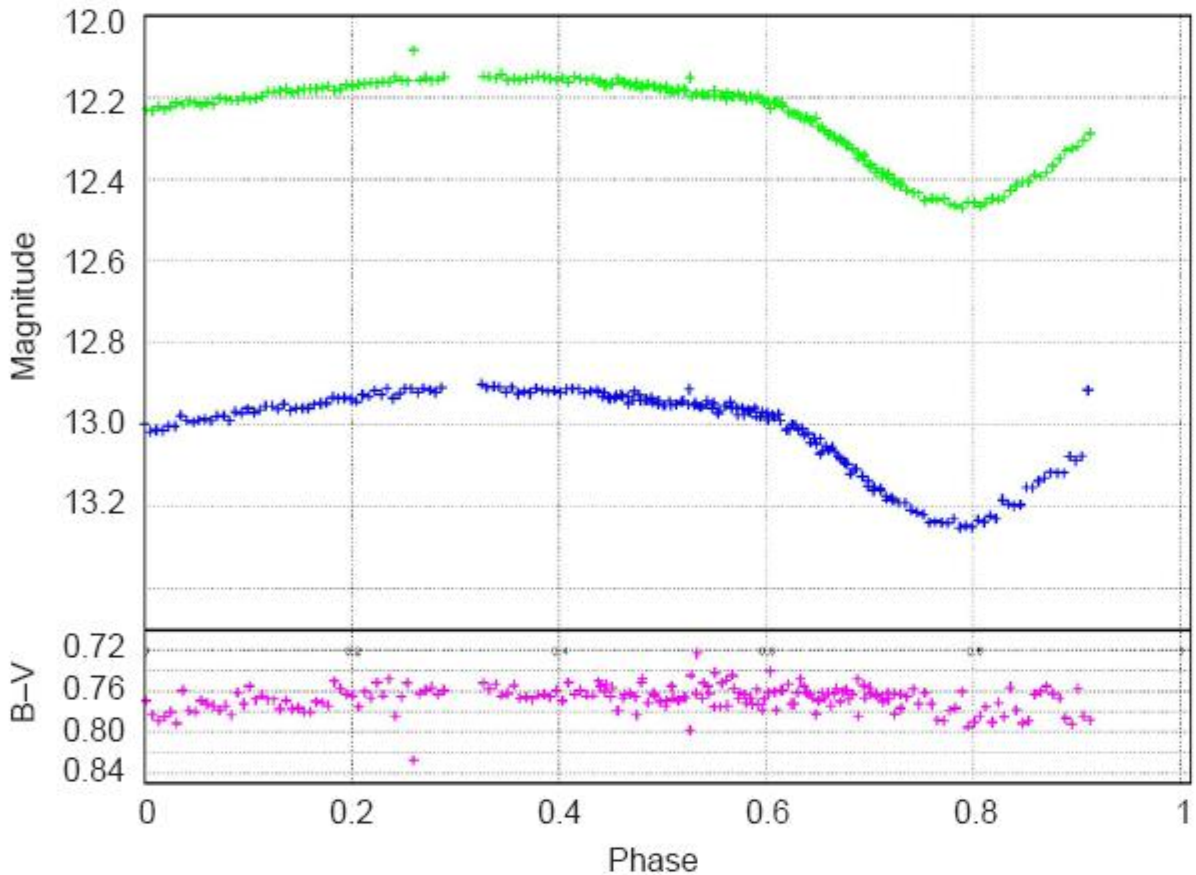


Figure 4. Light curve for NSVS 9091011 in Bessell B and V filters and the B–V color versus orbital phase. Note that the light curve varies smoothly, and only one eclipse is observed. Note that for this set of observations we do not have coverage over the entire phase.

Binary Stars: New Light Curves (Gokhale et al., 2016, *in prep*)

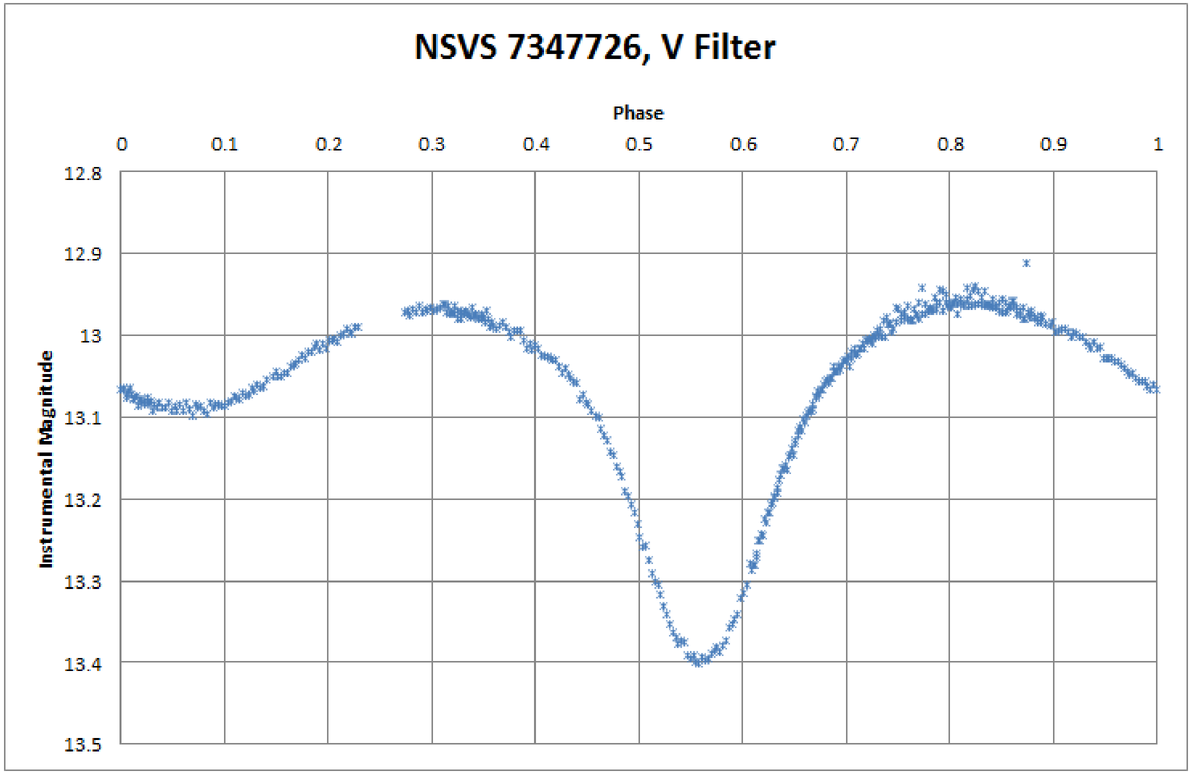


Figure 5. Light curve for NSVS 7347726 in the V filter versus orbital phase plotted from data obtained at the NURO telescope.
Note the difference in depth of the eclipses and the continuously varying light curve.

Binary Stars: New Light Curves (Gokhale et al., 2016, *in prep*)

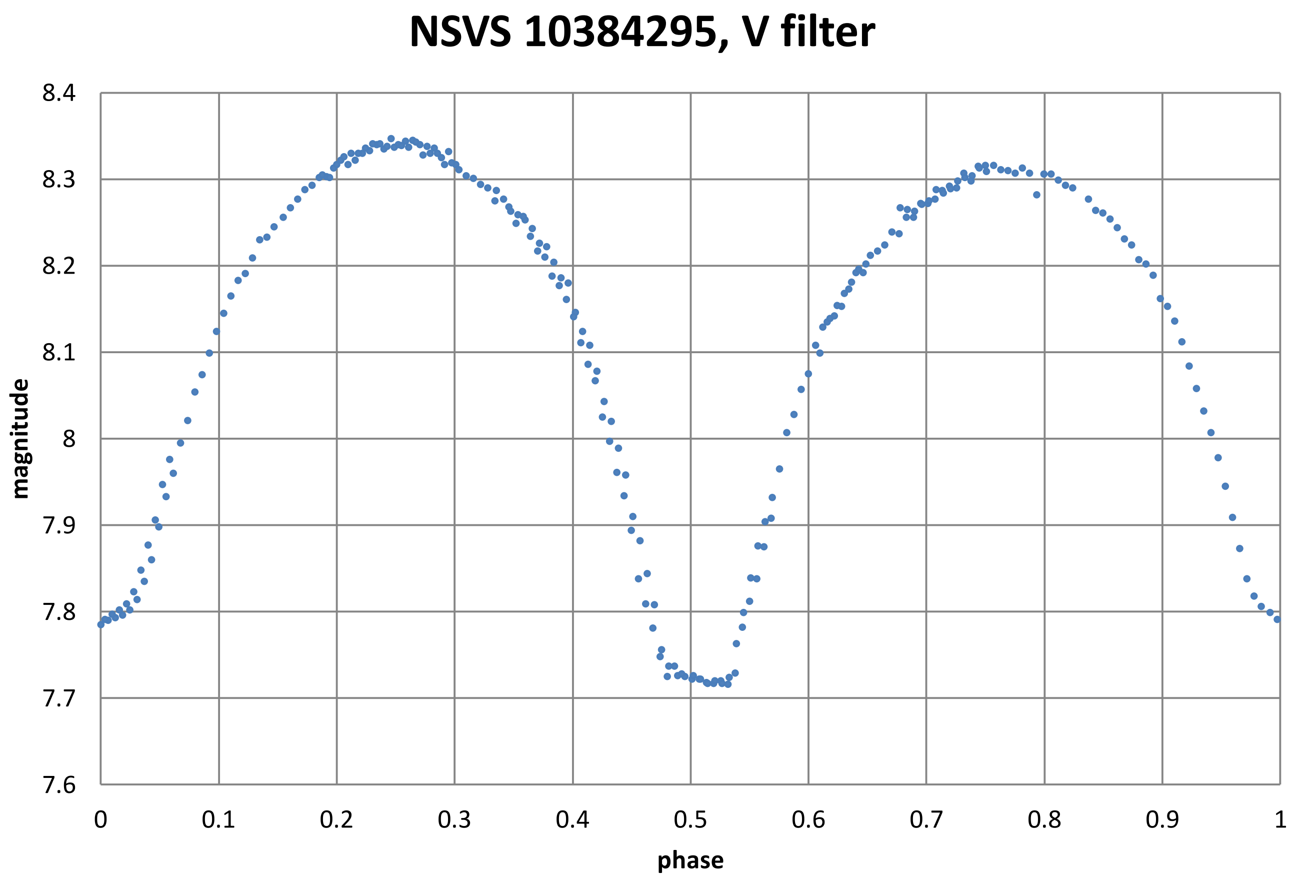


Figure 6. Light curve for NSVS 10384295 in the V filter versus orbital phase plotted from data obtained at the NURO telescope.
Note the similarity in the depth of the eclipses and the continuously varying light curve.

Binary Stars: New Light Curves (Gokhale et al., 2016, *in prep*)

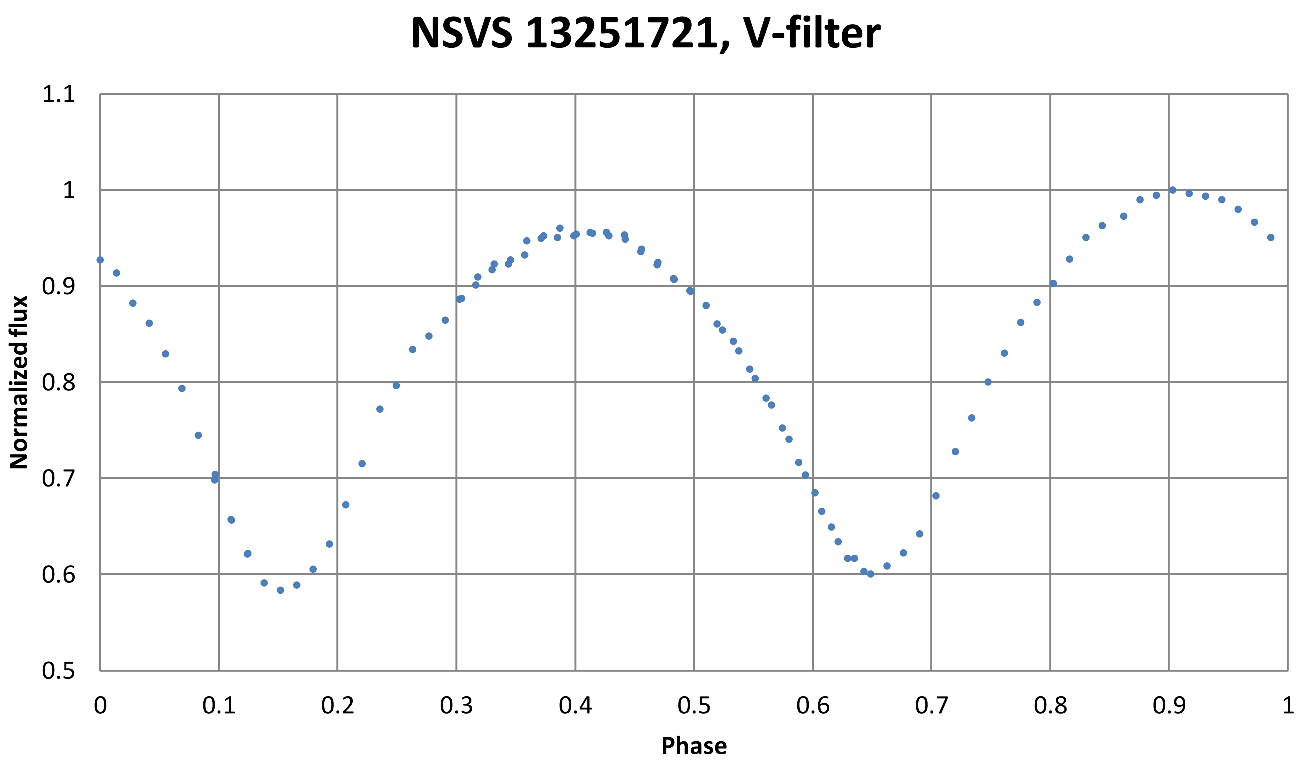


Figure 7. Light curve for NSVS 13251721 in the V filter versus orbital phase plotted from data obtained at the NURO telescope.

Note the similarity in the depth of the eclipses and the continuously varying light curve.

Light Curve Analysis

- Fourier analysis can be used to
  a) Classify systems as either Algols, β-lyrae or W UMa stars.
  b) Quantify the O'Connell effect
- The Fourier fit is given by:

$$m(\phi) = \sum_{n=0}^{8} a_n \cos(2\pi n(\phi - \theta)) + b_n \sin(2\pi n(\phi - \theta))$$

where,

a_n and b_n are the Fourier coefficients,

φ is the phase and,

θ is the phase offset.

Light Curve Fourier Analysis

According to Rucinski (1997):

- a_2 coefficient quantifies the tidal proximity effect in detached systems,
- a_4 accounts for the symmetrical deviations from the exact double cosine term caused by the eclipses.
- If,

$$a_4 > a_2(0.125 - a_2)$$ β-lyrae system

$$a_4 < a_2(0.125 - a_2)$$ Detached system or Algol

- And if,

$$|a_4| < 0.02$$ W UMa or RR-Lyrae

$$m(\phi) = \sum_{n=0}^{8} a_n \cos(2\pi n(\phi - \theta)) + b_n \sin(2\pi n(\phi - \theta))$$

Light Curve Fourier Analysis

Target	*Filter*	a_2	a_4	$a_2(0.125 - a_2)$	*Classification*
ASAS J105855+1722.2	B	–0.15329	–0.03029	–0.04265907	β Lyr
	V	–0.15191	–0.03138	–0.04206368	β Lyr
	R	–0.15199	–0.03246	–0.04210057	β Lyr
NSVS 5066754	B	–0.18786	–0.05218	–0.05877538	β Lyr
	G	–0.19084	–0.05357	–0.06027592	β Lyr
	R	–0.19253	–0.05343	–0.06113507	β Lyr
NSVS 9091101	B	–0.01819	0.006372	–0.0026043	β Lyr/RR Lyr
	V	–0.0048	0.008484	–0.00062277	β Lyr/RR Lyr
	R	–0.01047	0.006927	–0.00141852	β Lyr/RR Lyr
NSVS 9091101 (TSO)	B	–0.038966	–0.005532	–0.0063891	β Lyr/RR Lyr
	G	–0.039086	–0.00707	–0.006413465	β Lyr/RR Lyr
	R	–0.038606	–0.00587	–0.006316173	β Lyr/RR Lyr

Classification of systems based on Fourier coefficients.

The O'Connell Effect

- The OC effect is the difference in the heights of the maxima in light curves of eclipsing binary systems.
- One way to quantify this effect is to simply calculate the difference in magnitudes at the primary and secondary maxima:

$$\Delta m = m_p - m_s$$

Target	*Filter*	$\lvert 2b_1 \rvert$	Δm (Fourier)	Δm (Average)
ASAS J105855+1722.2	B	0.047	0.037	0.036
	V	0.034	0.030	0.026
	R	0.026	0.027	0.026
NSVS 5066754	B	0.072	0.086	0.083
	G	0.060	0.077	0.070
	R	0.052	0.058	0.059

The O’Connell Effect

- Following McCartney (1997, 1999), we define two other quantities, the O’Connell Effect Ratio (OCR) and the Light Curve Asymmetry (LCA) as follows:

$$\mathrm{OER} = \frac{\int_{0.0}^{0.5} (I(\theta) - I(0.0))d\theta}{\int_{0.5}^{1.0} (I(\theta) - I(0.0))d\theta}$$

$$\mathrm{LCA} = \sqrt{\int_{0.0}^{0.5} \frac{(I(\theta) - I(1.0-\theta))^2}{I(\theta)^2} d\theta}$$

- Essentially, the LCA measures the deviance from symmetry of the two halves of the light curve.
  - If both halves are perfectly symmetric, then we would expect the LCA to be zero

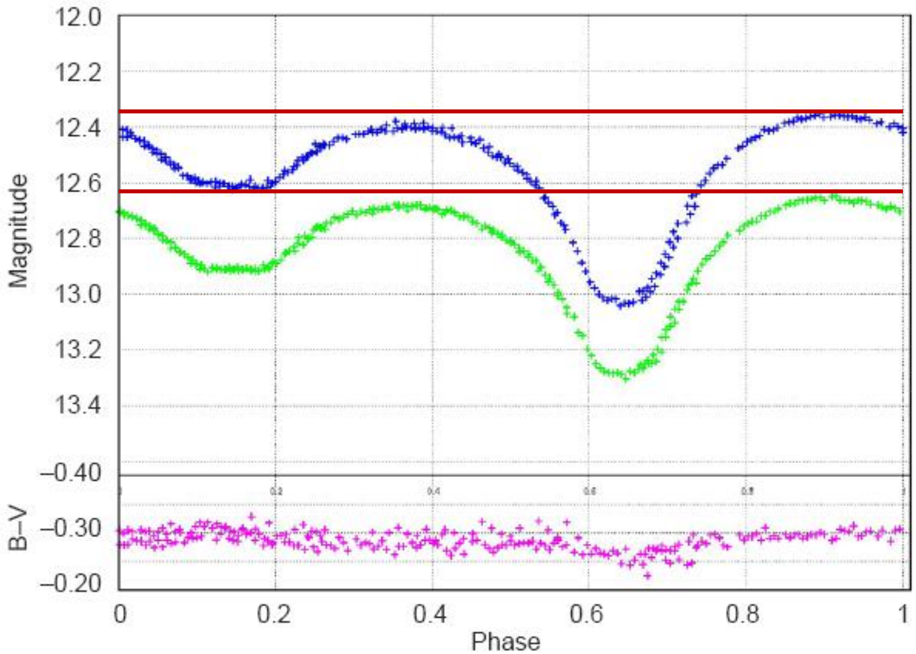
The O'Connell Effect

- The OER is the ratio of the area under the curves for phases θ = 0.0 to θ = 0.5 and phases θ = 0.5 to θ = 1.0.
- An OER = 1 implies no OC effect, whilst for $\Delta m > 0$, the OER > 1; and for $\Delta m < 0$ the OER is < 1.

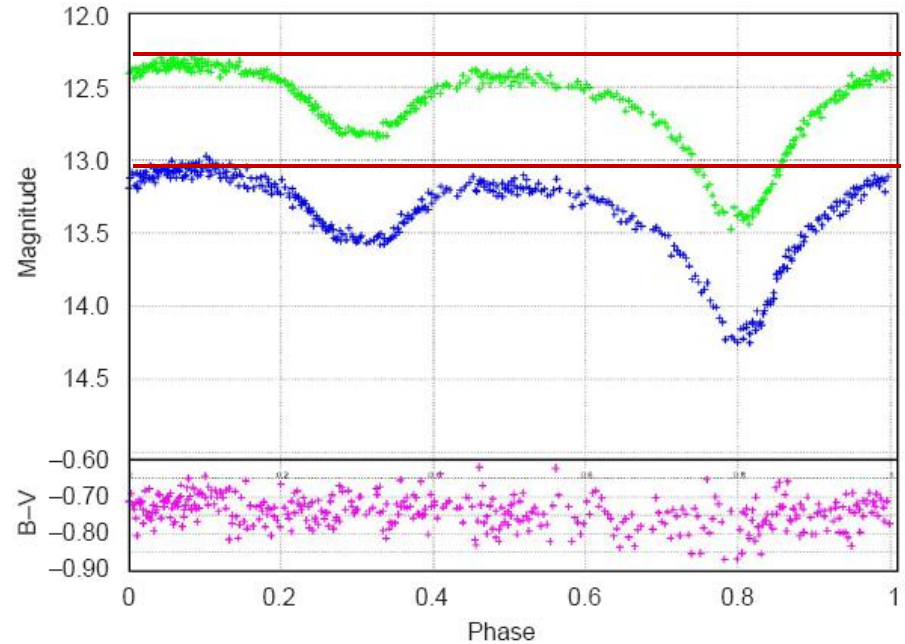
$$\Delta m = m_p - m_s$$

Target	*Filter*	*OER*	*LCA*
ASAS J105855+1722.2	B	1.08629	0.024018
	V	1.06753	0.018802
	R	1.05793	0.014743
NSVS 5066754	B	1.14588	0.054379
	G	1.12555	0.044532
	R	1.11302	0.040538

The OC Effect: Light Curves



ASAS J105855+1722.2



NSVS 5066754

Target	*Filter*	*OER*	*LCA*
ASAS J105855+1722.2	B	1.08629	0.024018
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	R	1.05793	0.014743
NSVS 5066754	B	1.14588	0.054379
	G	1.12555	0.044532
	R	1.11302	0.040538

The O’Connell Effect: Models

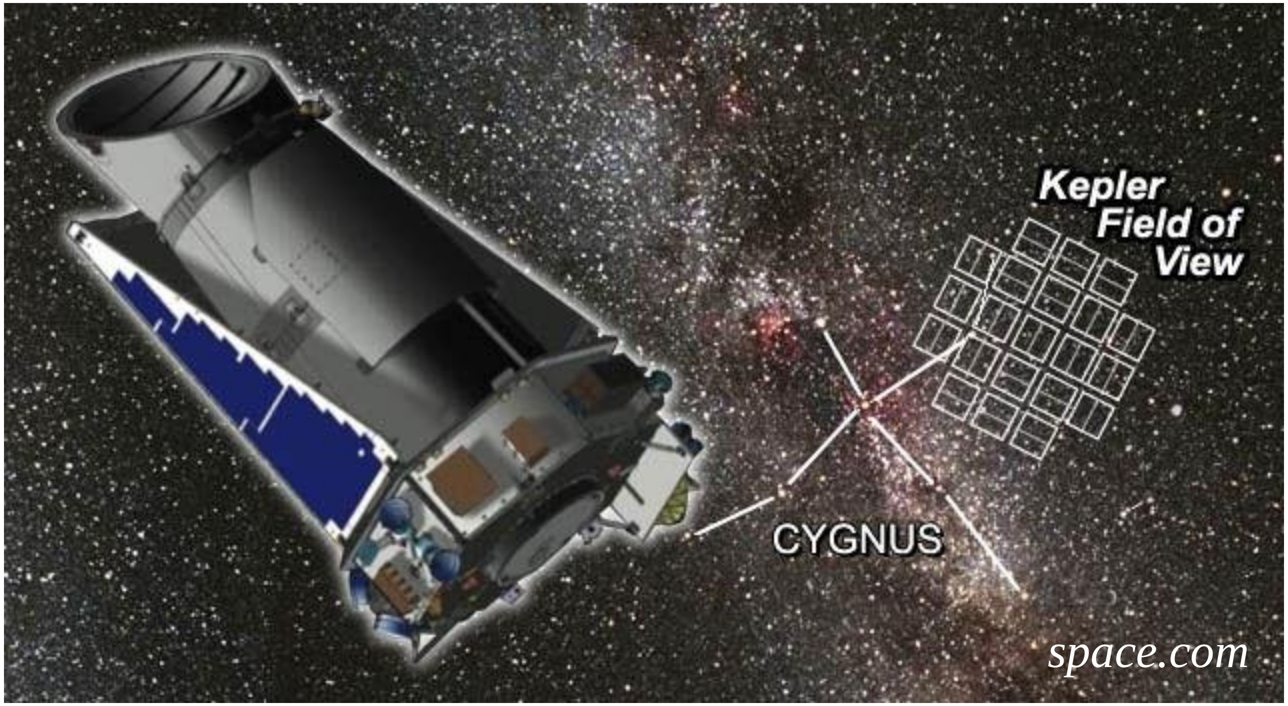
- So-called ‘periastron effect’
  - Suggested by Roberts (1906) that ‘*this might be caused by tidal effects and by an increase in mutual radiation at periastron between stars moving in eccentric orbits*’ [O’Connell, 1951].
- Star spots on either or both components
  - Cool spots (star spots akin to sunspots)
  - Hot spots (mass transfer?)
- Third object
  - Gas stream around one of the stars
  - Circumbinary material

!None of these explanations appear satisfactory!

The OC Effect: Unresolved Issues

- O'Connell showed that this effect is not a 'periastron' effect
  - Seen in binaries with circular orbits
  - Δm both positive and negative
- Star spots have finite lifetimes.
  - The OC effect persists over several cycles in some systems
  - OC changes over several cycles in other systems
- Hot spots are plausible only in mass transferring systems
  - OC effect seen in detached, semi-detached, and overcontact systems
- Gas stream or circumbinary material will have to be unevenly distributed, which seems implausible.

The Kepler Mission



The primary goal of the Kepler Mission is to survey our region of the Milky Way galaxy to discover hundreds of Earth-size or larger planets in or near the habitable zone of solar-like stars and determine how many of the billions of stars in our galaxy have such planets.

http://www.jpl.nasa.gov/

Binary Stars: Kepler LCs

Kepler stared at the Cygnus field for almost 4 years, and there are about 2878 EBs identified in this field; many of which show the OC effect!

Barbara A. MIKULSKI ARCHIVE FOR SPACE TELESCOPES

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Kepler Home | Mission | Getting Started | Data Search | Target Search | Stellar17 | CasJobs | FFI+ Search

Kepler Data Search

Kepler Abstract Search

FAQ

Kepler Science Center

Search & Retrieval

Download Options

Data Products

Documentation

Data Release Notes

Data Reduction & Analysis

Related Sites

Publications/News

MAST Services

Images

Data Use Policy

Acknowledgments

Kepler Eclipsing Binaries (Revision 3) (downloaded 28 Dec, 2015)

This page lists the third revision (Beta) of the Kepler Eclipsing Binary Catalog as updated 26 Oct, 2015.
Note a few targets with multiple periods and multiple ephemerides have multiple entries.
For more information and updates, visit the Villanova Eclipsing Binary web site.
The previous release is described in Matijevic et all 2012 AJ 143,123

Display Column Headings/Notes:

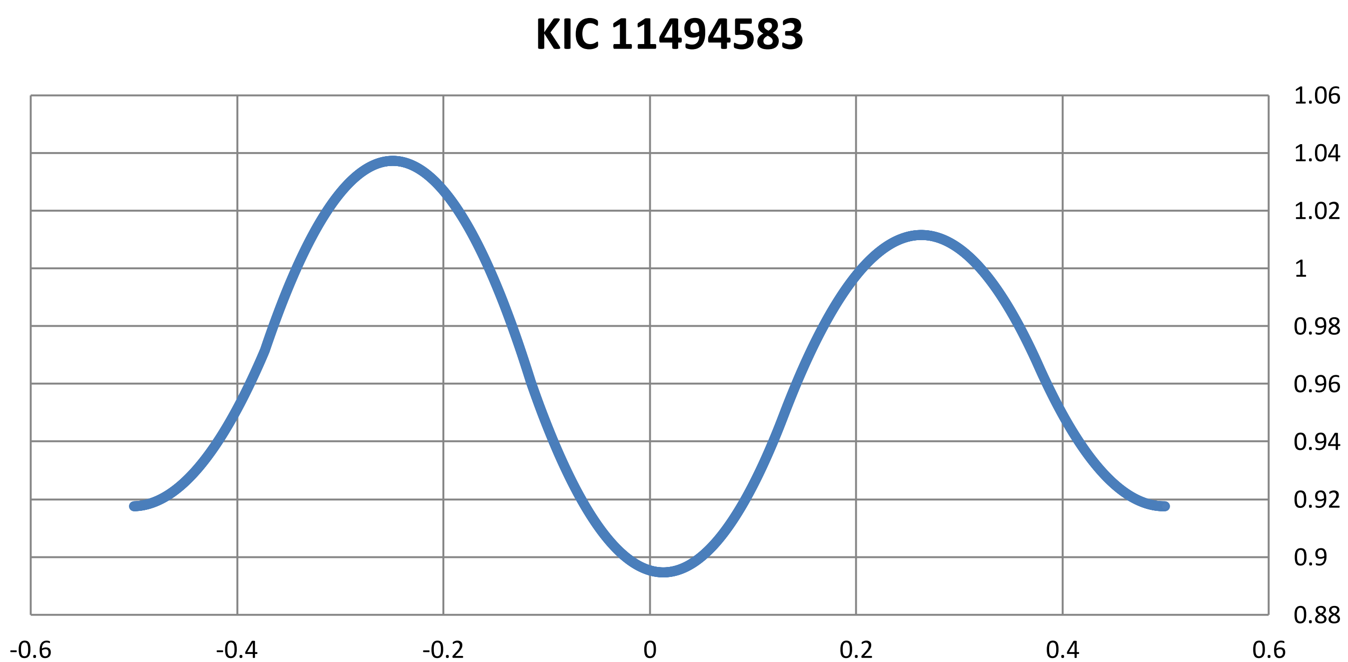
Number of entries = 2878

- To see available observations, click on Kepler ID entries below.
- Click on KOIs to see available KOI information.
- Click on the "Morph" entries to display (long cadence) light curve plots and fits for each ephemeride provided by the Villanova Eclipsing Binary Catalog web site.
- Click on Kepmag entries to see target overview provided by the Villanova web site.
- Click on column headings to sort values.

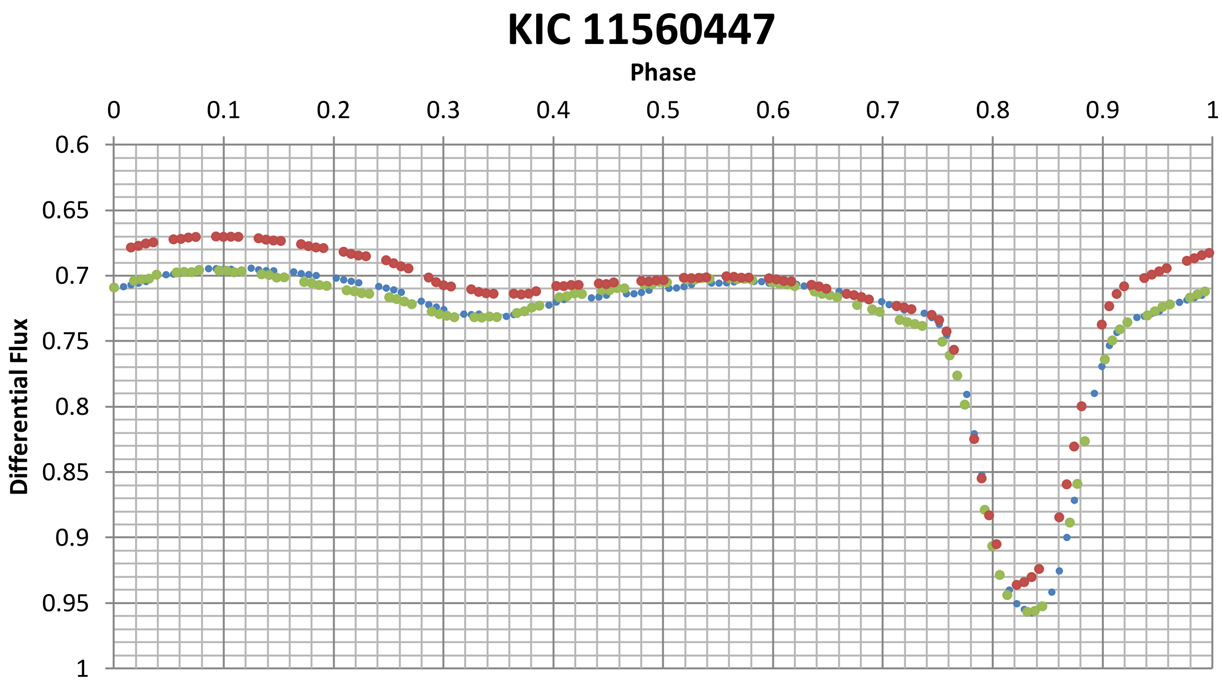
Kepler ID	KOI	Morph	Mult	BJD0	BJD0 Err	Period	Period Err	Kepmag	Teff	RA	Dec
1026032		0.15	1	54966.773813	0.030112	8.460438	2.30e-5	14.813	5715	291.04410	36.72930
1026957	958	0.01	1	54956.017106	0.011314	21.761306	8.81e-5	12.559	4845	291.25450	36.74360
1161345	984	0.24	1	55005.028983	0.023798	4.287456	8.60e-6	11.631	5836	291.04880	36.83990
1432214	998	0.00	1	55047.039254	0.037980	161.788300	1.58e-3	15.661	5814	291.38270	37.07300
1433410		0.74	1	54999.951811	0.014174	0.283275	3.10e-6	14.119	6003	291.63770	37.08230

Kepler LCs

- It is easy to download Kepler EB data from the Villinova (http://keplerebs.villanova.edu/) and MAST websites (https://archive.stsci.edu/kepler/kepler_fov/search.php).
- Here is an example of one cycle of the EB KIC 11494583.
- The LC clearly shows the O'Connell effect.



More Kepler LCs



- Different cycles folded on top of each other.
  - Note that the LCs do not overlap, implying activity on one or both stars in the EB; starspots?
  - The magnitude of the OC effect is changing from one cycle to another.
  - What is going on here!?

Research Plan: Summer 2016/2017

- Obtain BVR photometry on as many Kepler EBs showing the OC effect.
  - 31-inch NURO telescope at Lowell Observatory (~ 10 nights)
  - 14-inch Meade and/or 17-inch planewave at Truman
  - 0.8m telescope at McDonald Observatory in Texas (~10 nights)
  - Collaborate with amateur astronomers (ASKC!)
- Generate LCs, and determine the OC effect for each object.
- Look for correlations between binary type (detached, semi-detached, over-contact etc) and magnitude/sign of OC effect.
- Look for correlations between Δm, OER, and LCR.
- Generate Fourier fits, classify systems as Algols, β-lyrae, or WUMa stars.
- Model systems, and test the cool star-spot model especially in the context of time evolution of the OC effect.

Research Plan: Summer 2016/2017

- DSLR photometry *(https://www.aavso.org/dslr-observing-manual)* on Kepler field
  - Lower cost [$1000ish]
  - Larger field of view (?)
  - New, unique, and expanding field
  - Potentially low hanging fruit for publication in JAAVSO

$500-$1000

$75

$300 [optional]

EB Stars: How to contribute!

- We are looking for collaborators to collect photometric data on Kepler EBs.
  - Funding from Missouri NASA-EPSCoR for supplies/travel
  - More grant opportunities in 2016-17 through MOSGC

- We are also looking for collaborators in our Light Pollution study in Missouri
  - Pilot project funded by MOSGC 2015-16
  - Plan to apply for MOSGC grants in 2016-17