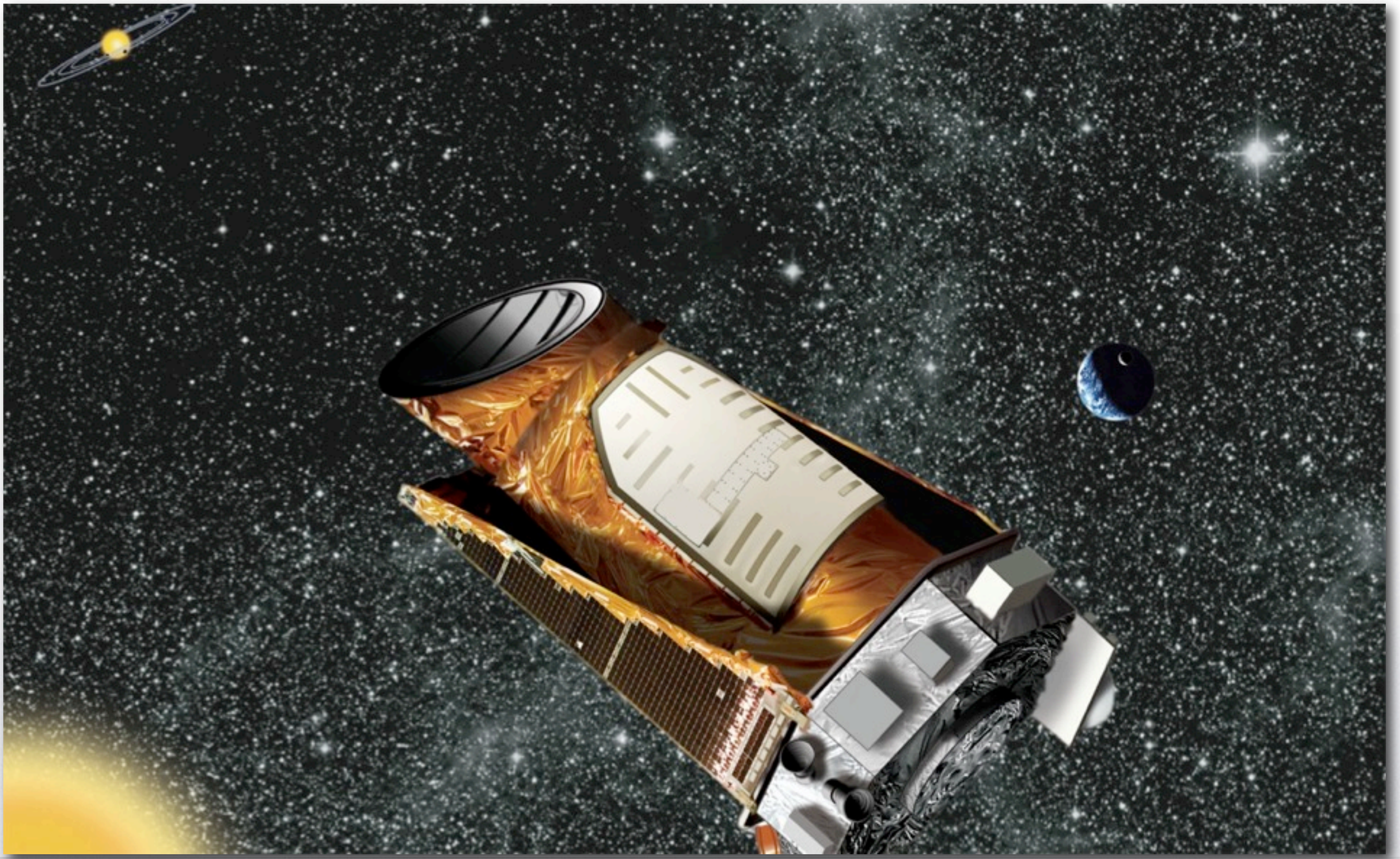
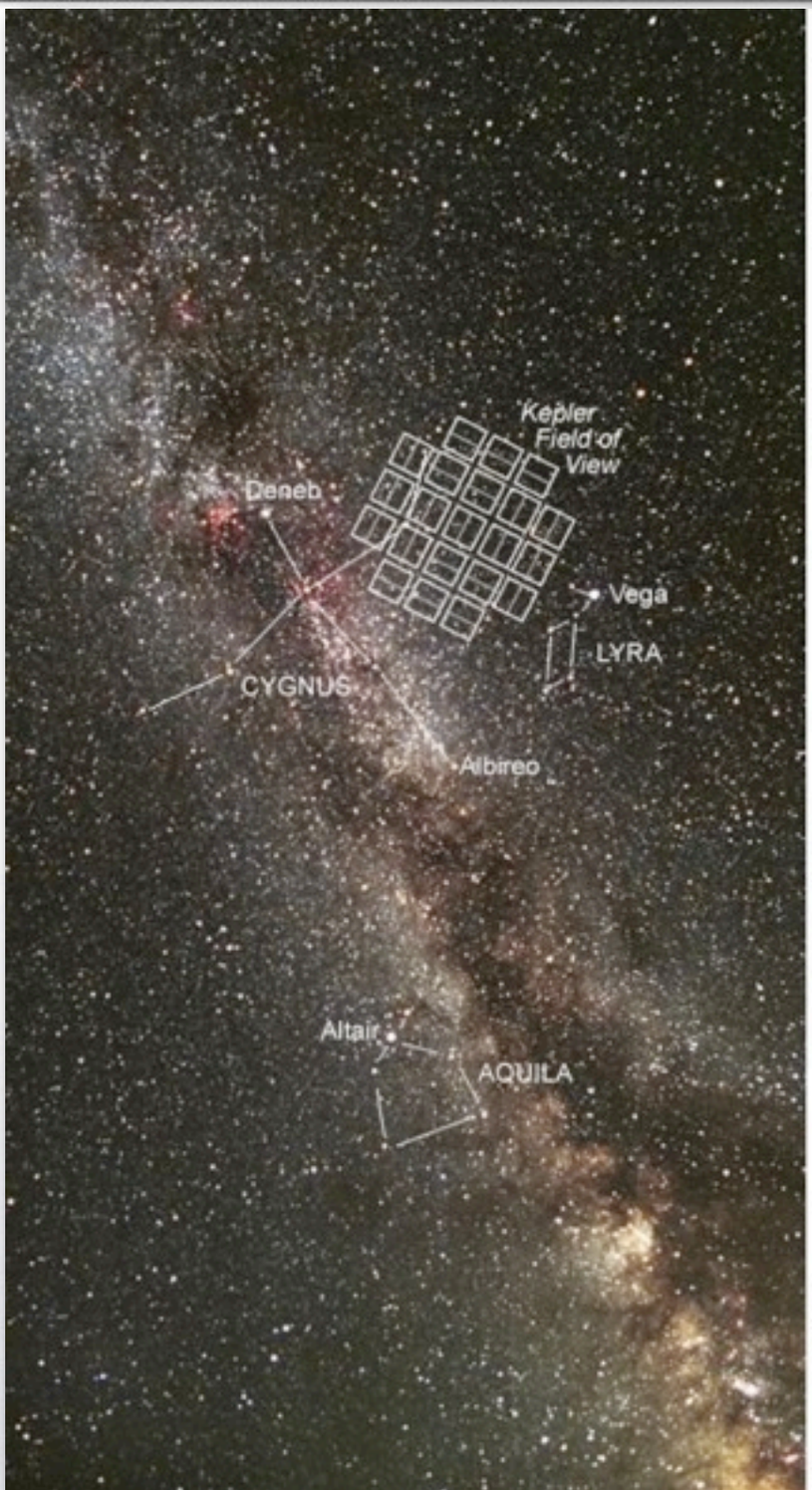
Kepler's Multi-Eclipsing Hierarchical Triples: "Photodynamical Fits" & Accurate Masses and Radii

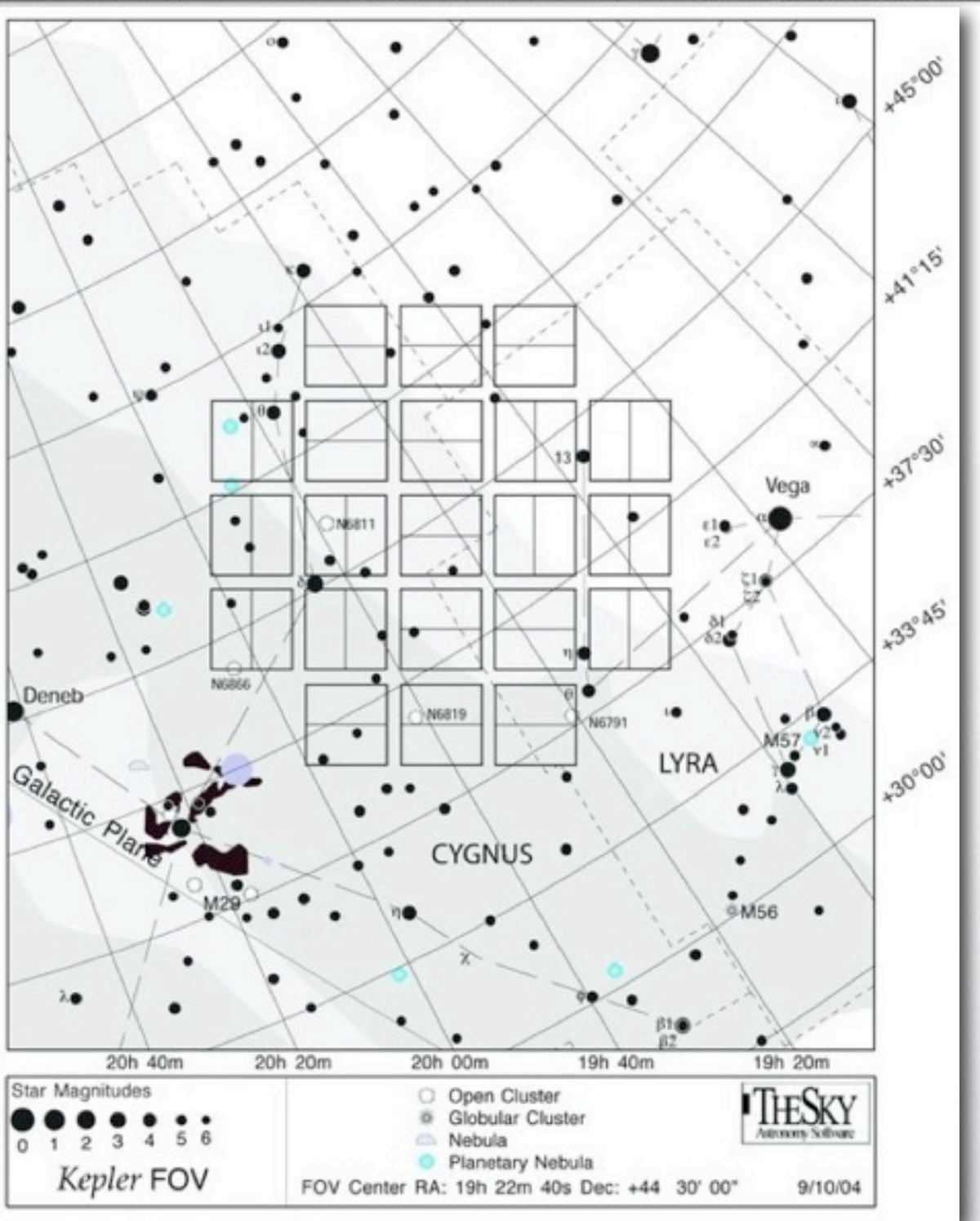
Josh Carter

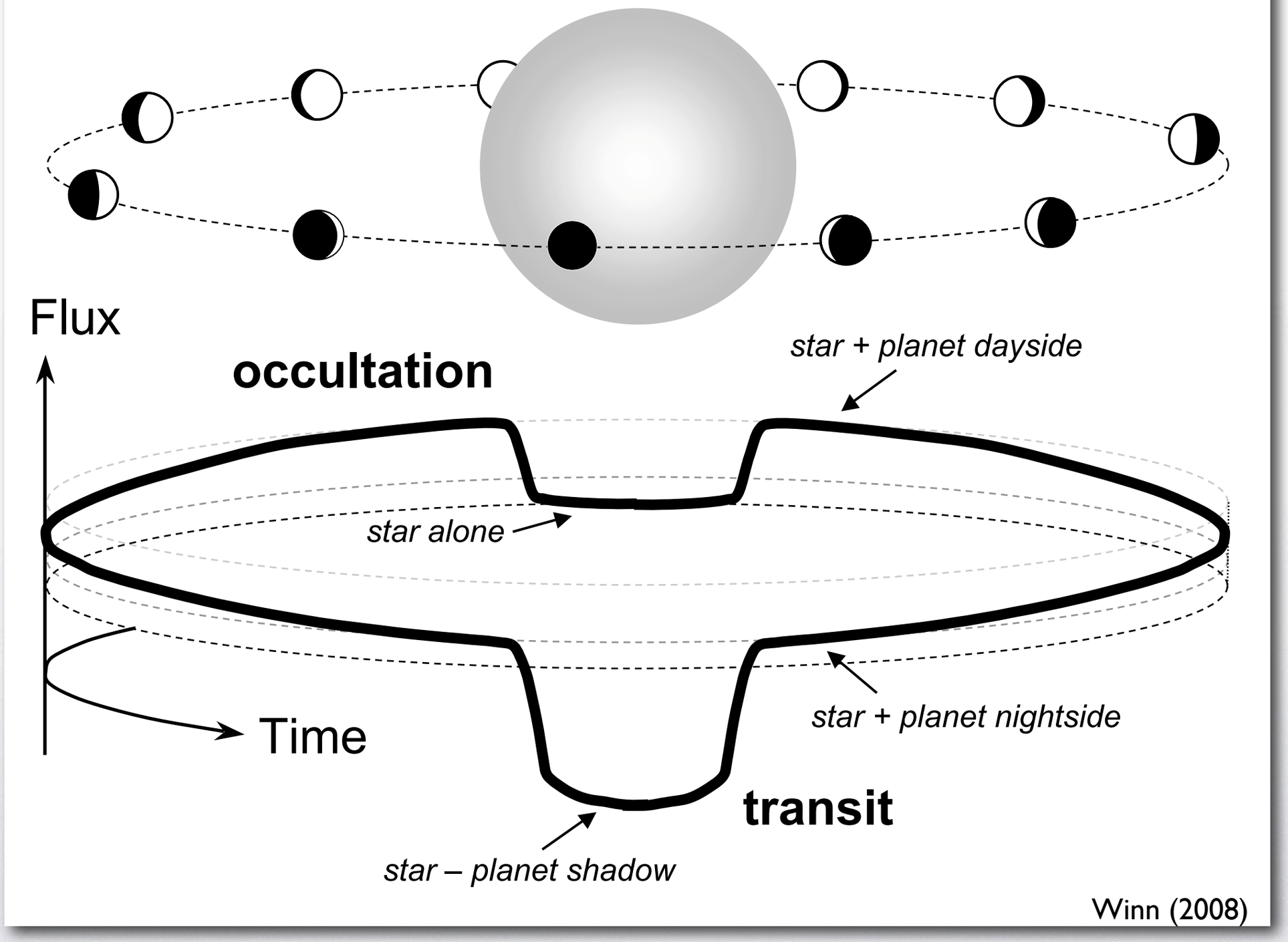
Hubble Fellow

(Smithsonian Astrophysical Observatory)

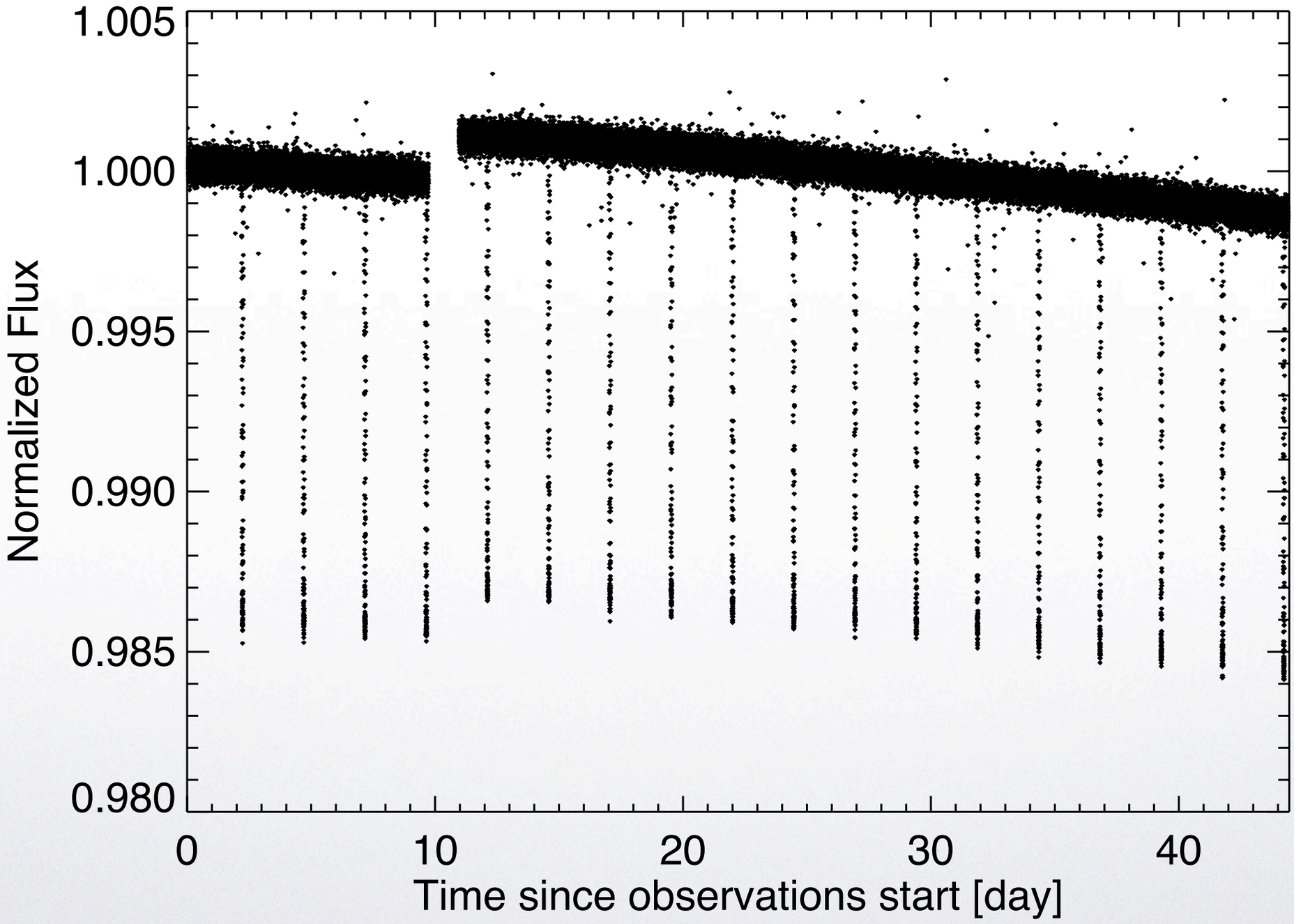



Kepler
Field of
View
Deneb
Vega
LYRA
CYGNUS
Albireo
Altair
AQUILA

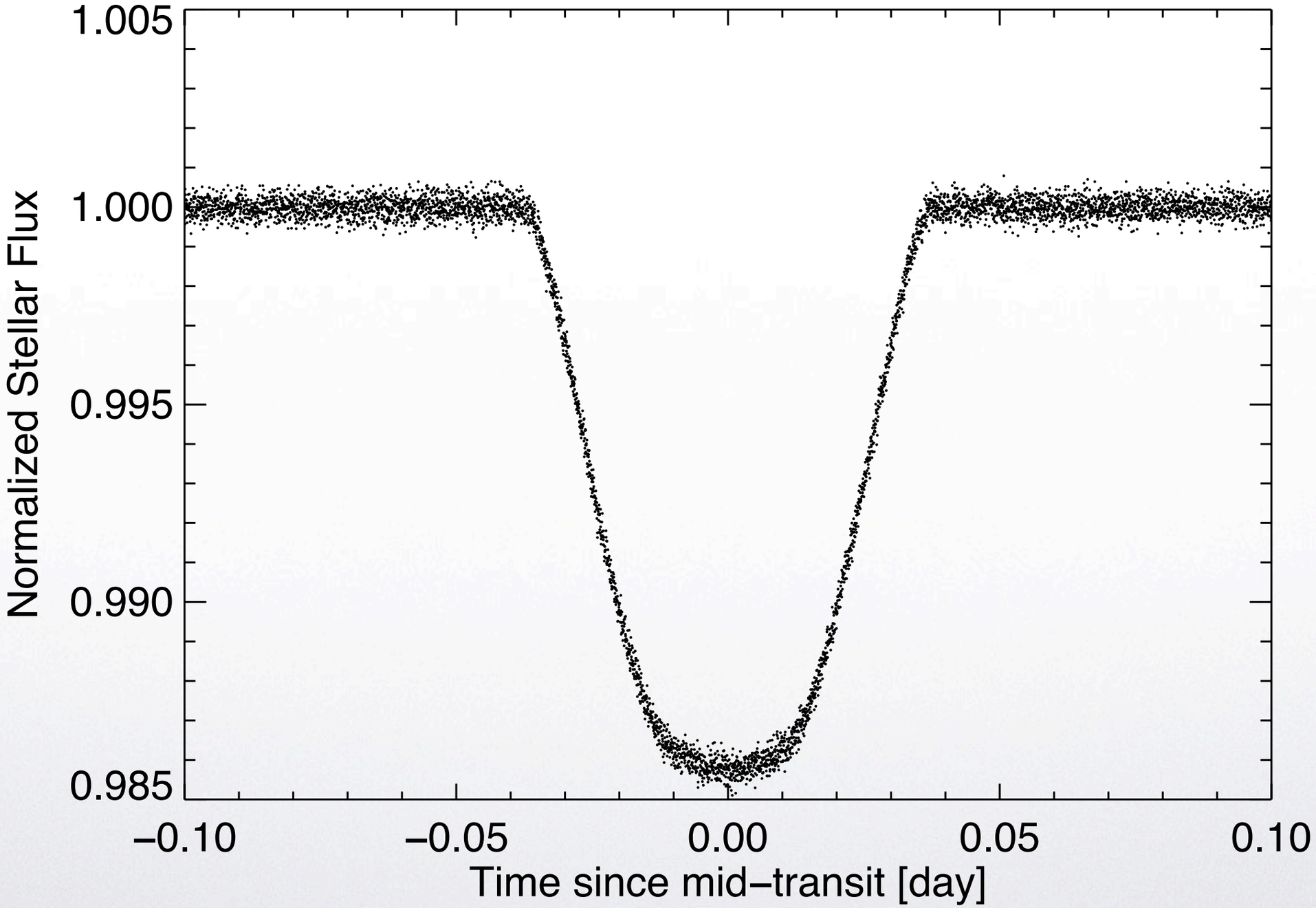

+45°00'
+41°15'
+37°30'
+33°45'
+30°00'
Vega
LYRA
CYGNUS
Deneb
Galactic Plane
M57
M56
M29
N6811
N6866
N6819
N6791
20h 40m
20h 20m
20h 00m
19h 40m
19h 20m
Star Magnitudes
0 1 2 3 4 5 6
Kepler FOV
Open Cluster
Globular Cluster
Nebula
Planetary Nebula
TheSky
Astronomy Software
FOV Center RA: 19h 22m 40s Dec: +44 30' 00"
9/10/04

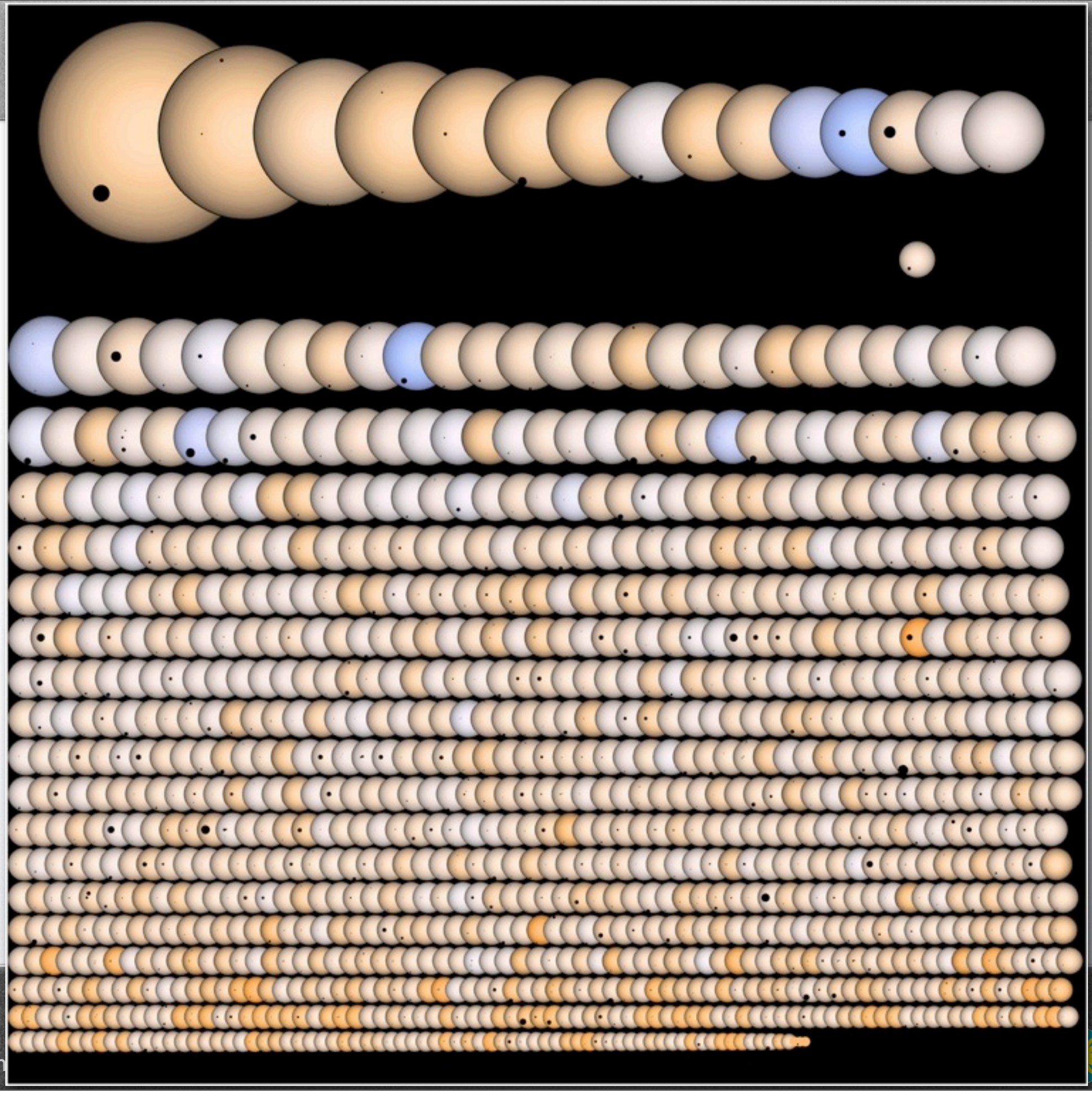

Flux
occultation
star + planet dayside
star alone
Time
star + planet nightside
transit
star – planet shadow

Winn (2008)

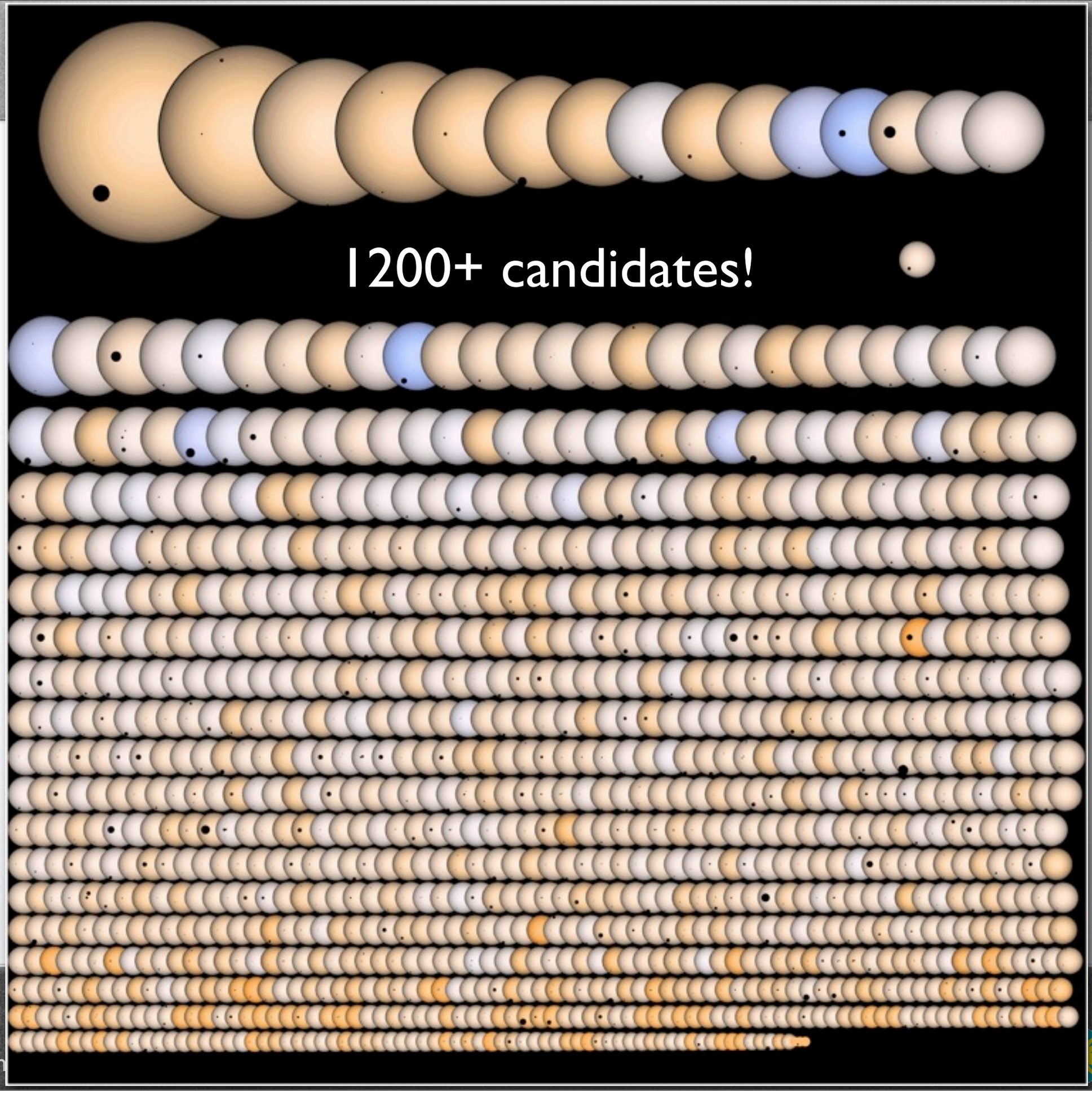

1.005
1.000
0.995
0.990
0.985
0.980
Normalized Flux
0
10
20
30
40
Time since observations start [day]

Kepler-1 = TrES-2





credit:
J. Rowe



credit:
J. Rowe

Planets...

Characteristics of planetary candidates observed by *Kepler*, II: Analysis of the first four months of data

William J. Borucki[0,1], David G. Koch[1], Gibor Basri[2], Natalie Batalha[3], Timothy M. Brown[5], Stephen T. Bryson[1], Douglas Caldwell[6], Jørgen Christensen-Dalsgaard[7], William D. Cochran[8],

Kepler-9: A System of Multiple Planets Transiting a Sun-Like Star, Confirmed by Timing Variations

Matthew J. Holman,[1*] Daniel C. Fabrycky,[1] Darin Ragozzine,[1] Eric B. Ford,[2] Jason H. Steffen,[3] William F. Welsh,[4] Jack J. Lissauer,[5,6] David W. Latham,[1] Geoffrey W. Marcy,[7]

KEPLER'S FIRST ROCKY PLANET: KEPLER-10b*

Natalie M. Batalha[1], William J. Borucki[2], Stephen T. Bryson[2], Lars A. Buchhave[3], Douglas A. Caldwell[4], Jørgen Christensen-Dalsgaard[5,6], David Ciardi[7], Edward W. Dunham[8], Francois Fressin[3], Thomas N. Gautier III[9], Ronald L. Gilliland[10], Michael R. Haas[2], Steve B. Howell[11], Jon M. Jenkins[4], Hans Kjeldsen[5], David G. Koch[2],

A Closely-Packed System of Low-Mass, Low-Density Planets Transiting Kepler-11

Jack J. Lissauer[1], Daniel C. Fabrycky[2], Eric B. Ford[3], William J. Borucki[1], Francois Fressin[4], Geoffrey W. Marcy[5], Jerome A. Orosz[6], Jason F. Rowe[7], Guillermo Torres[4],

...Stars

***Kepler* Eclipsing Binary Stars. II. 2165 Eclipsing Binaries in the Second Data Release**

Robert W. Slawson

SETI Insitute, 189 Bernardo Ave., Mountain View, CA 94043

rslawson@seti.org

Andrej Prša

KEPLER OBSERVATIONS OF TRANSITING HOT COMPACT OBJECTS

Jason F. Rowe[1,15], William J. Borucki[1], David Koch[1], Steve B. Howell[2], Gibor Basri[3], Natalie Batalha[4], Timothy M. Brown[5], Douglas Caldwell[6], William D. Cochran[7], Edward Dunham[8], Andrea K. Dupree[9], Jonathan J. Fortney[10], Thomas N. Gautier III[11], Ronald L. Gilliland[12], Jon Jenkins[6], David W. Latham[9],

A THIRD HOT WHITE DWARF COMPANION DETECTED BY *KEPLER*

Joshua A. Carter[1,2,3], Saul Rappaport[1], & Daniel Fabrycky[2,3,4]

Accepted for publication in The Astrophysical Journal

KOI-54: THE *KEPLER* DISCOVERY OF TIDALLY-EXCITED PULSATIONS AND BRIGHTENINGS IN A HIGHLY ECCENTRIC BINARY

William F. Welsh[1], Jerome A. Orosz[1], Conny Aerts[2], Timothy Brown[3,17], Erik Brugamyer[4], William Cochran[4], Ronald L. Gilliland[5], Joyce Ann Guzik[6], Donald W. Kurtz[7], David Latham[8], Geoff Marcy[9], Samuel N. Quinn[8], Wolfgang Zima[2], Christopher Allen[16], Natalie Batalha[10,11], Steve Bryson[11], Lars Buchhave[8], Douglas A. Caldwell[11,12], Thomas N. Gautier[13], Steven Howell[14], K. Kinemuchi[11,15], Khadeejah A. Ibrahim[16],

KOI-126: A Triply Eclipsing Hierarchical Triple with Two Low-Mass Stars

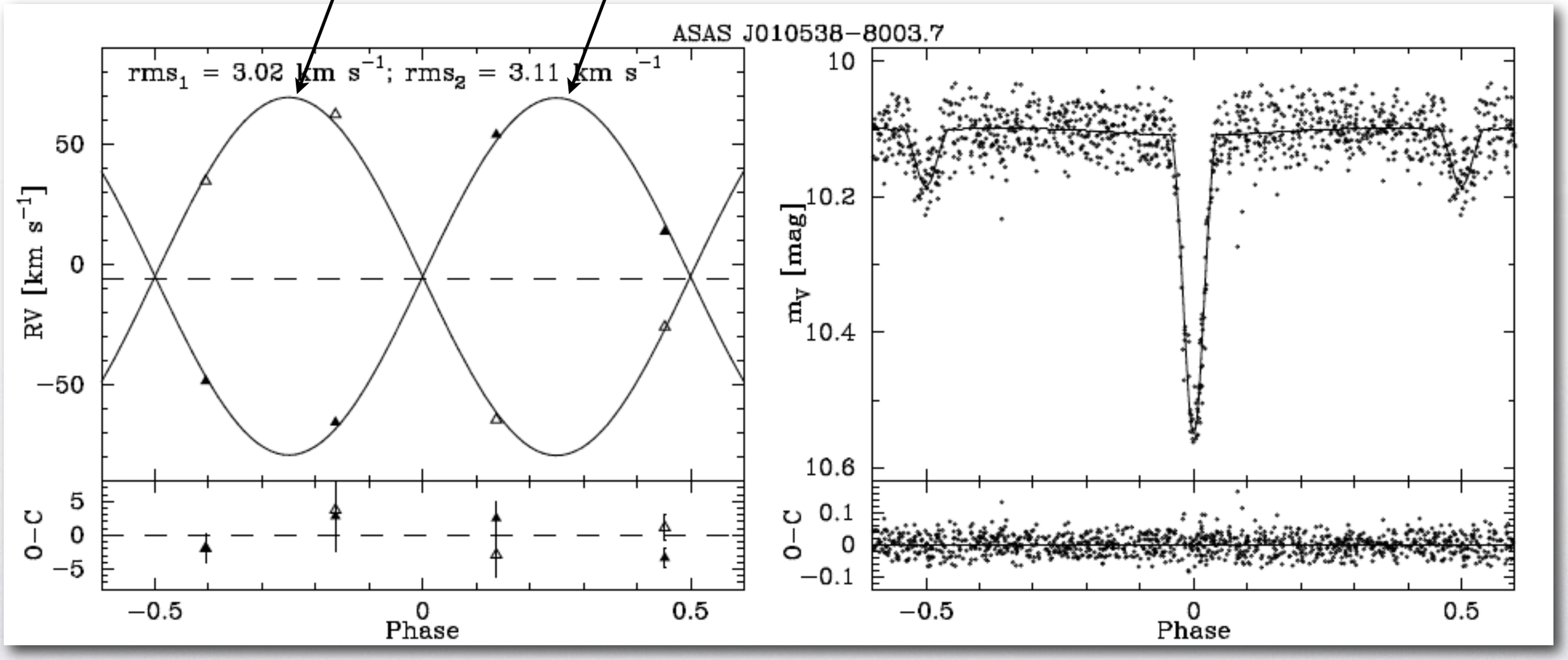
Joshua A. Carter,[1*] Daniel C. Fabrycky,[2] Darin Ragozzine,[1] Matthew J. Holman,[1] Samuel N. Quinn,[1] David W. Latham,[1] Lars A. Buchhave,[1,3] Jeffrey Van Cleve,[4,7] William D. Cochran,[5] Miles T. Cote,[4]

Absolute Dimensions

Reflex of A due to B

Reflex of B due to A

SB2



Hełminiak, Konacki, Ratajczak, Muterspaugh (2009)

Absolute Dimensions

Observables

From the light curve:

$$*\frac{M_A}{R_A^3}\left(1+q\right)$$

$$\frac{M_B}{R_B^3}\left(1+q^{-1}\right)$$

$$\sin i$$

From the RV:

$$f(M_A, M_B) = \frac{M_A \sin^3 i}{(1+q^{-1})^2}$$

$$f(M_B, M_A) = \frac{M_B \sin^3 i}{(1+q)^2}$$

*Seager, Mallén-Ornelas (2003)

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↓

Mass ratio, q

*Seager, Mallén-Ornelas (2003)

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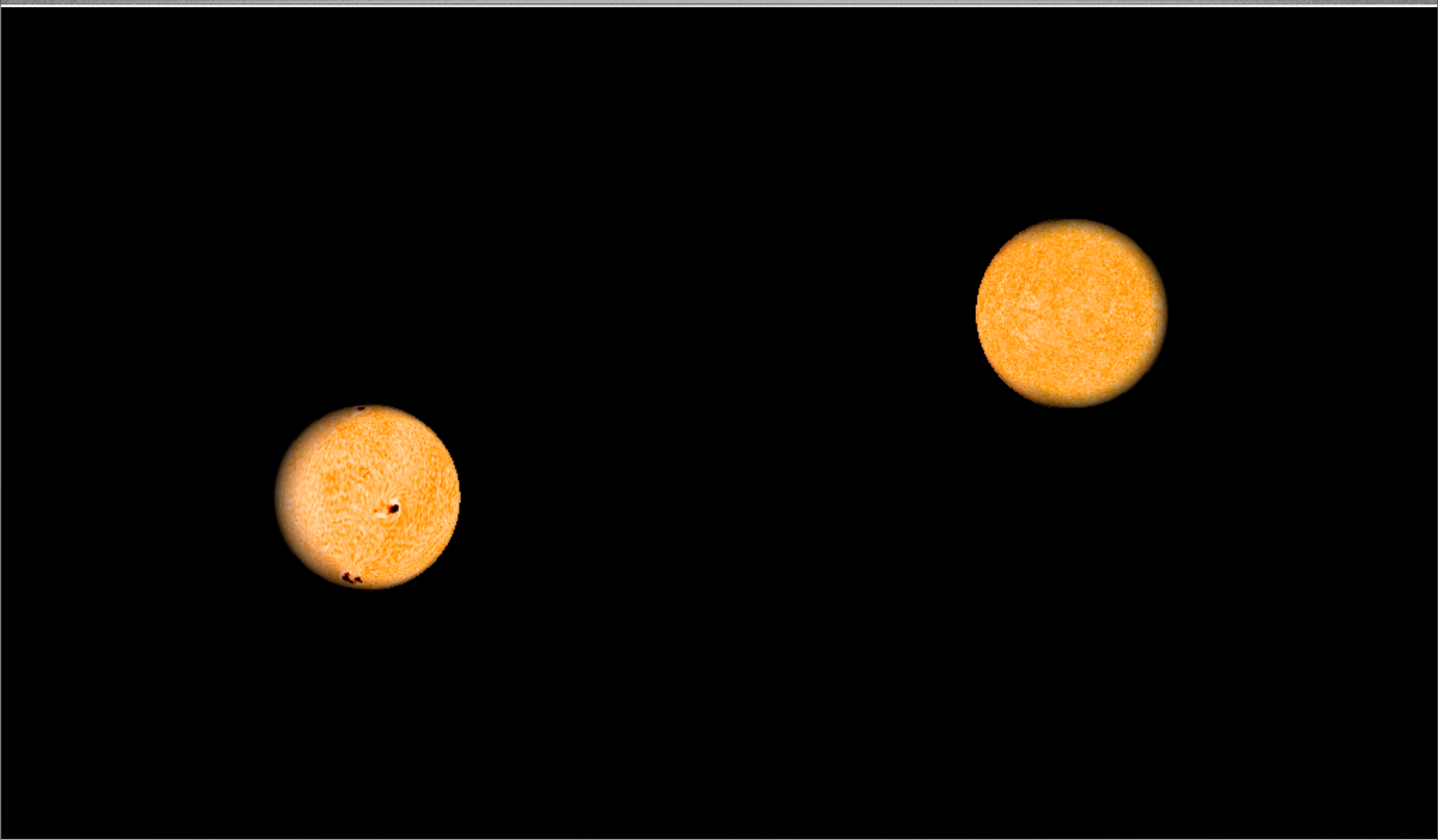
Mass ratio, q

Masses and Radii

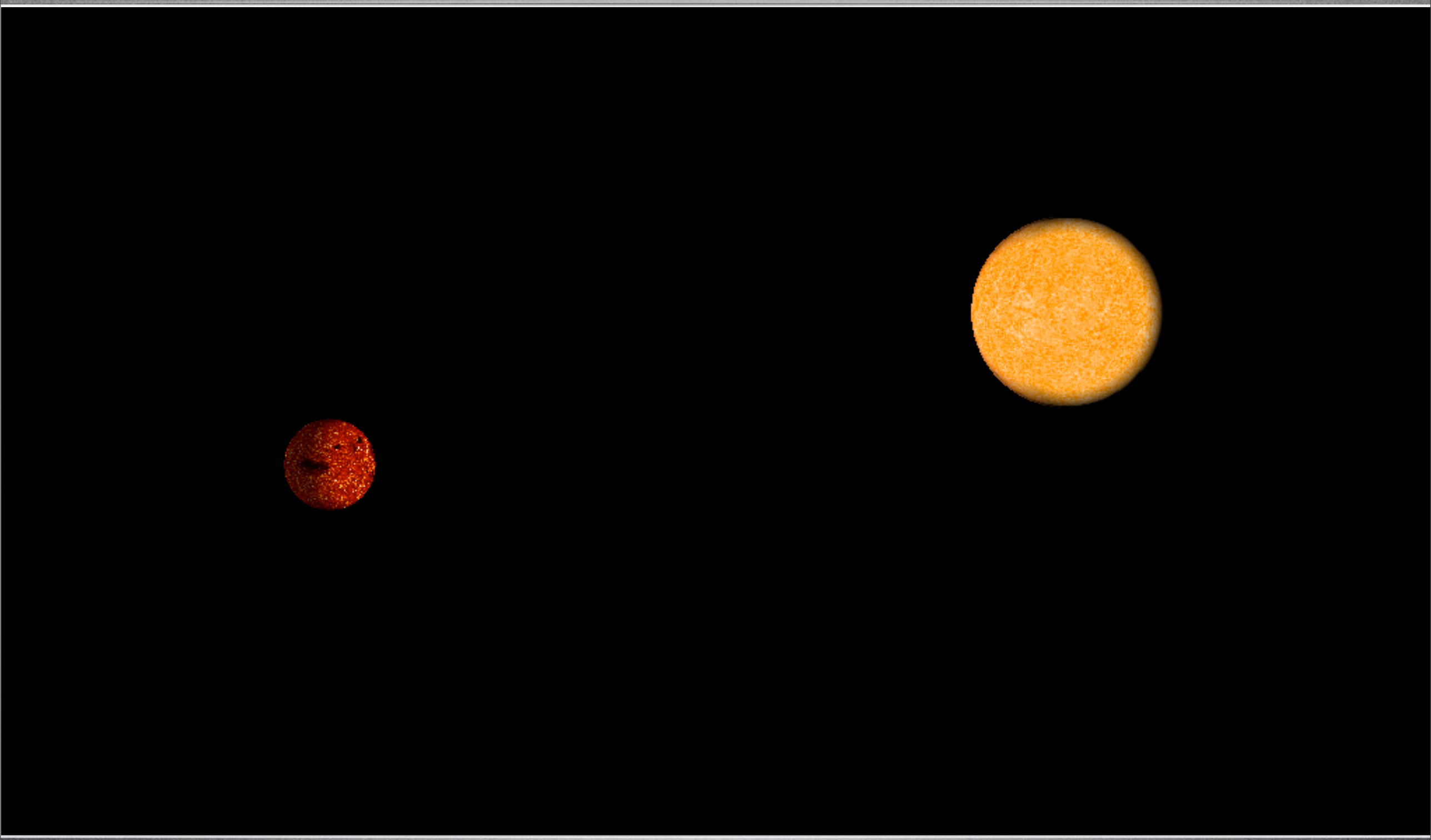
*Seager, Mallén-Ornelas (2003)

Eclipsing Binaries

Targets



Targets



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Masses and Radii!

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Mass ratio, q

Masses and Radii!

Absolute Dimensions - Low Mass

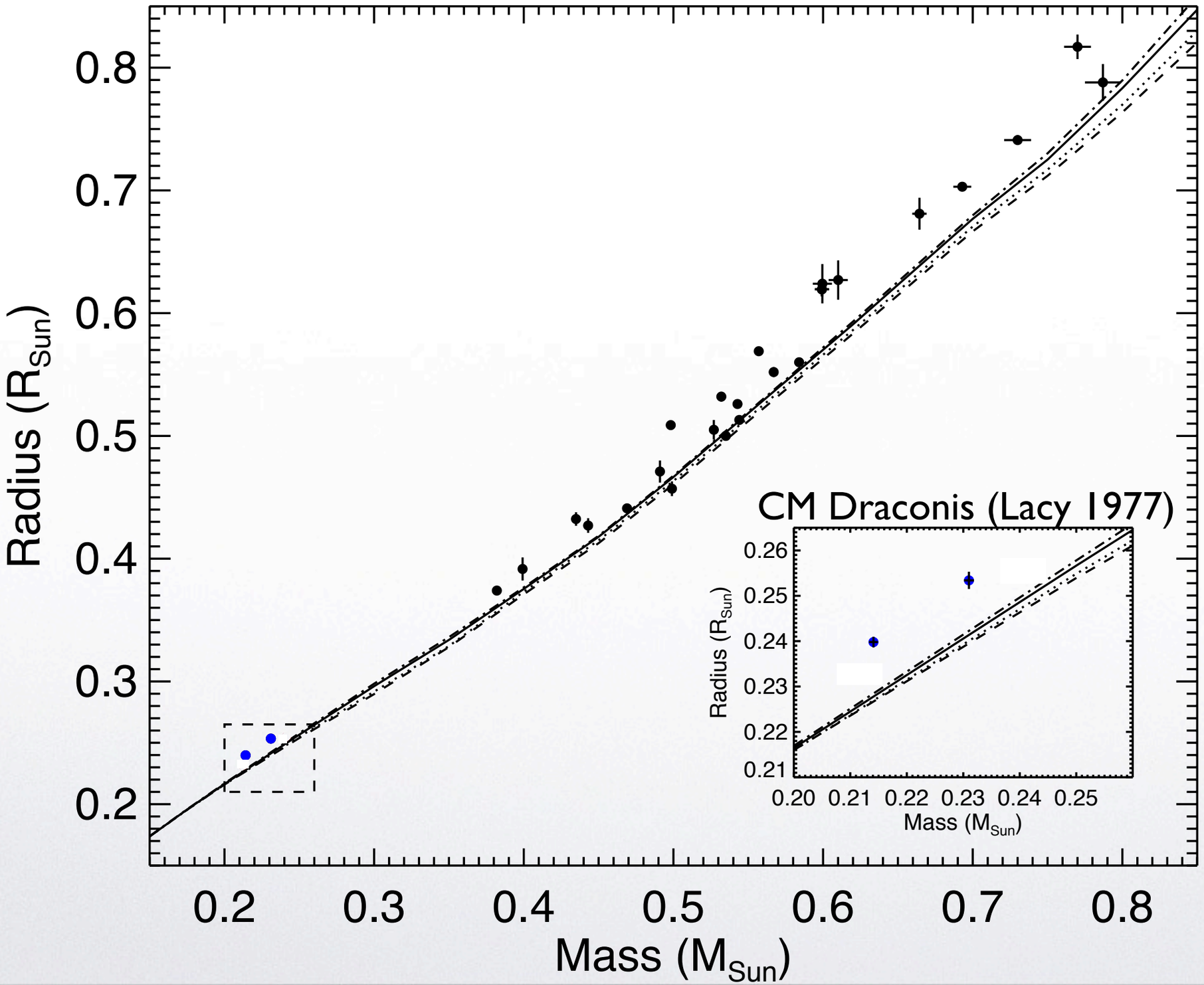
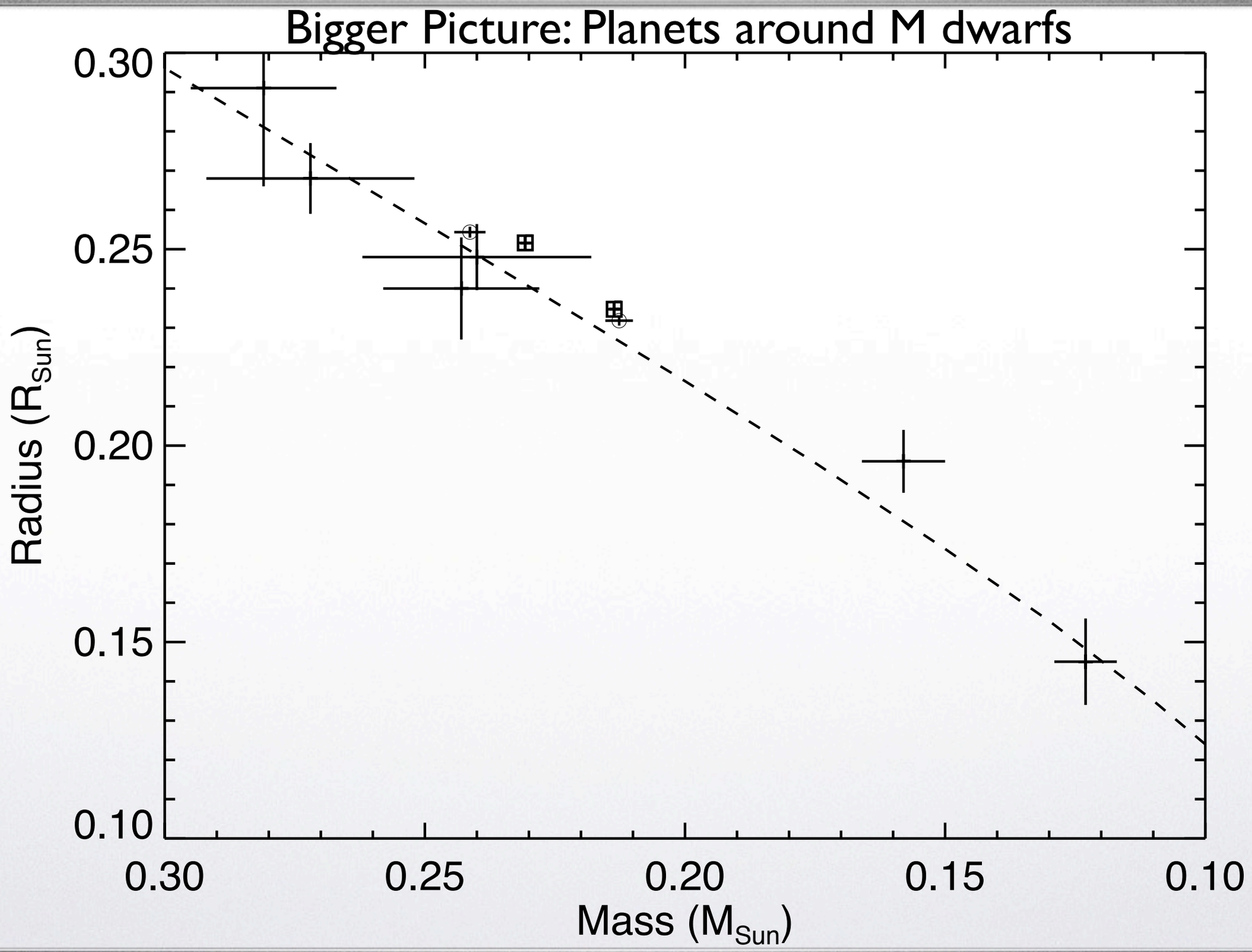


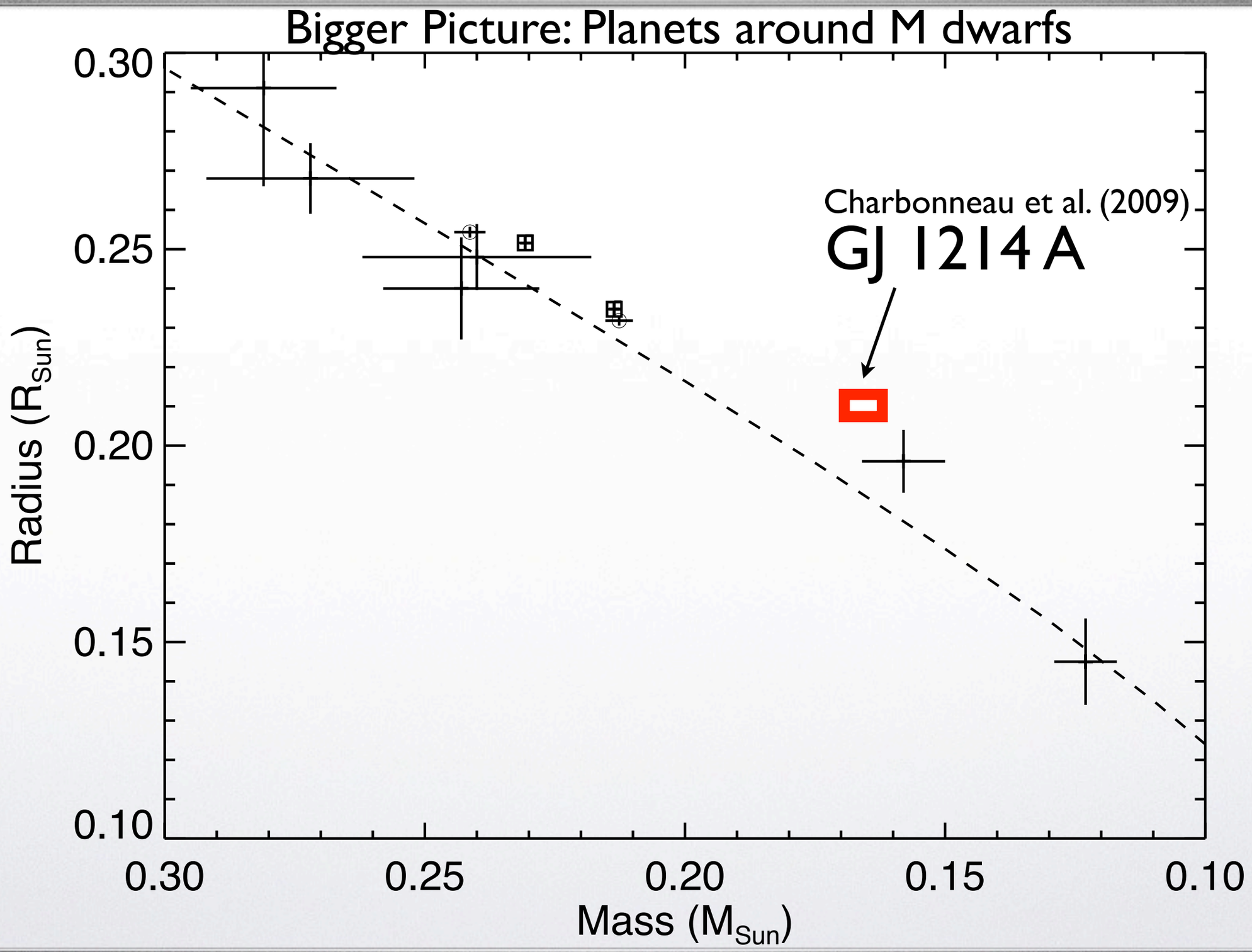
Figure modified from Carter et al. (2011)

Data from Kraus et al. (2011), Cakirli, Ibanoglu, Dervisoglu (2010)

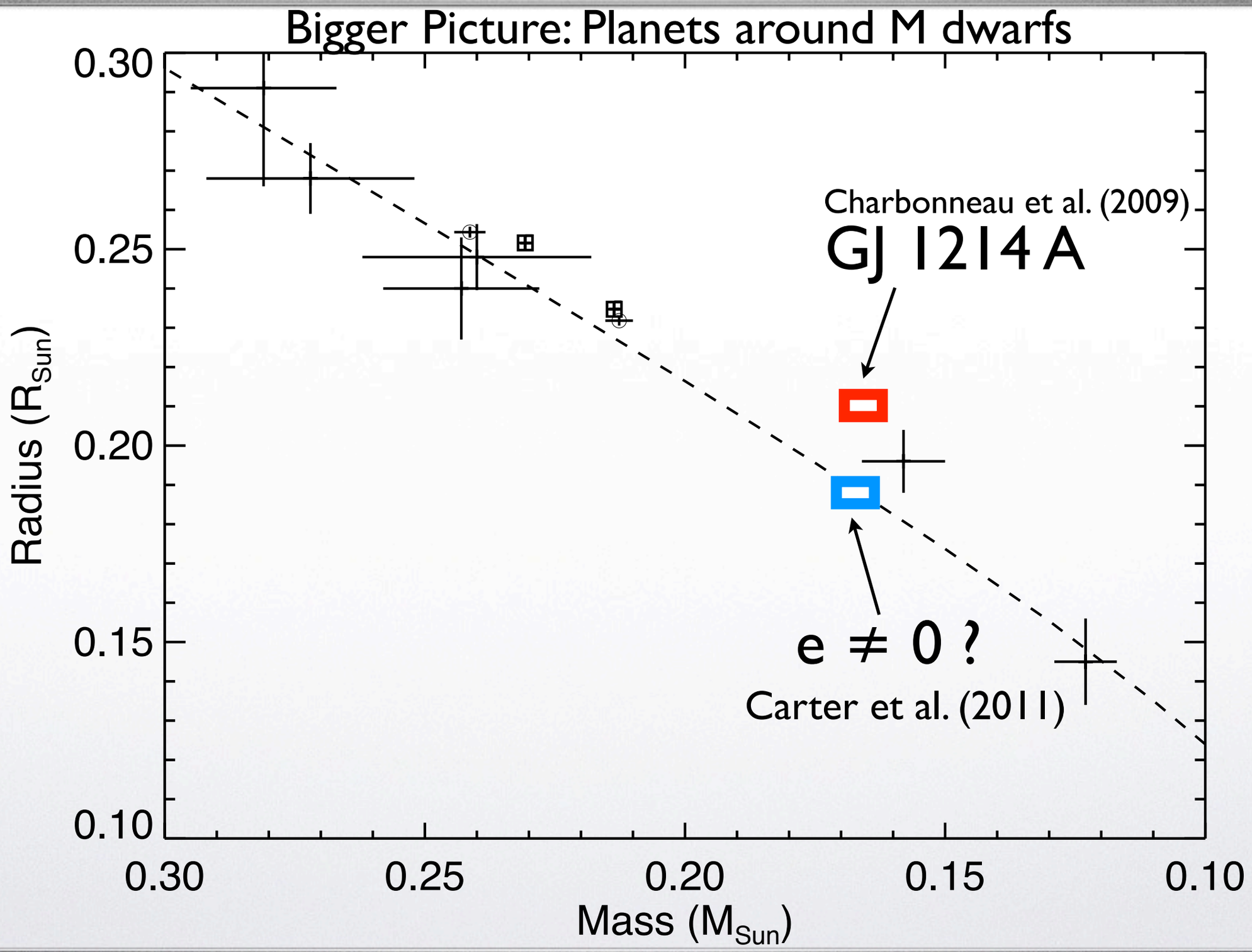
Absolute Dimensions - Low Mass



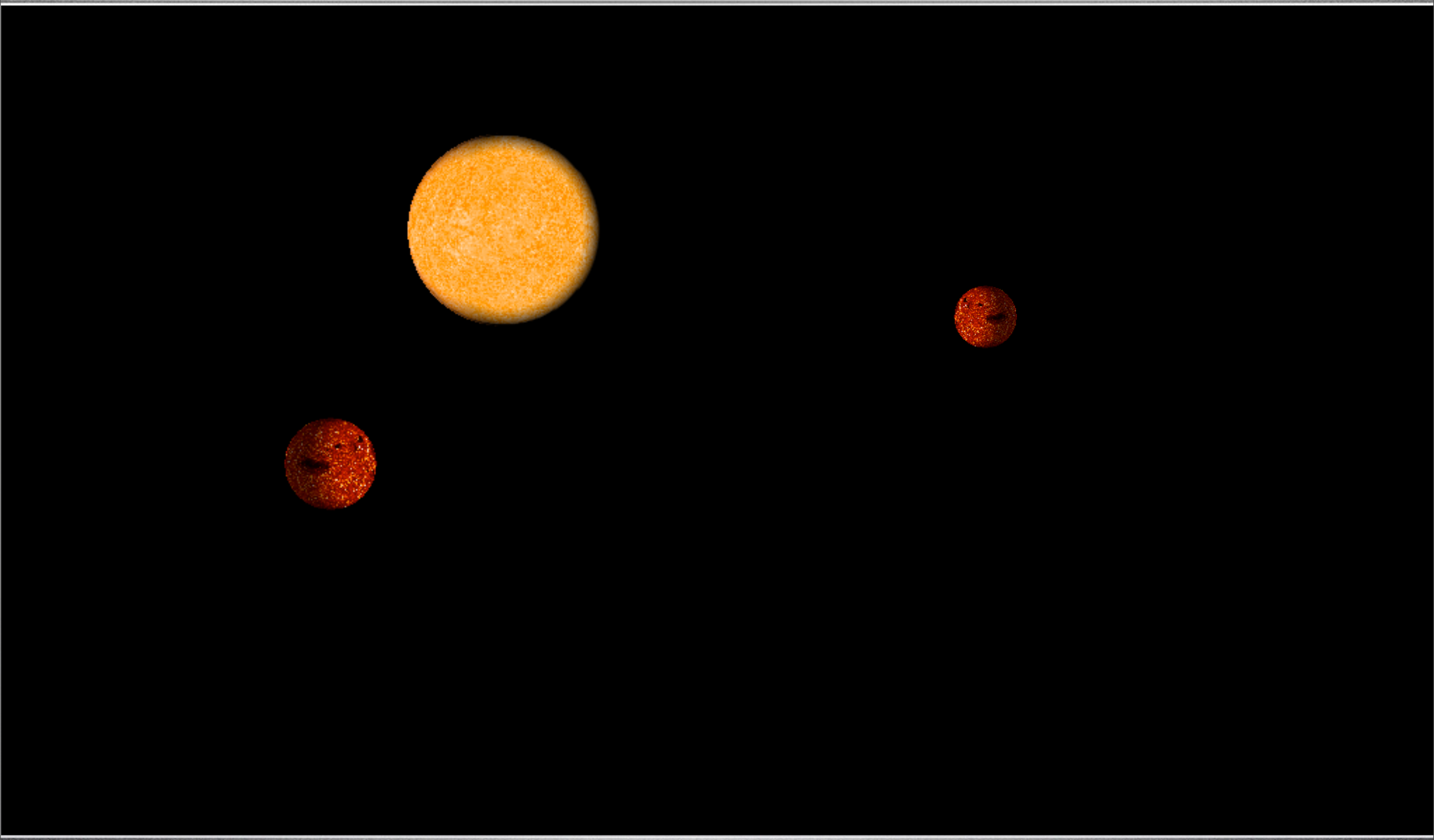
Absolute Dimensions - Low Mass

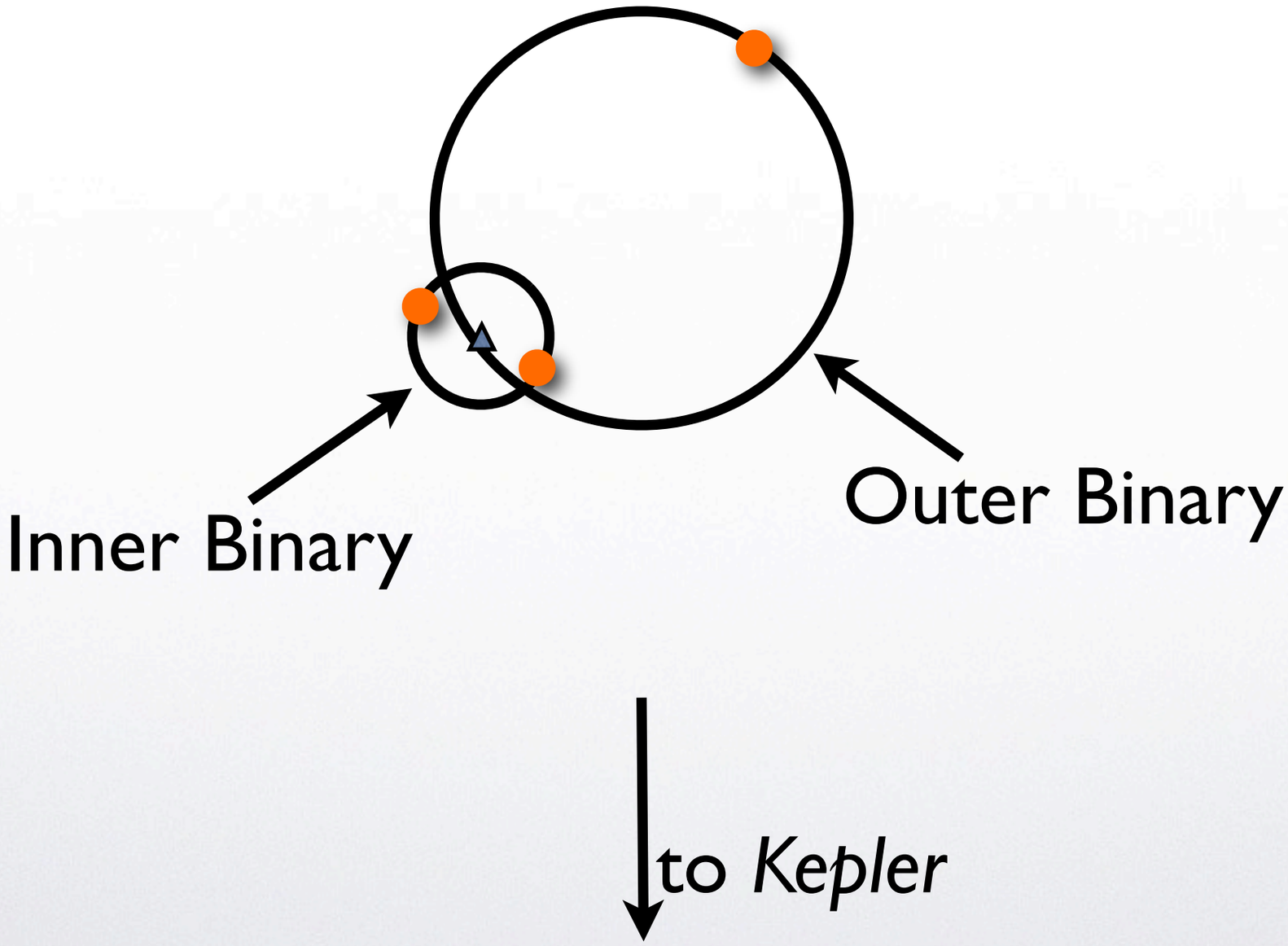


Absolute Dimensions - Low Mass

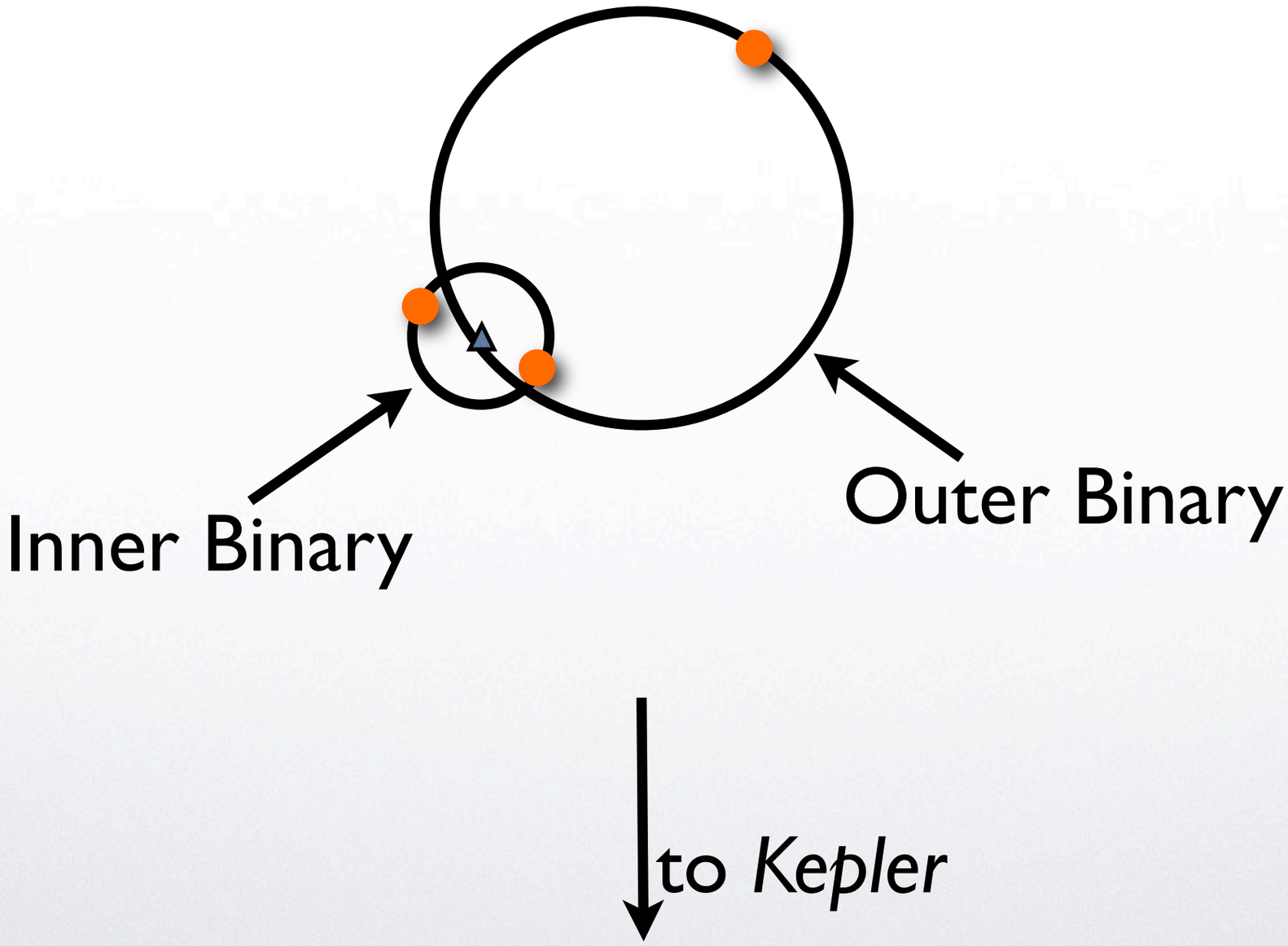


Multi-Eclipsing Hierarchical Triples

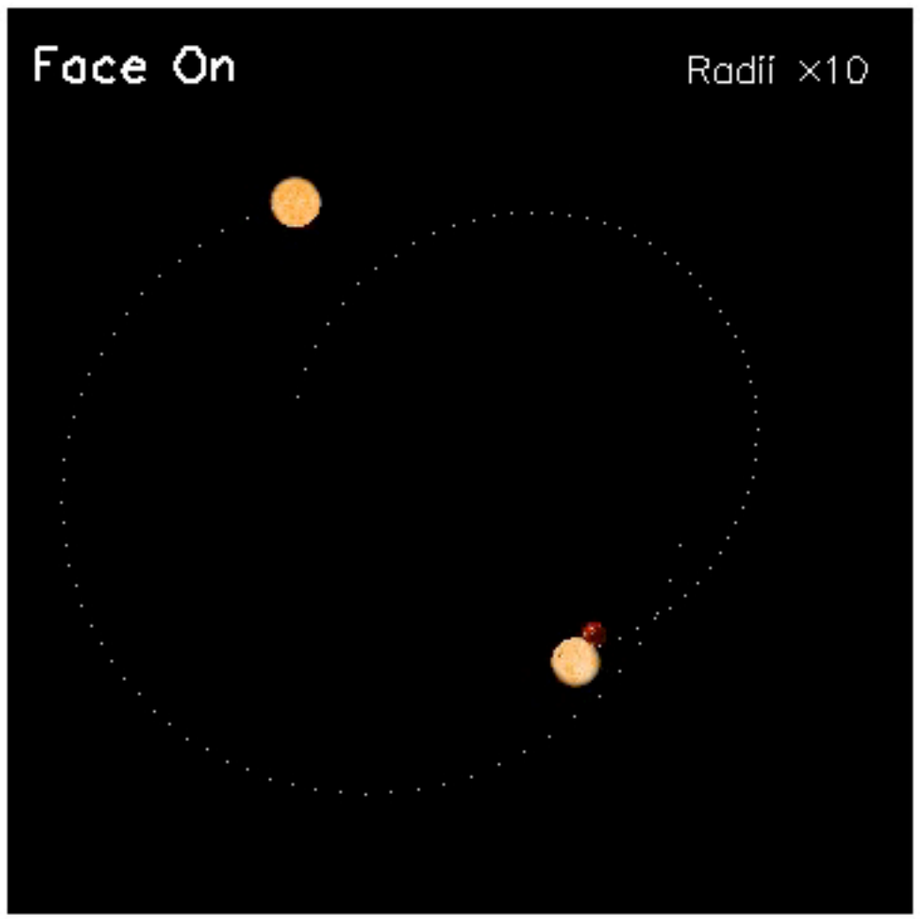


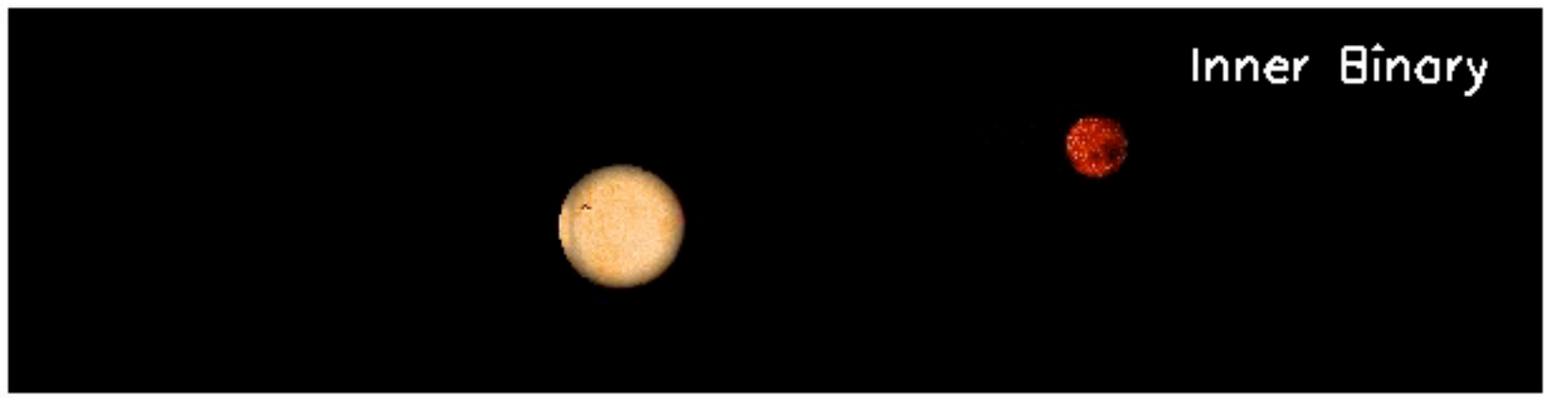

Inner Binary
Outer Binary
to *Kepler*

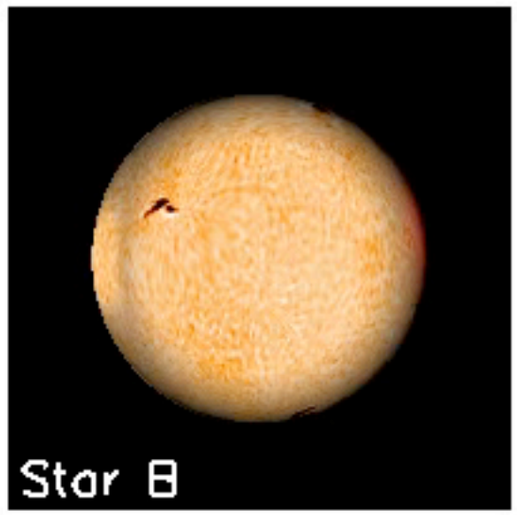
Multi-Eclipsing Hierarchical Triples

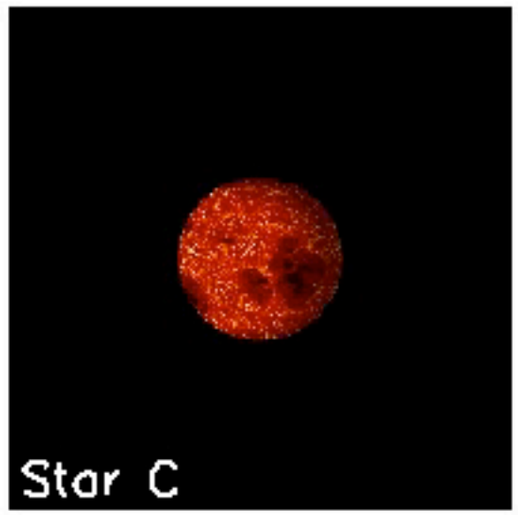


KIC-7289157

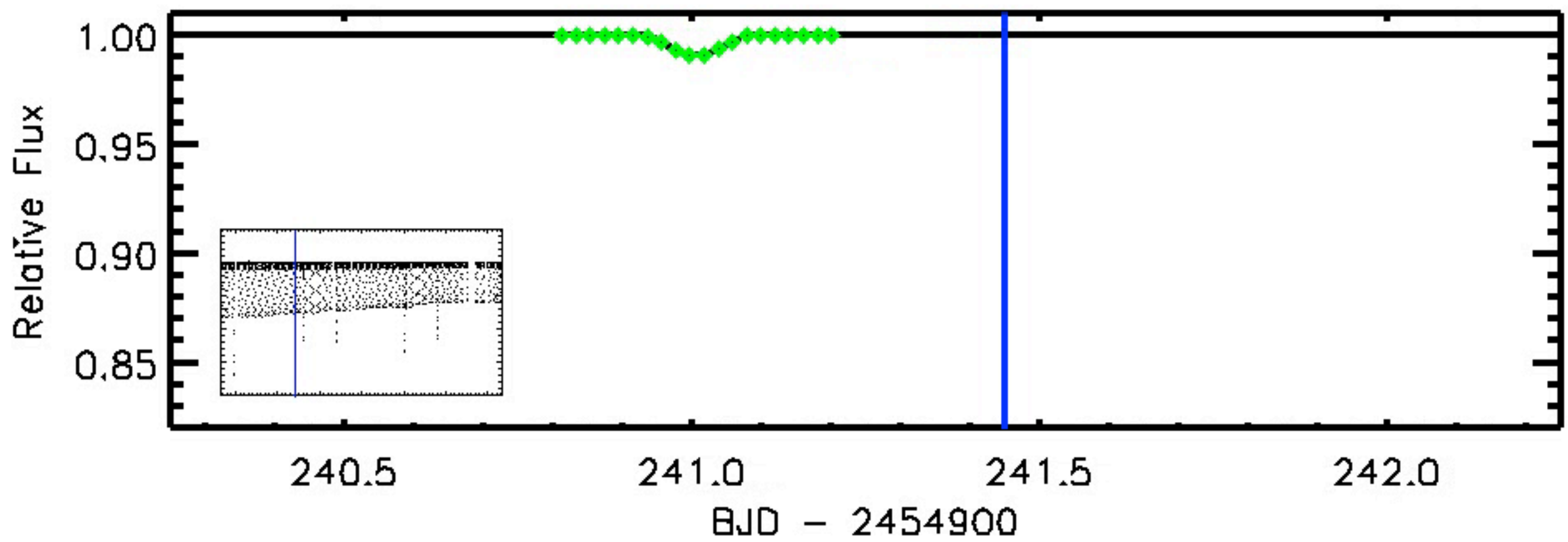

Face On
Radii ×10


Inner Binary


Star B


Star C

Star A


1.00
0.95
0.90
0.85
Relative Flux
240.5
241.0
241.5
242.0
BJD – 2454900

- The dynamical interaction between the stars is encoded in a variable light curve morphology:
  - Non-linear conjunction times
  - Variable impact parameters (between eclipses and during eclipse)
  - Accelerations transverse to the line-of-sight (between eclipses and during eclipse)

Eclipsing Hierarchical Triples

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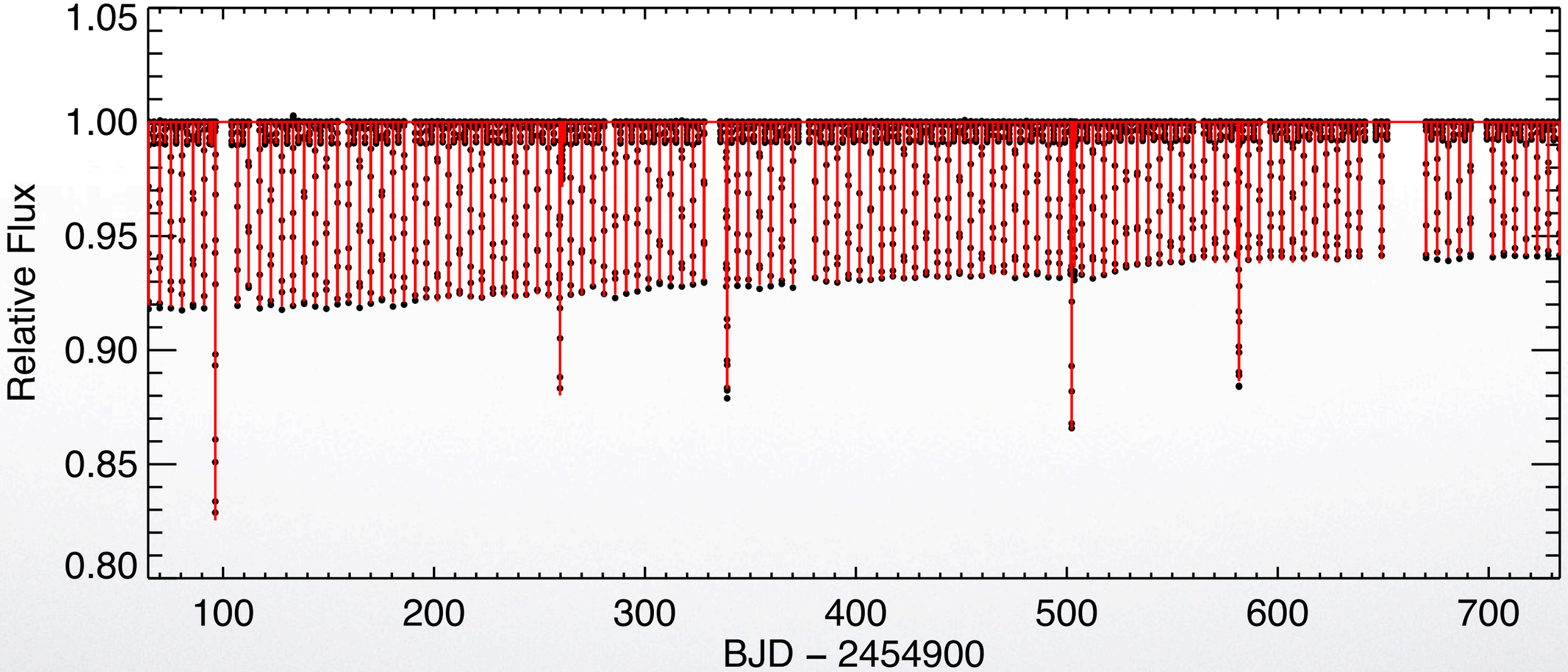
In the works... KIC 7289157



"Photodynamical" Model

- Dynamical:

➡Newton's Equations + Post-Newtonian acceleration in close, "inner" binary

➡Optional, additional perturbing accelerations in inner binary:

➡Non-dissipative equilibrium tide ("prolate distortion", k_2)

➡Rotationally-induced oblate distortion (k_2, spin frequency)

➡Tidal damping (Q); negligible on observation timescales

➡Correction to account for the finite speed of light.

- Photometric: Geometrical 3-body eclipse model

Eclipsing Hierarchical Triples "Photodynamical" Model

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$$\frac{M_A}{R_A^3}$$
$$\frac{M_B}{R_B^3}$$
$$\frac{M_C}{R_C^3}$$
$$\frac{M_B}{M_A}, \quad \frac{M_C}{M_A}, \quad \frac{M_B}{M_C}$$

From the RV (of A):

$$f(M_A, M_B + M_C) = \frac{(M_B+M_C)\sin^3 i}{\left(1+q_{A,B+C}^{-1}\right)^2}$$

Observables

From the light curve:

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$$\frac{M_C}{R_C^3}$$
$$\frac{M_B}{M_A}, \frac{M_C}{M_A}, \frac{M_B}{M_C}$$

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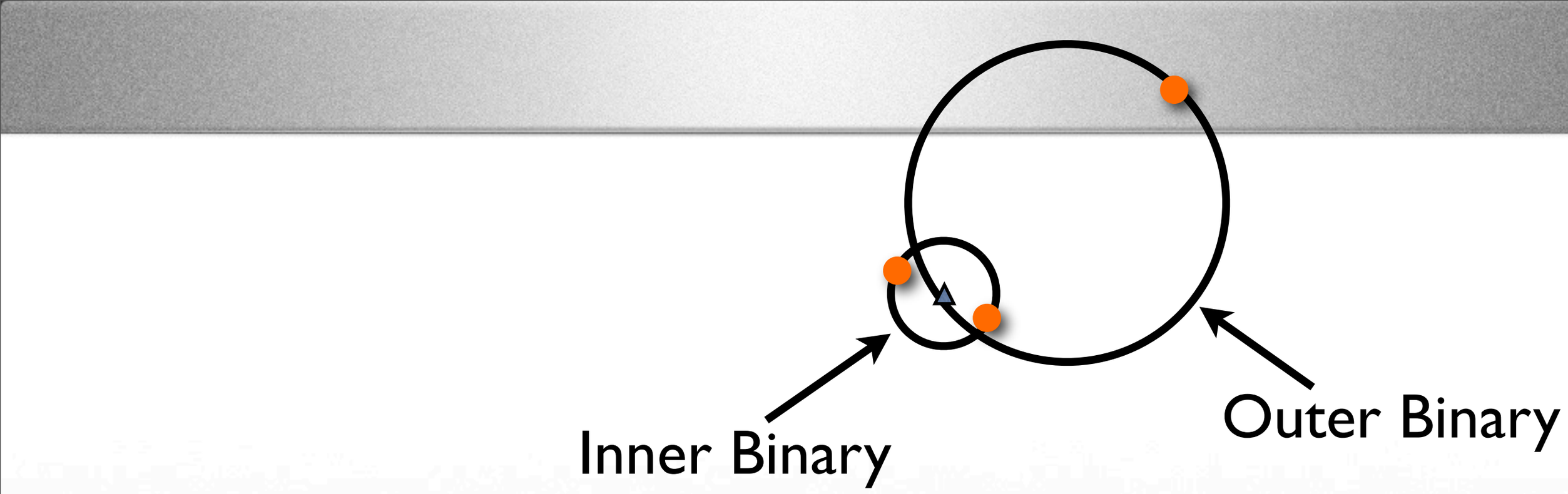
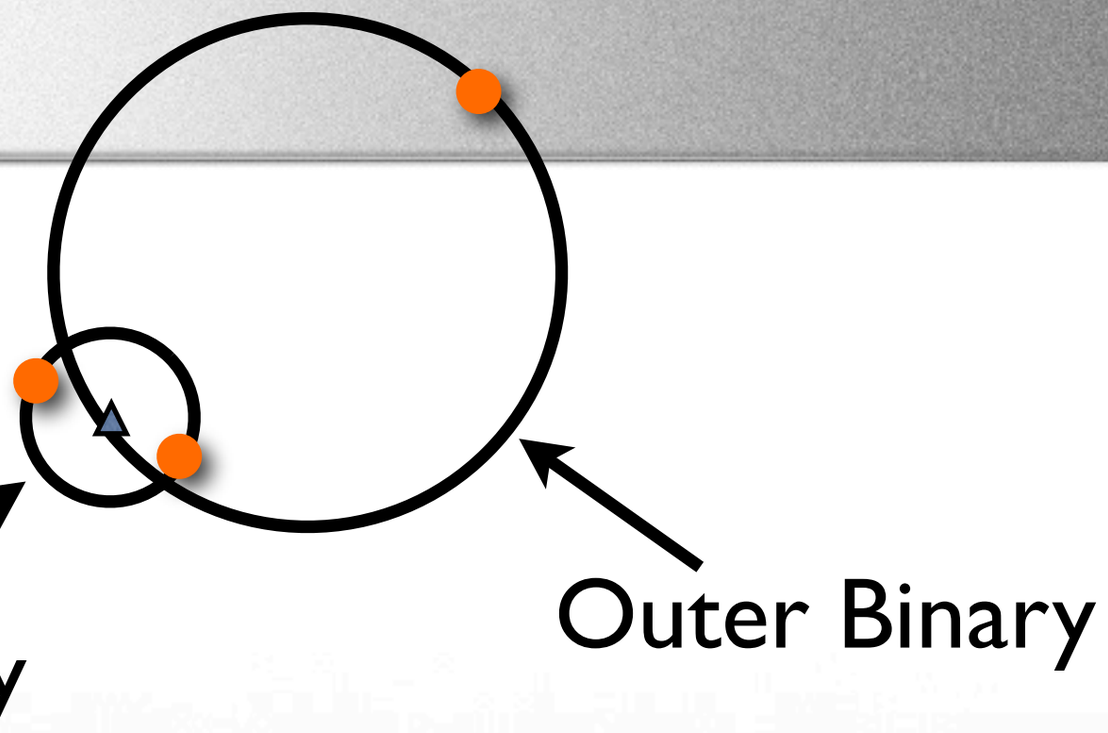
Masses and Radii!



- Timescale for secular (orbit averaged) variations in the orbital elements depends on the period ratio squared, mass ratios; need to be short enough to see some action in a human lifetime:

- Short periods (<1yr), small period ratios (20:1 or better)

Eclipsing Hierarchical Triples



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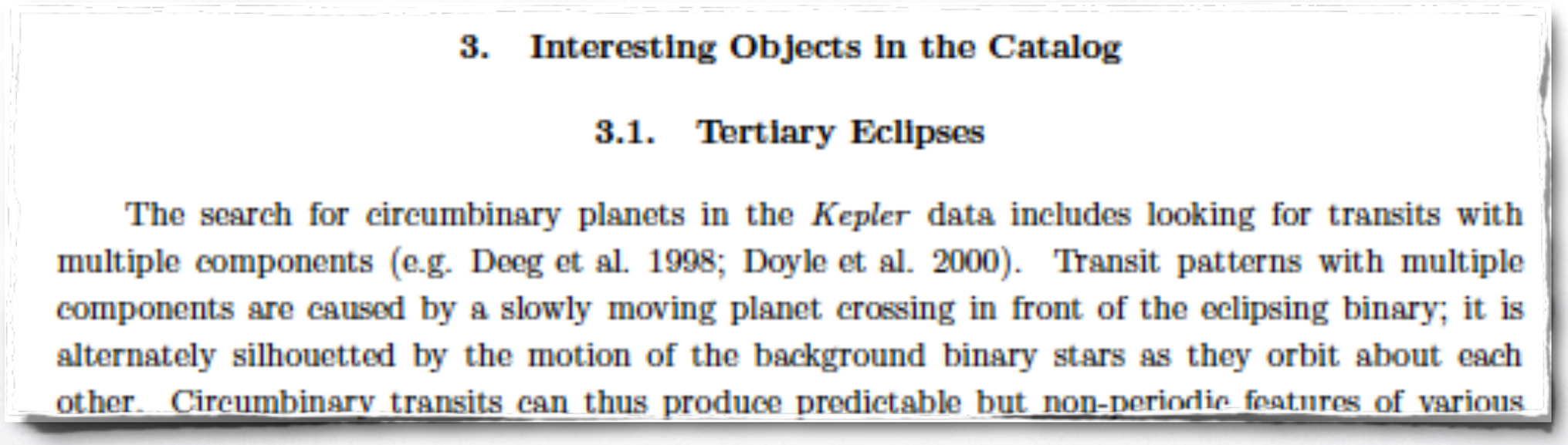
- *Kepler* is observationally biased towards detecting multi-eclipsing dynamical triples: and we* find them!



3. Interesting Objects in the Catalog

3.1. Tertiary Eclipses

The search for circumbinary planets in the *Kepler* data includes looking for transits with multiple components (e.g. Deeg et al. 1998; Doyle et al. 2000). Transit patterns with multiple components are caused by a slowly moving planet crossing in front of the eclipsing binary; it is alternately silhouetted by the motion of the background binary stars as they orbit about each other. Circumbinary transits can thus produce predictable but non-periodic features of various

Slawson et al. (2011)

*Thanks to the hard work of Jerry Orosz, Laurance Doyle, Bill Welsh and the rest of Kepler EB team...

Eclipsing Hierarchical Triples

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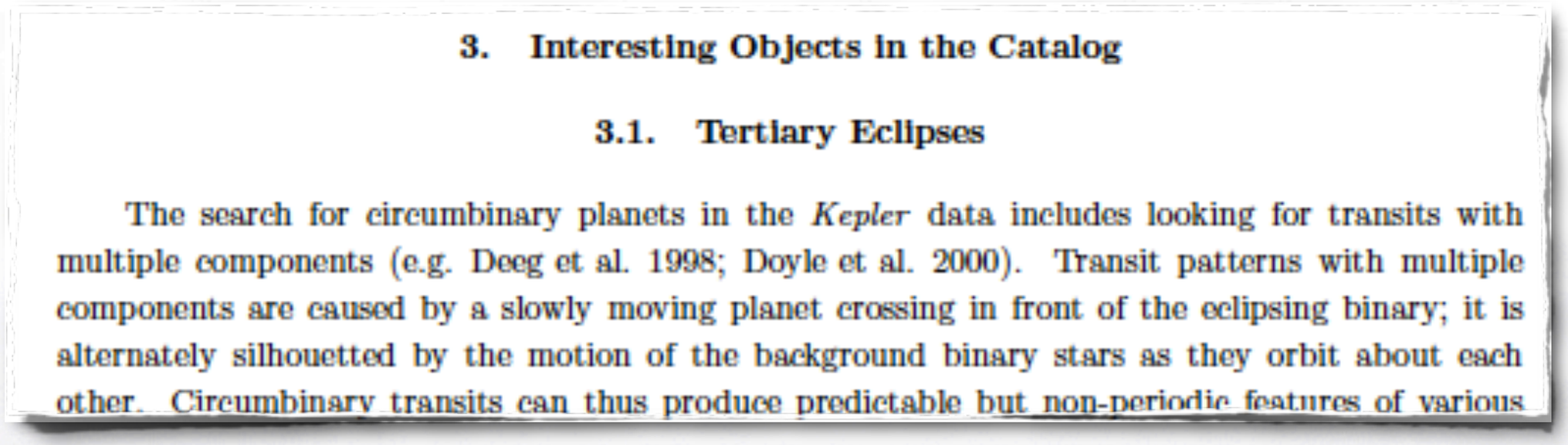


3. Interesting Objects in the Catalog

3.1. Tertiary Eclipses

The search for circumbinary planets in the *Kepler* data includes looking for transits with multiple components (e.g. Deeg et al. 1998; Doyle et al. 2000). Transit patterns with multiple components are caused by a slowly moving planet crossing in front of the eclipsing binary; it is alternately silhouetted by the motion of the background binary stars as they orbit about each other. Circumbinary transits can thus produce predictable but non-periodic features of various

Slawson et al. (2011)

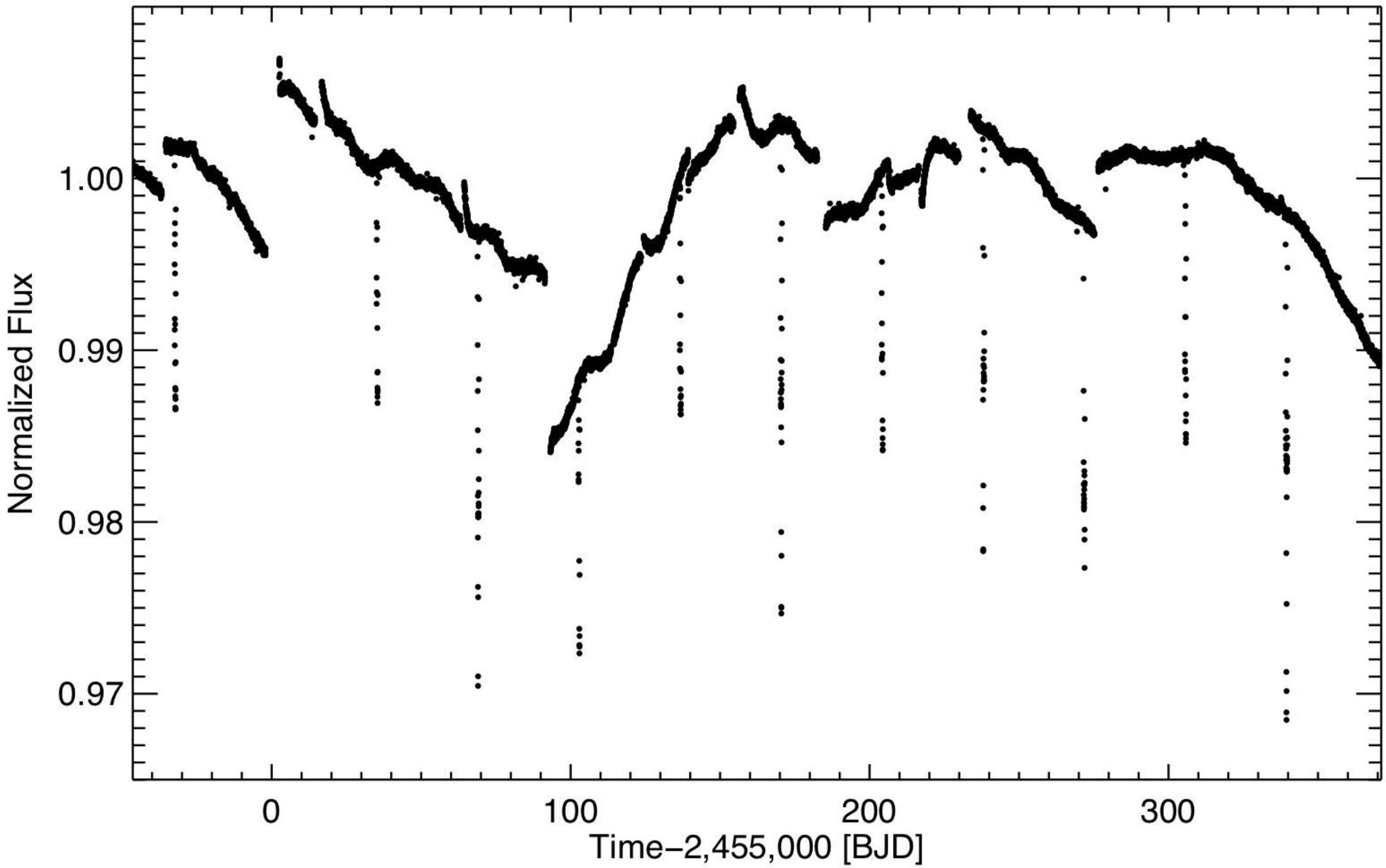
*Thanks to the hard work of Jerry Orosz, Laurance Doyle, Bill Welsh and the rest of Kepler EB team...

KOI-126: A Triply Eclipsing Hierarchical Triple with Two Low-Mass Stars

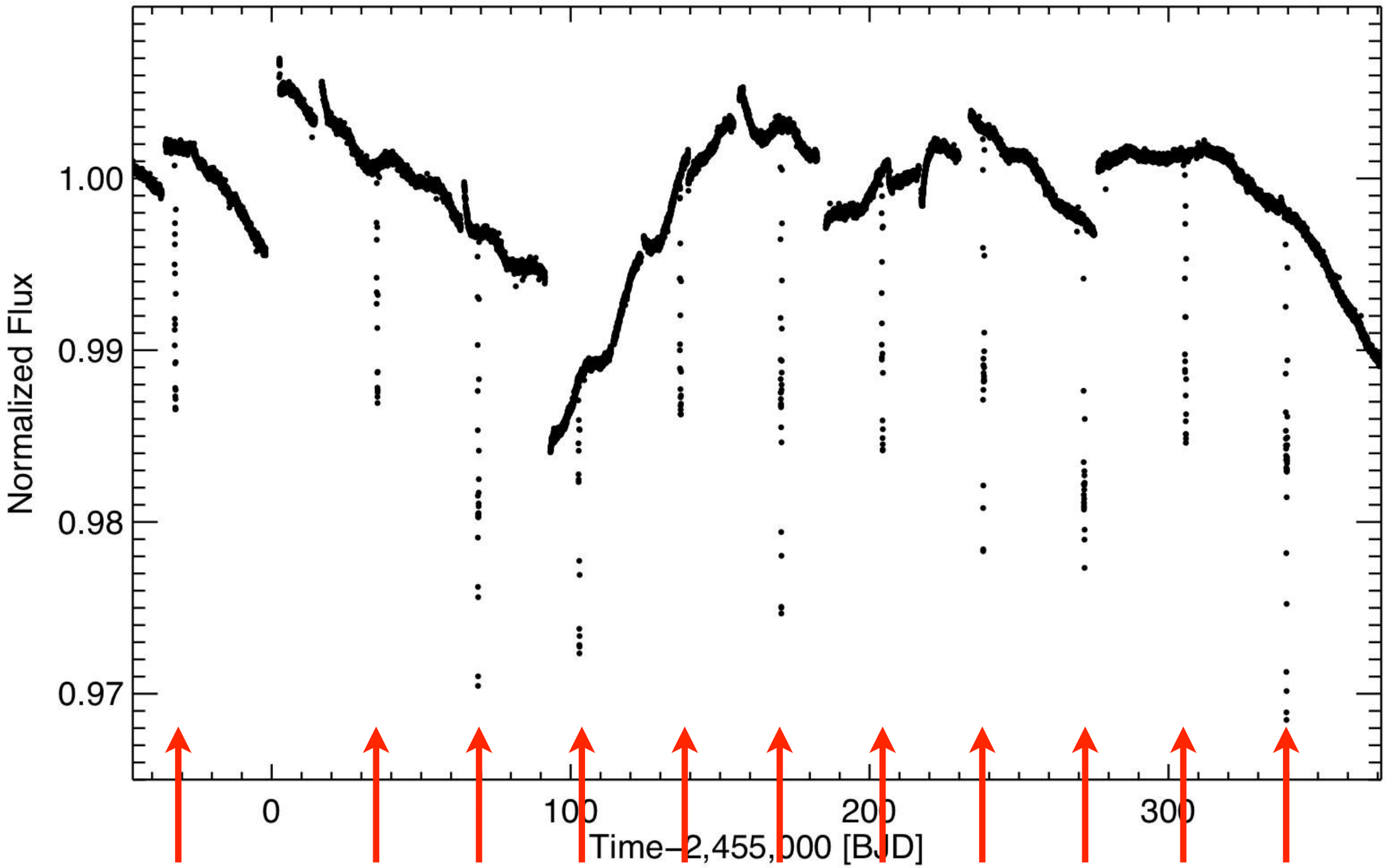
Joshua A. Carter,[1*] Daniel C. Fabrycky,[2] Darin Ragozzine,[1] Matthew J. Holman,[1] Samuel N. Quinn,[1]
David W. Latham,[1] Lars A. Buchhave,[1,3] Jeffrey Van Cleve,[4,7] William D. Cochran,[5] Miles T. Cote,[4]

Carter, Fabrycky, et al. (2011)

KOI-126

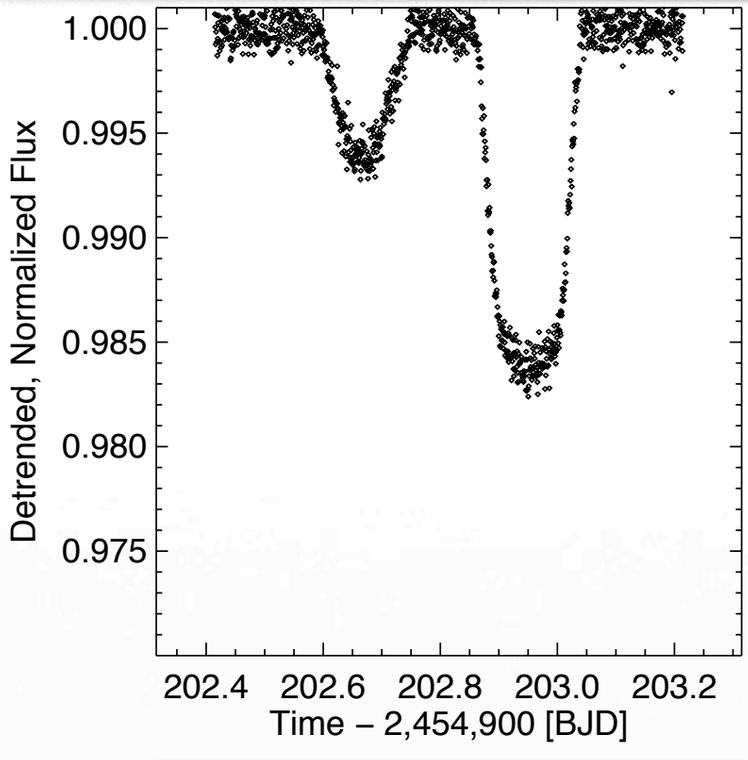

1.00
0.99
0.98
0.97
Normalized Flux
0
100
200
300
Time–2,455,000 [BJD]

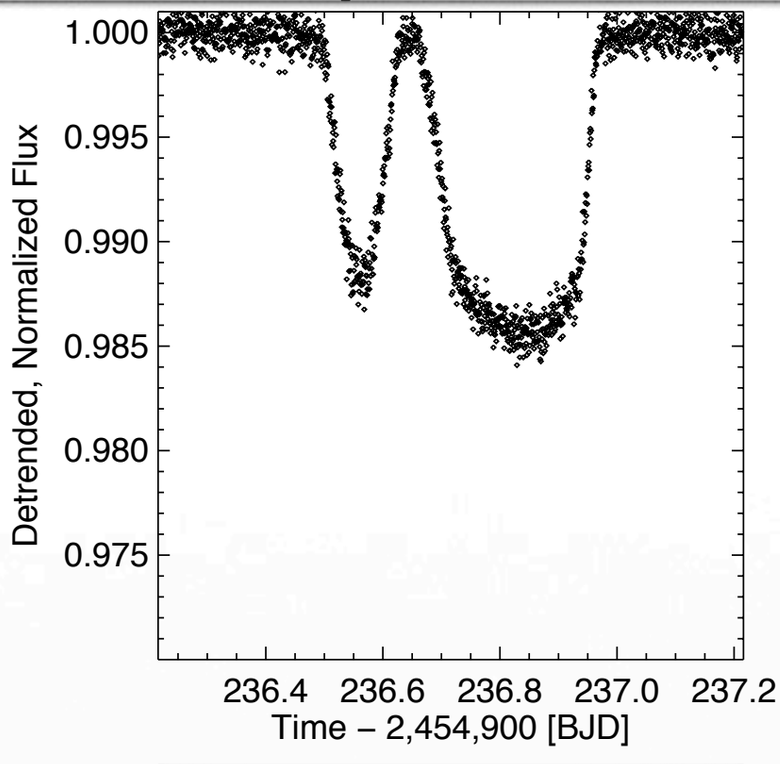
KOI-126

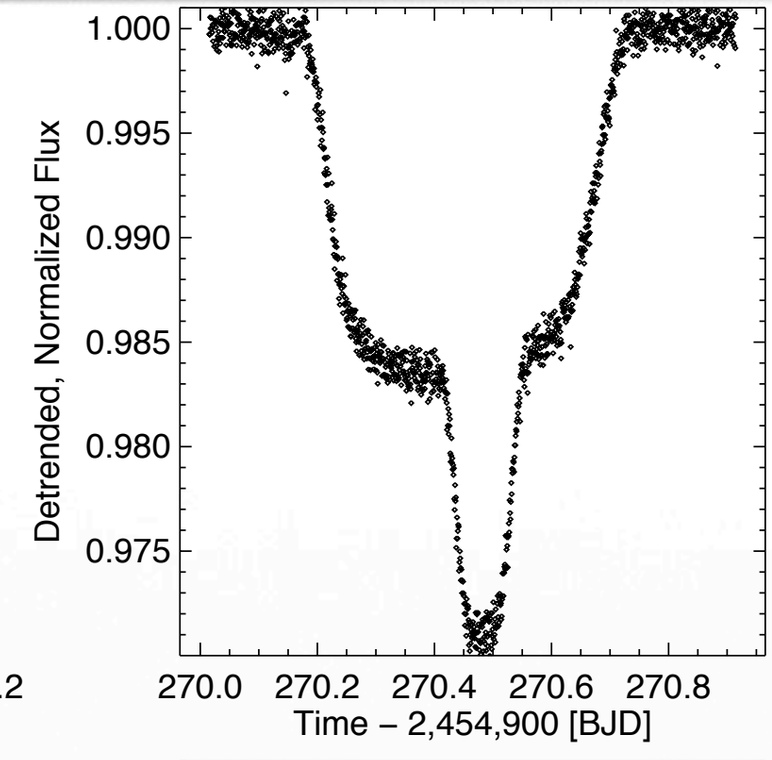

1.00
0.99
0.98
0.97
Normalized Flux
0
100
200
300
Time–2,455,000 [BJD]

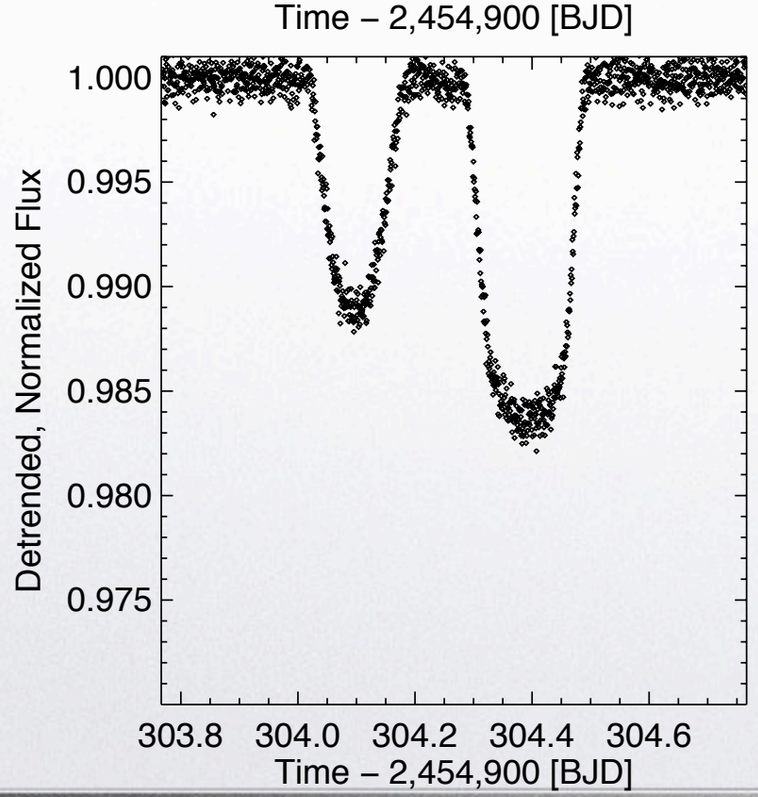
KOI-126: Light Curve Close-up

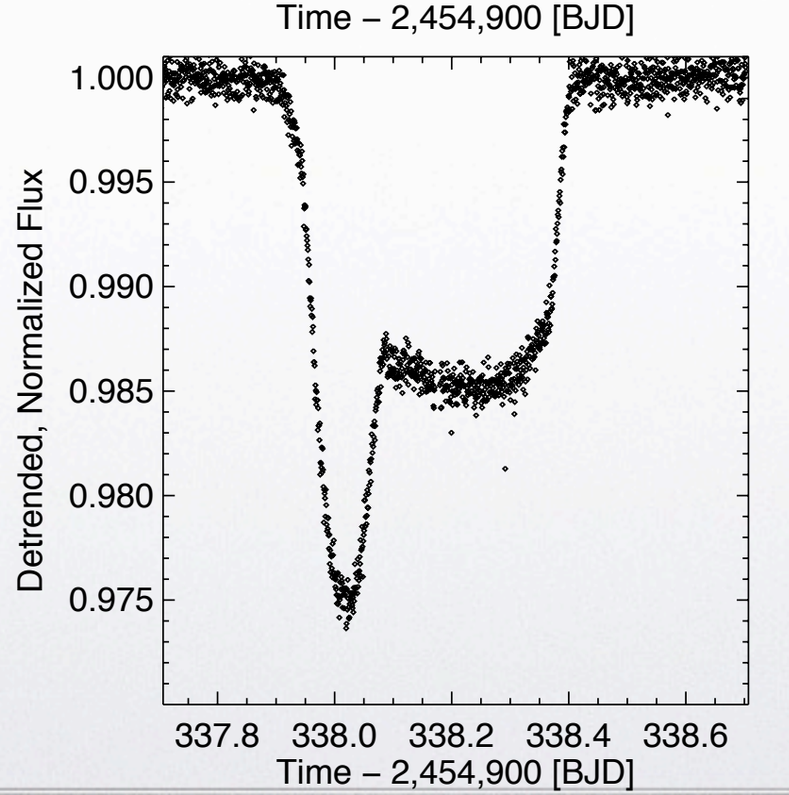
KOI-126: Light Curve Close-up

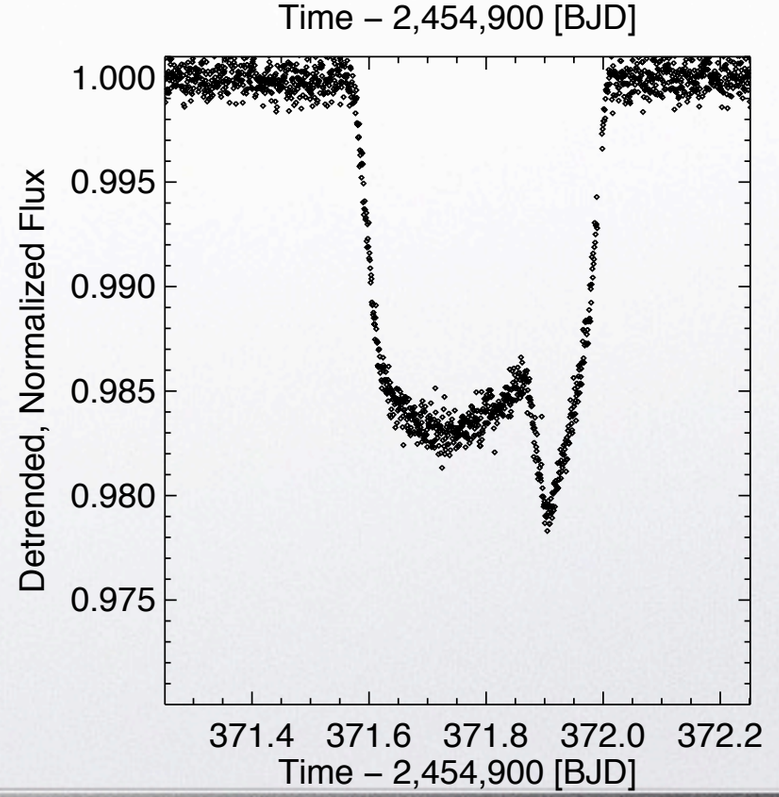




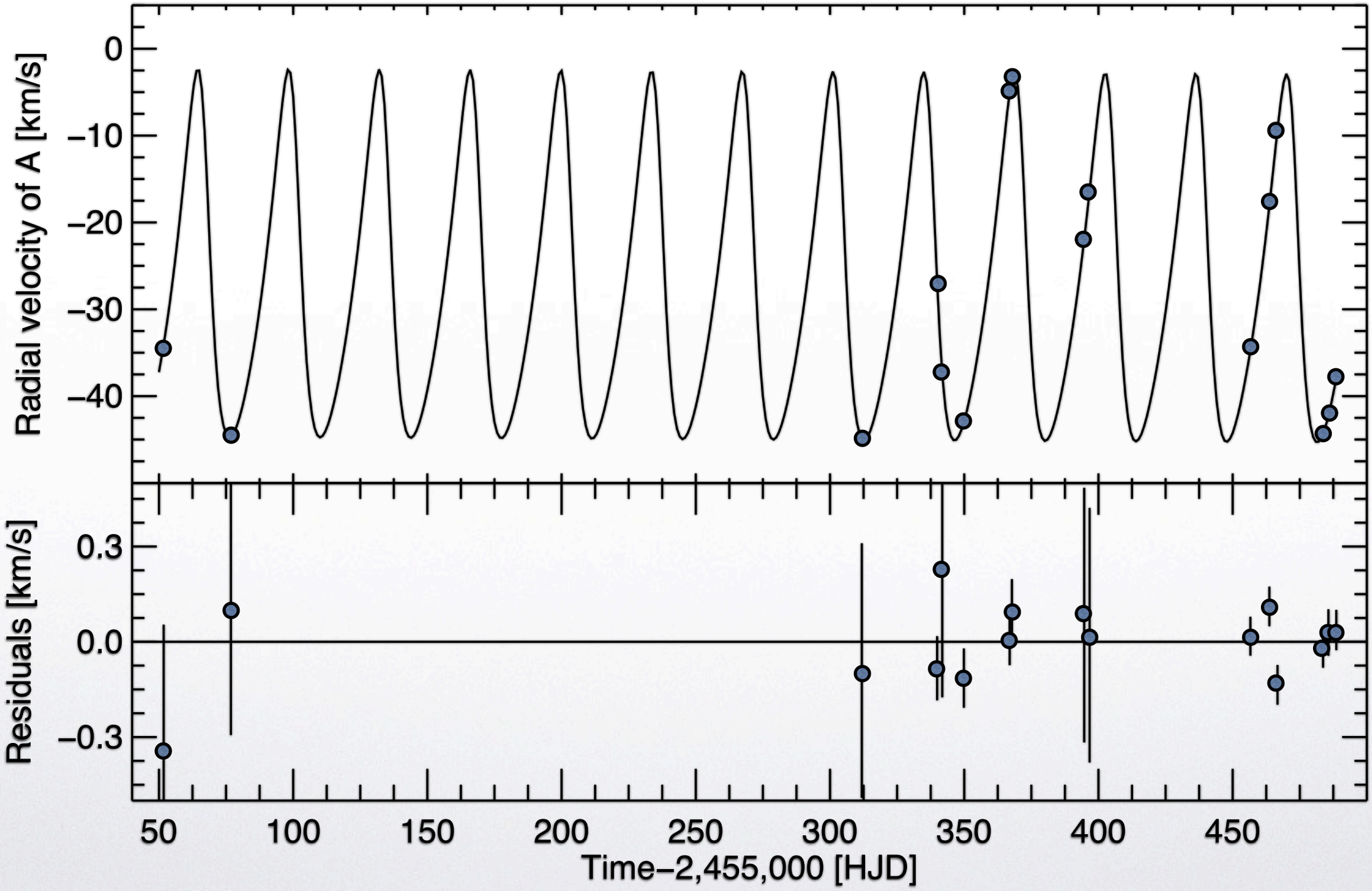




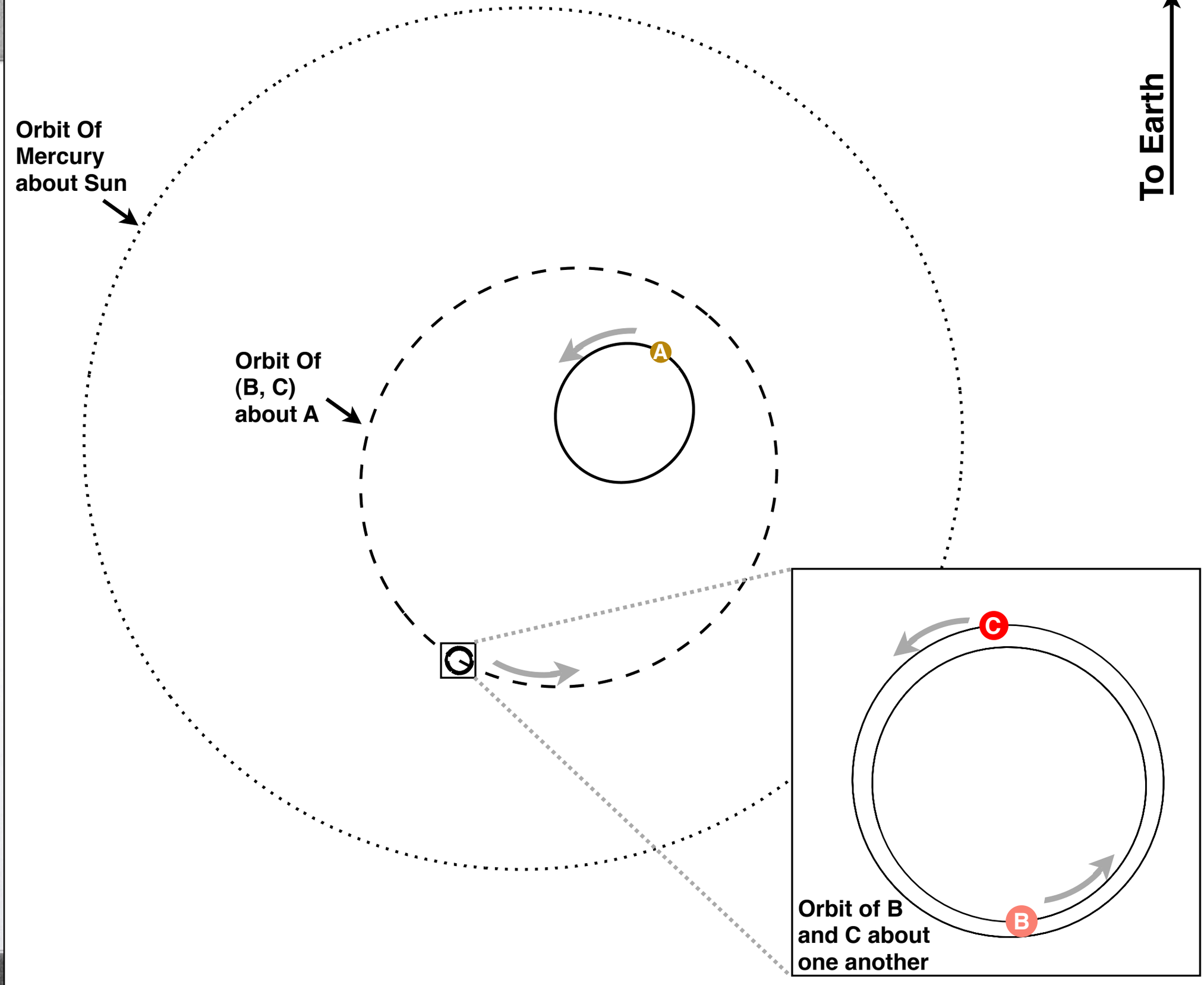




KOI-126


Radial velocity of A [km/s]
0
−10
−20
−30
−40
Residuals [km/s]
0.3
0.0
−0.3
50
100
150
200
250
300
350
400
450
Time−2,455,000 [HJD]

KOI-126: A Triply-Eclipsing Stellar System

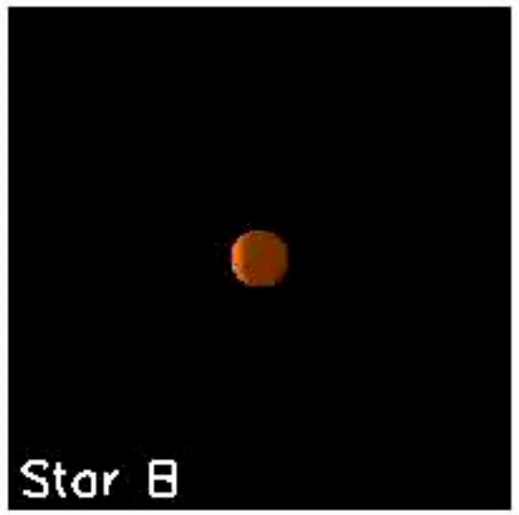


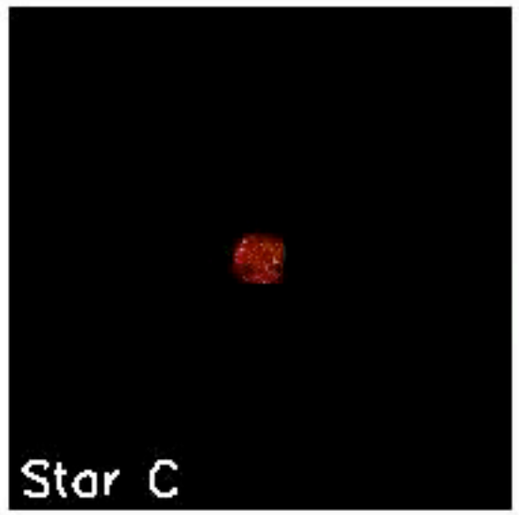
Orbits and Stars to Scale

KOI-126

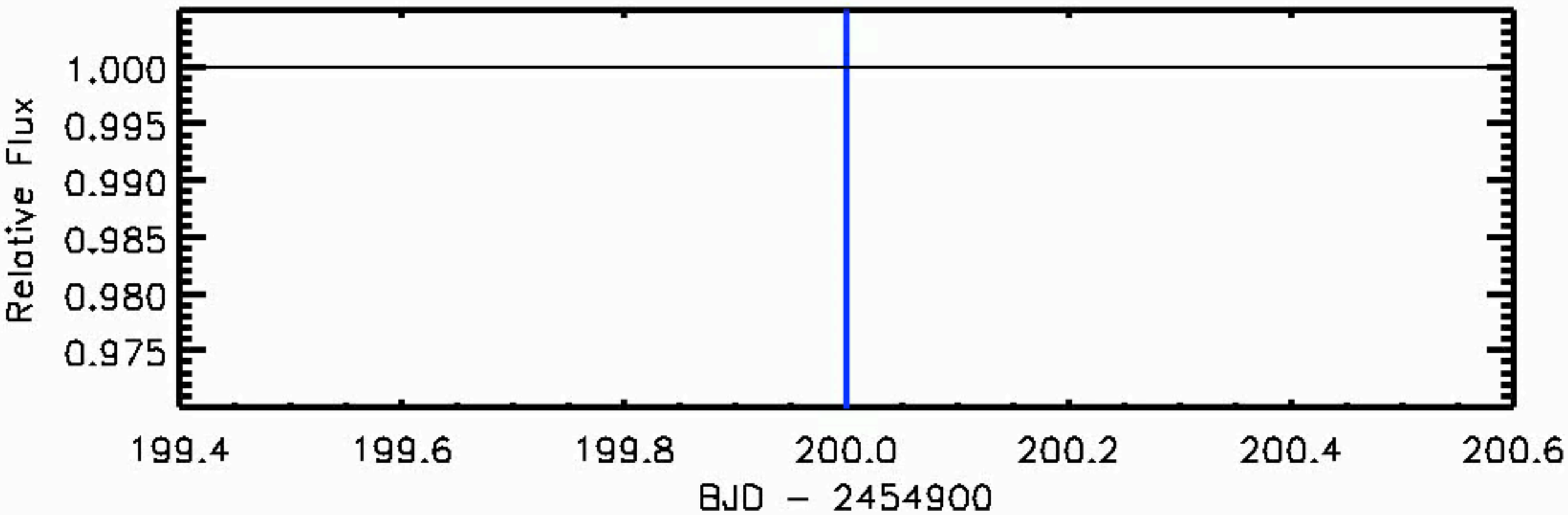
Face On
Radii ×10

Inner Binary

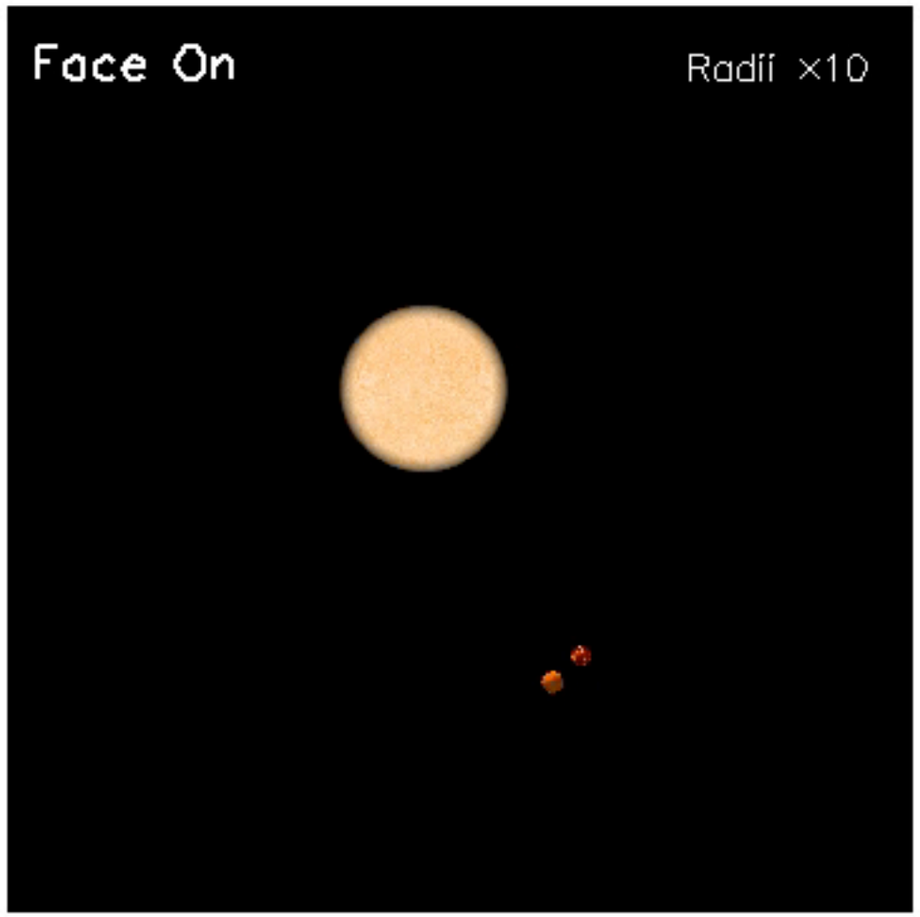

Star B


Star C

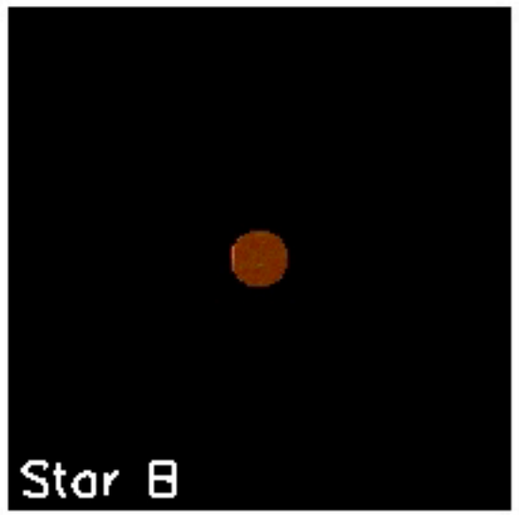
Star A

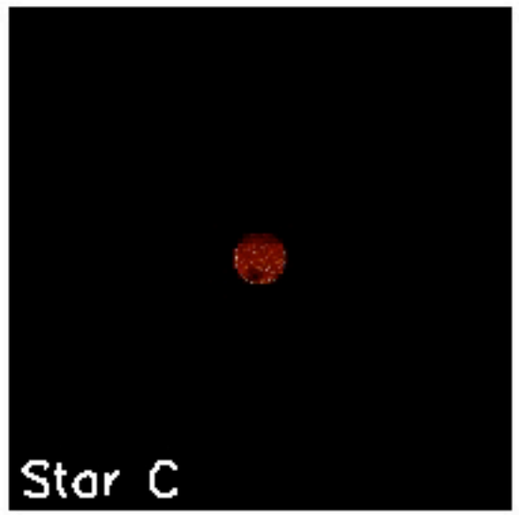

1.000
0.995
0.990
0.985
0.980
0.975
Relative Flux
199.4
199.6
199.8
200.0
200.2
200.4
200.6
BJD – 2454900

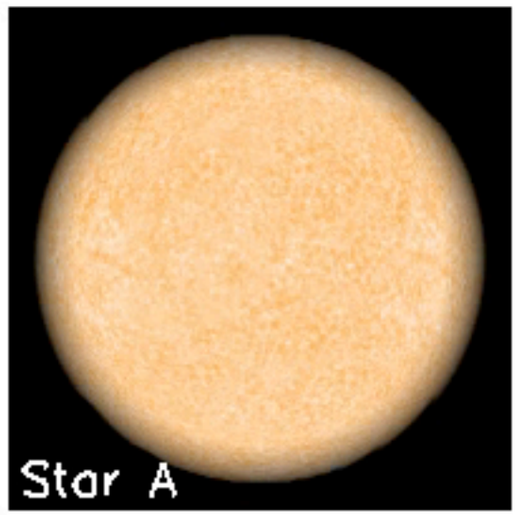
KOI-126

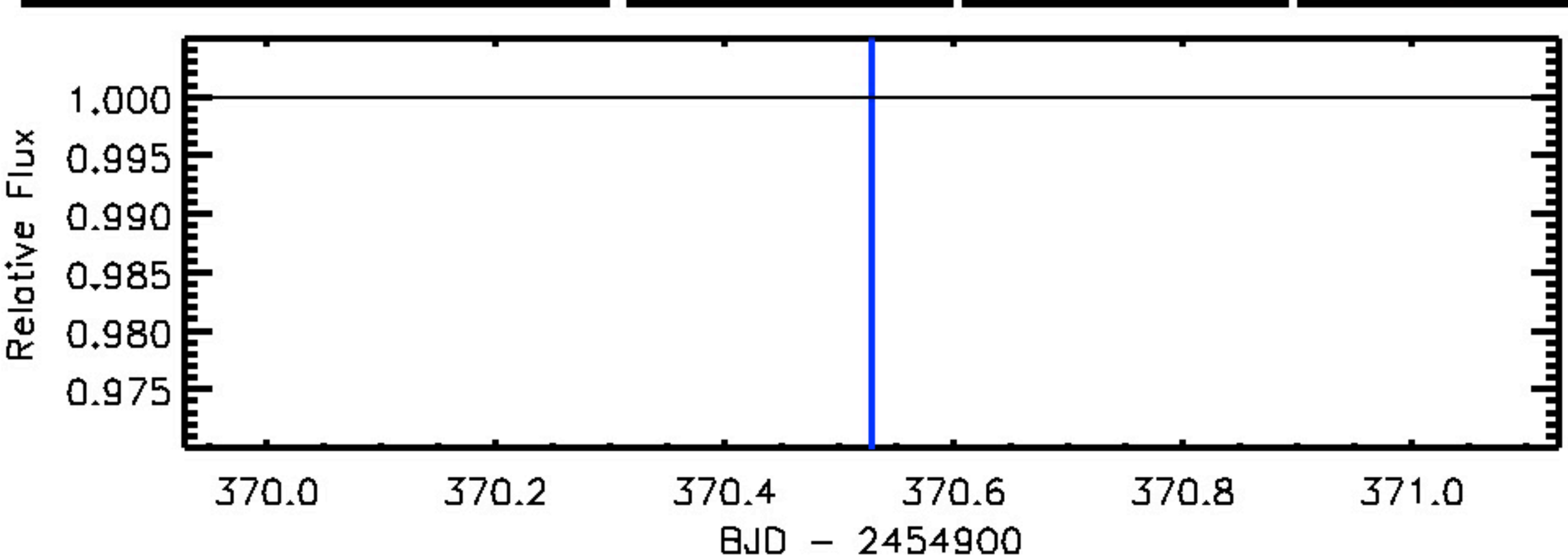

Face On
Radii ×10

Inner Binary

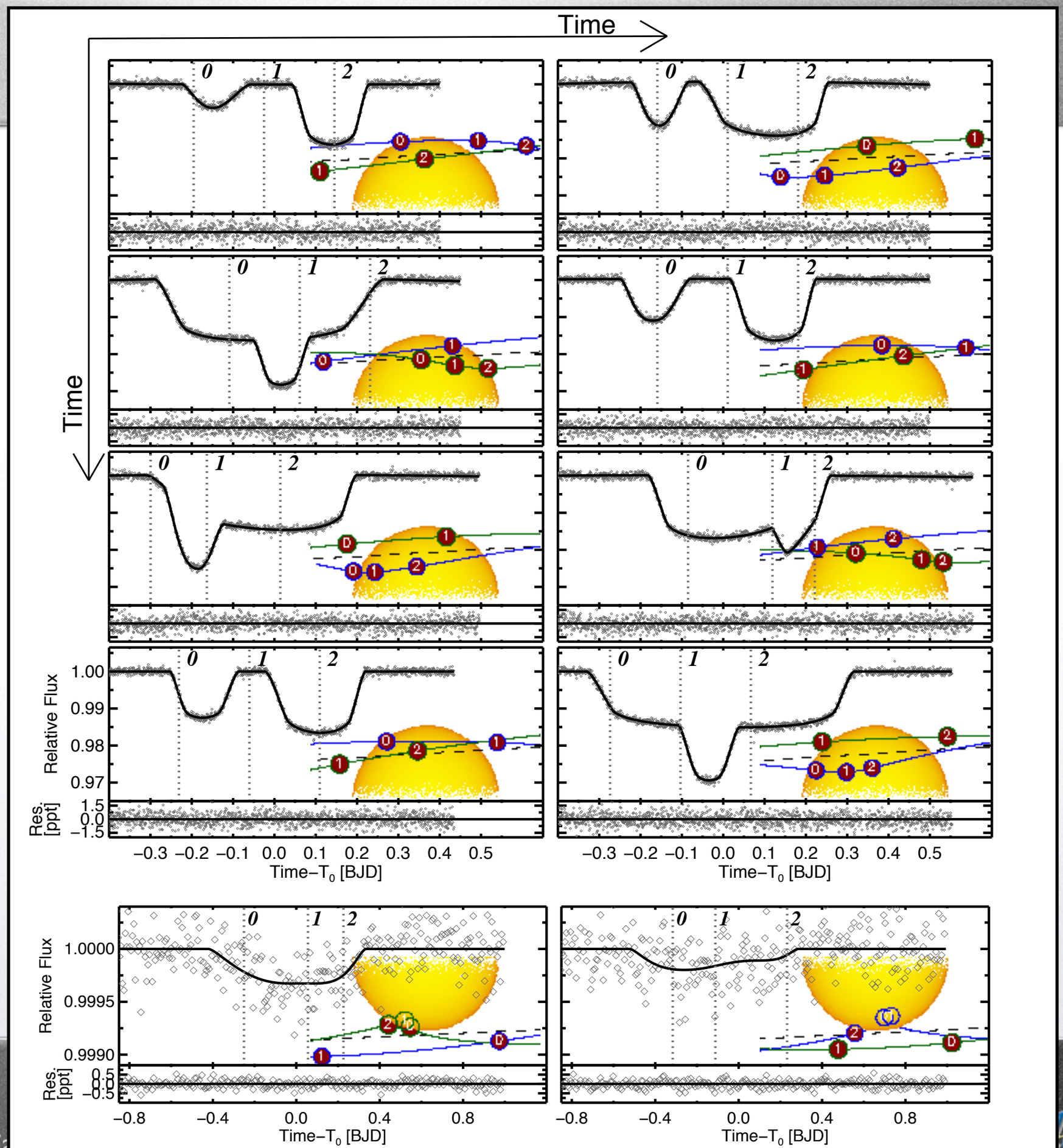

Star B


Star C

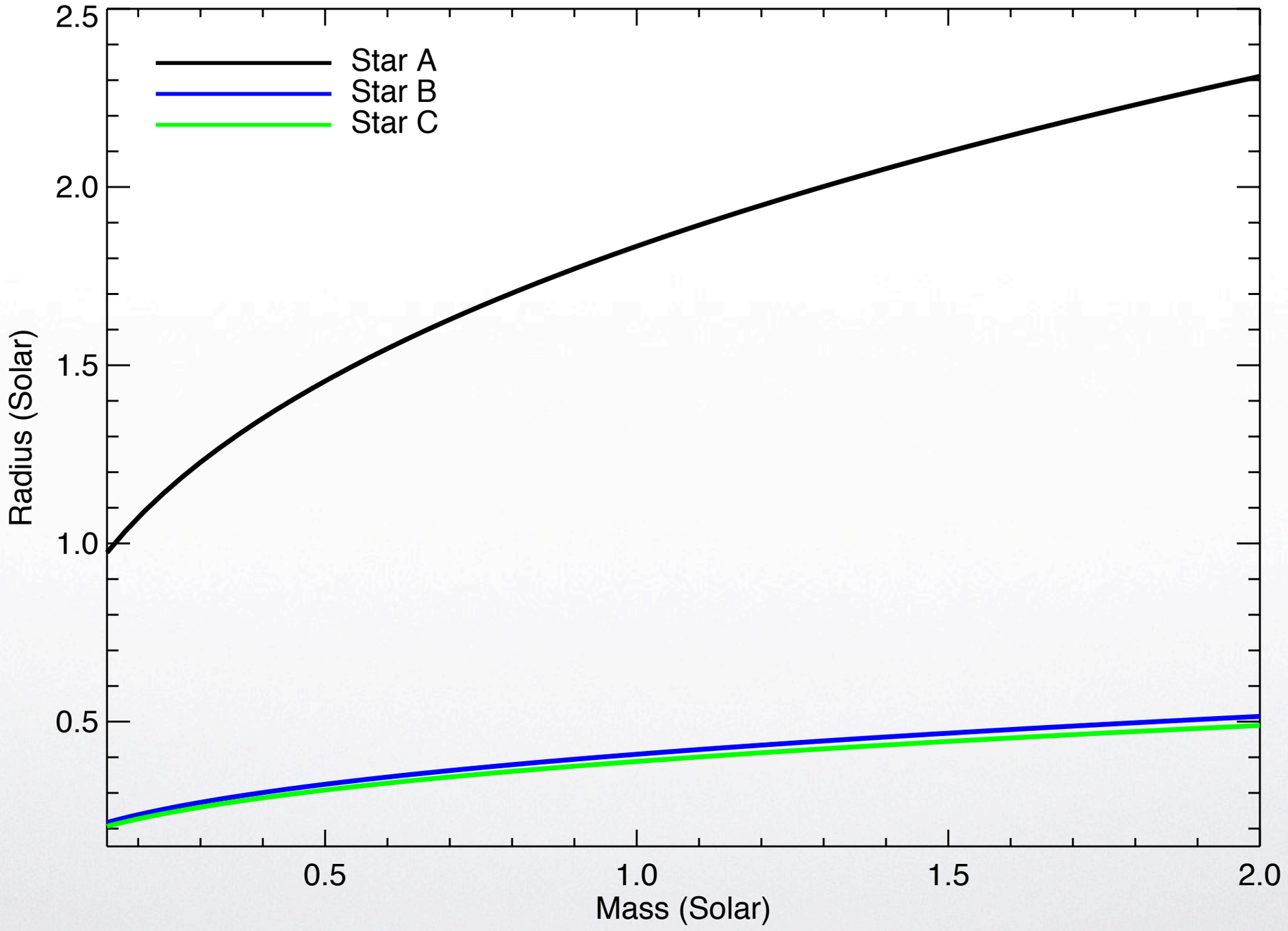

Star A


1.000
0.995
0.990
0.985
0.980
0.975
Relative Flux
370.0
370.2
370.4
370.6
370.8
371.0
BJD – 2454900

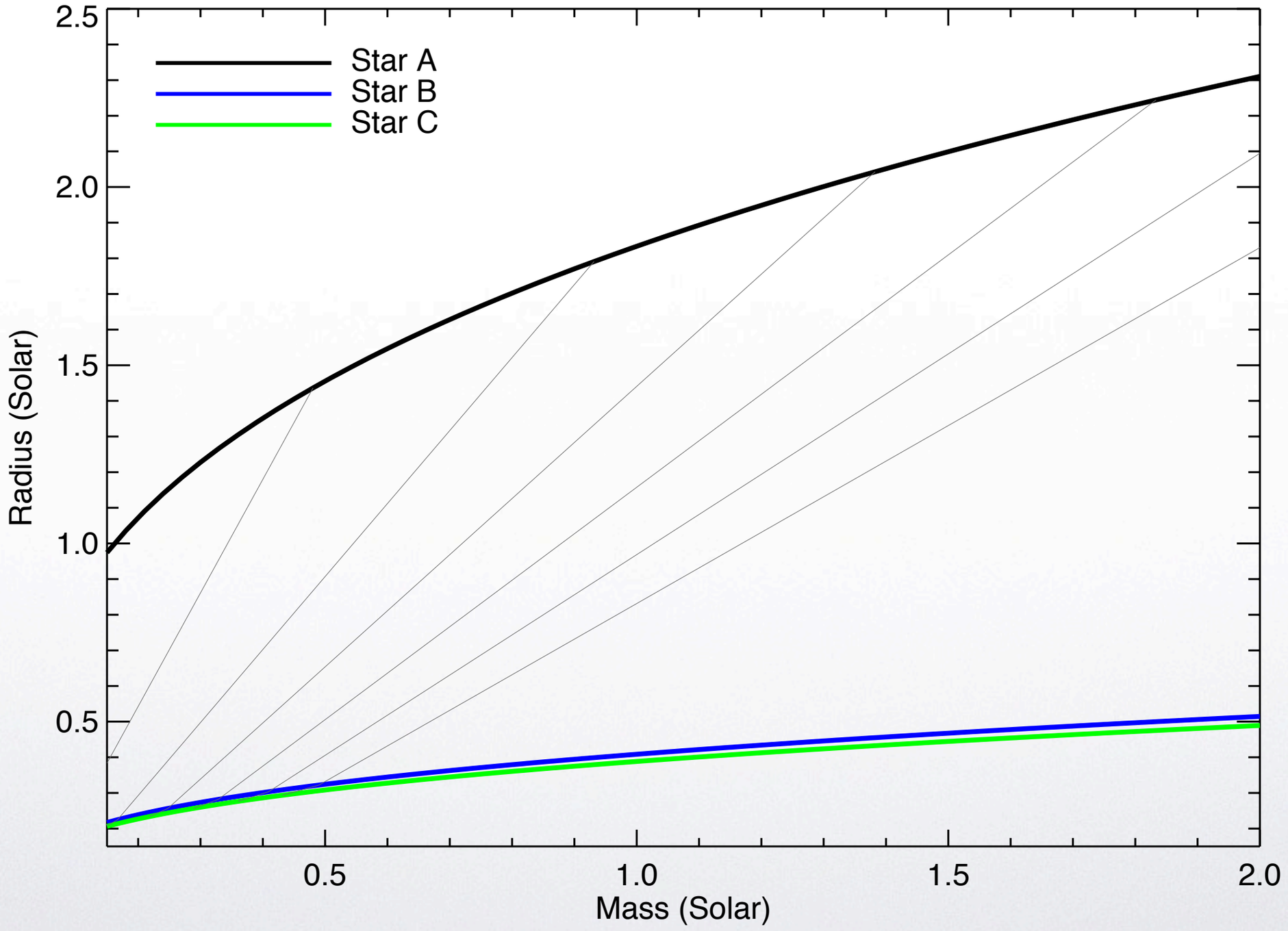
KOI-126


Time
Time
Relative Flux
Res. [ppt]
Time–T0 [BJD]
Time–T0 [BJD]
Relative Flux
Res. [ppt]
Time–T0 [BJD]
Time–T0 [BJD]

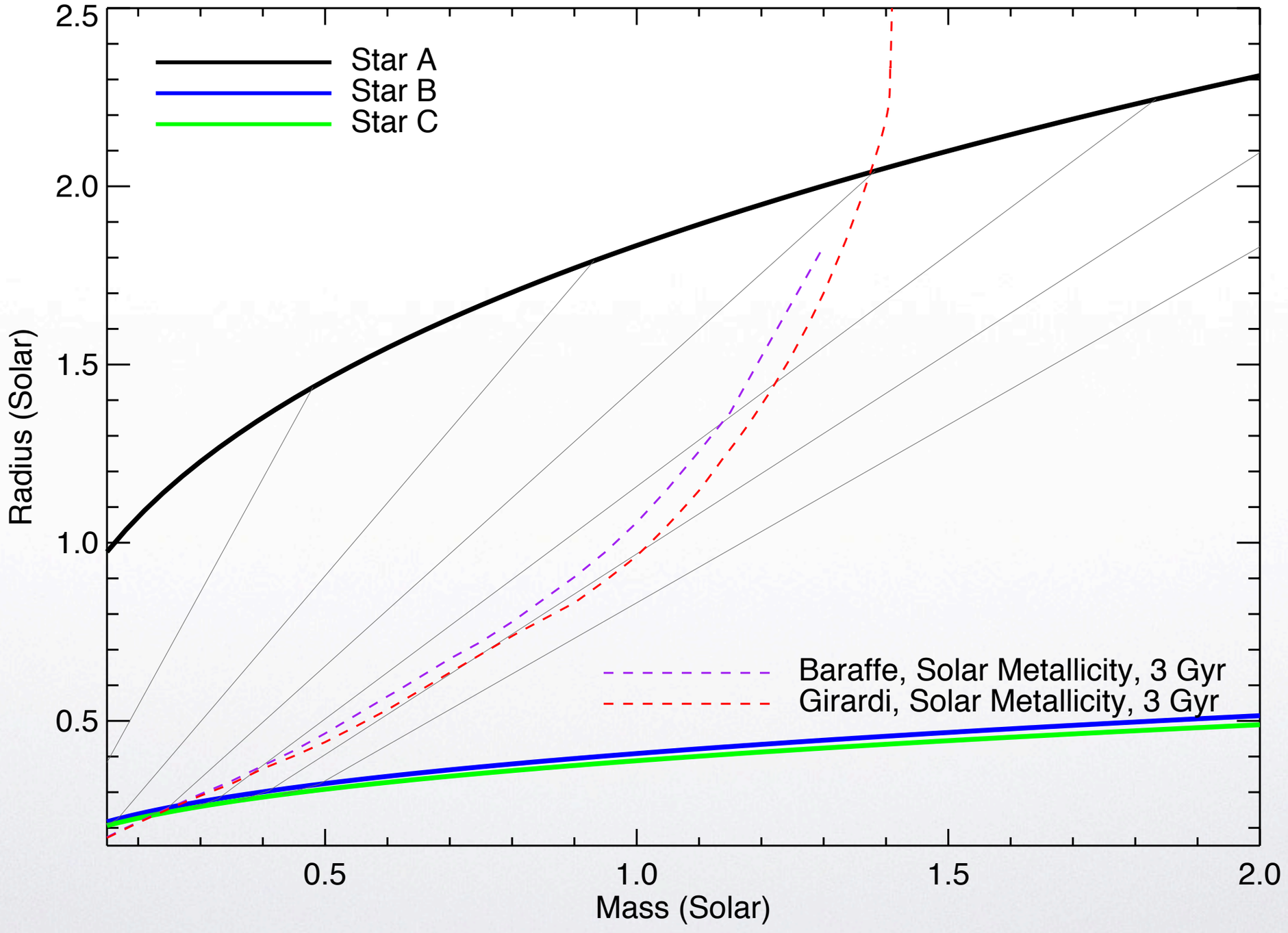
Absolute Dimensions



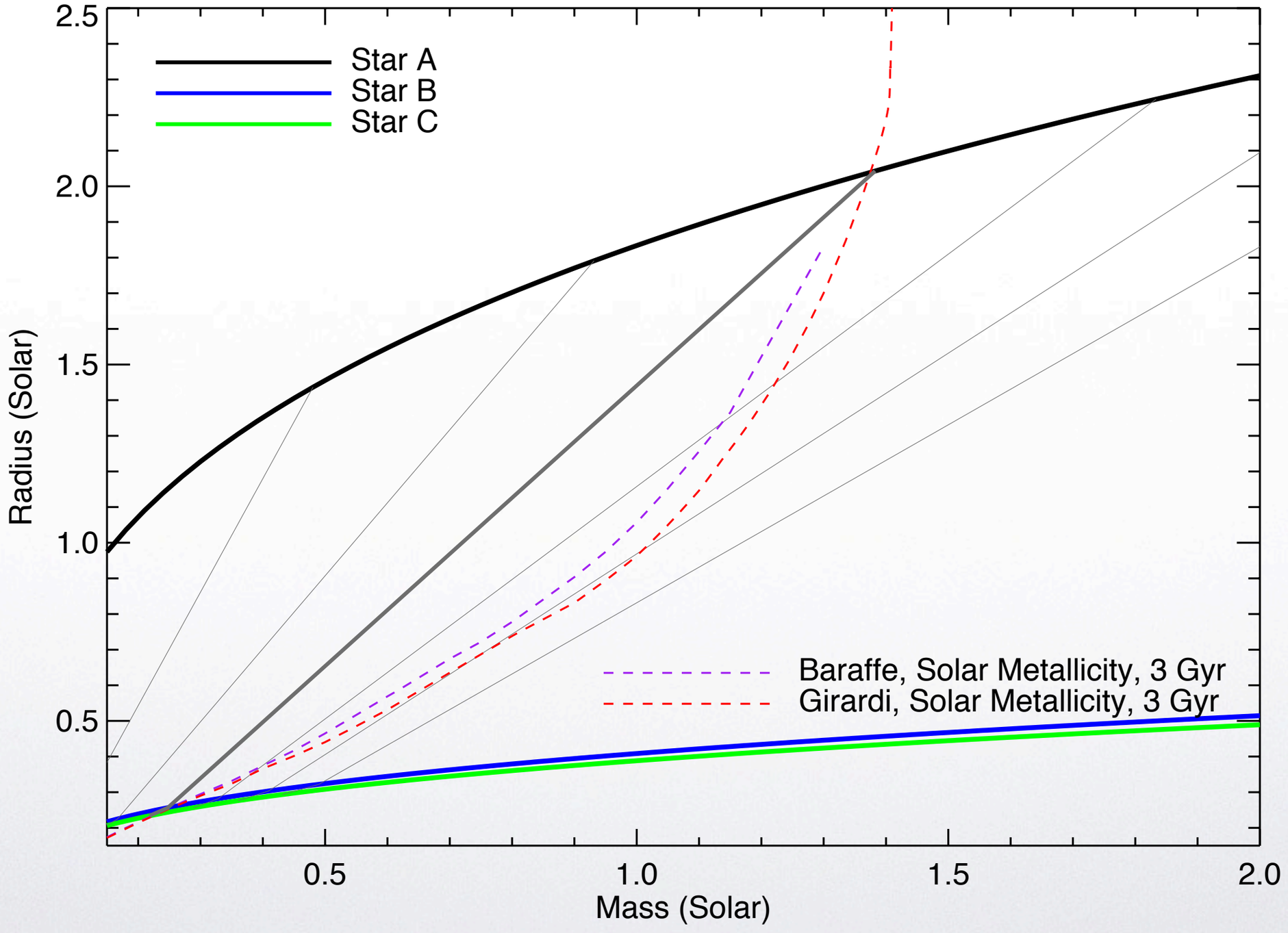
Absolute Dimensions



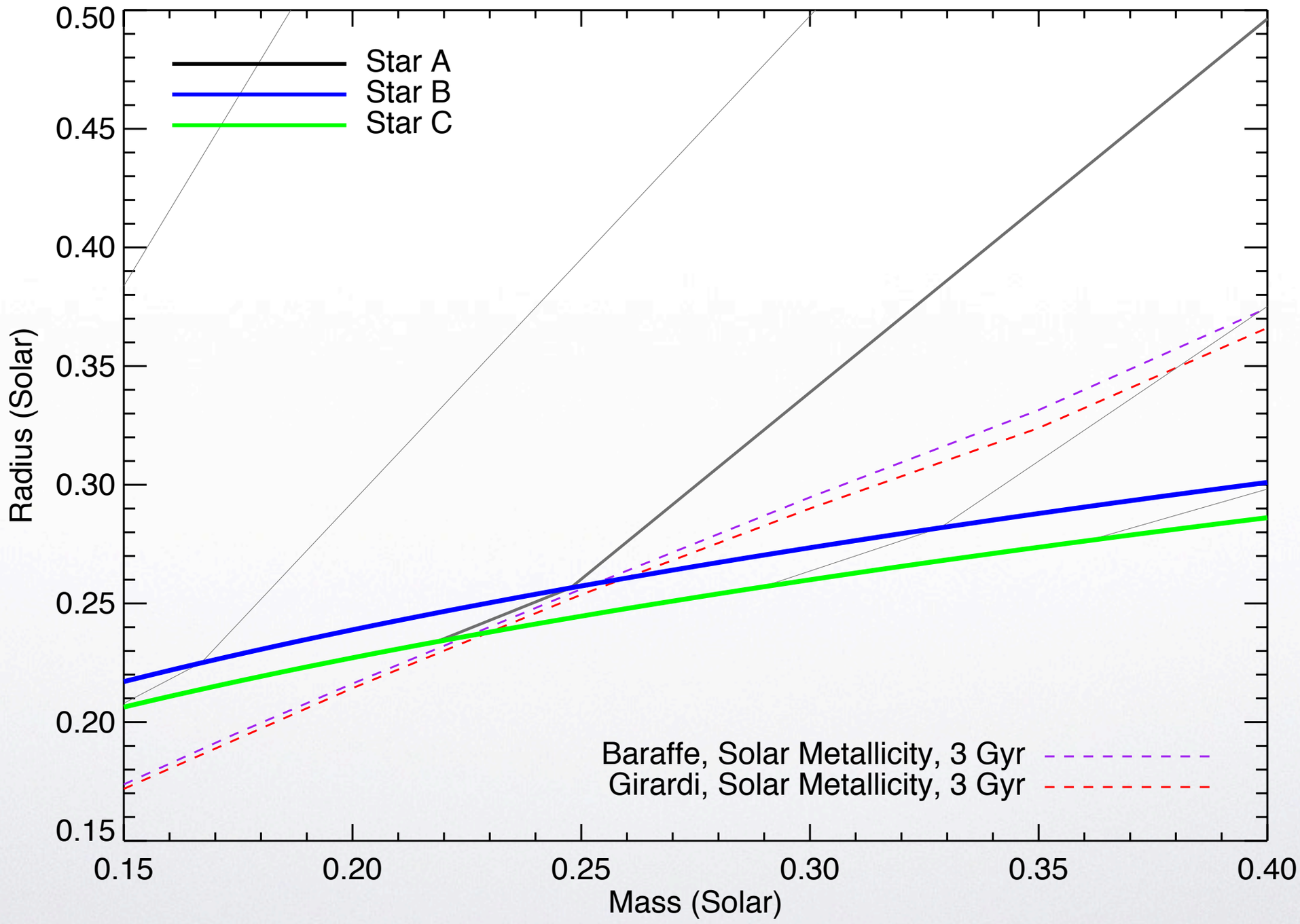
Absolute Dimensions



Absolute Dimensions



Absolute Dimensions



Absolute Dimensions

Parameter	Value
Masses	
M_A	$1.347 \pm 0.032\ M_\odot$
M_B	$0.2413 \pm 0.0030\ M_\odot$
M_C	$0.2127 \pm 0.0026\ M_\odot$
Radii	
R_A	$2.0254 \pm 0.0098\ R_\odot$
R_B	$0.2543 \pm 0.0014\ R_\odot$
R_C	$0.2318 \pm 0.0013\ R_\odot$

Absolute Dimensions

Parameter	Value
Masses	~2%
M_A	$1.347 \pm 0.032\ M_\odot$
M_B	$0.2413 \pm 0.0030\ M_\odot$
M_C	$0.2127 \pm 0.0026\ M_\odot$
Radii	~0.5%
R_A	$2.0254 \pm 0.0098\ R_\odot$
R_B	$0.2543 \pm 0.0014\ R_\odot$
R_C	$0.2318 \pm 0.0013\ R_\odot$

Absolute Dimensions

Parameter	Value
Masses	~2%
M_A	$1.347 \pm 0.032\ M_\odot$
M_B	$0.2413 \pm 0.0030\ M_\odot$
M_C	$0.2127 \pm 0.0026\ M_\odot$
Radii	~0.5%
R_A	$2.0254 \pm 0.0098\ R_\odot$
R_B	$0.2543 \pm 0.0014\ R_\odot$
R_C	$0.2318 \pm 0.0013\ R_\odot$

- System metallicity and age courtesy of KOI-126 A:
  - [Fe/H] ~ 0.15
  - Age ~ 4+/-1 Gyr

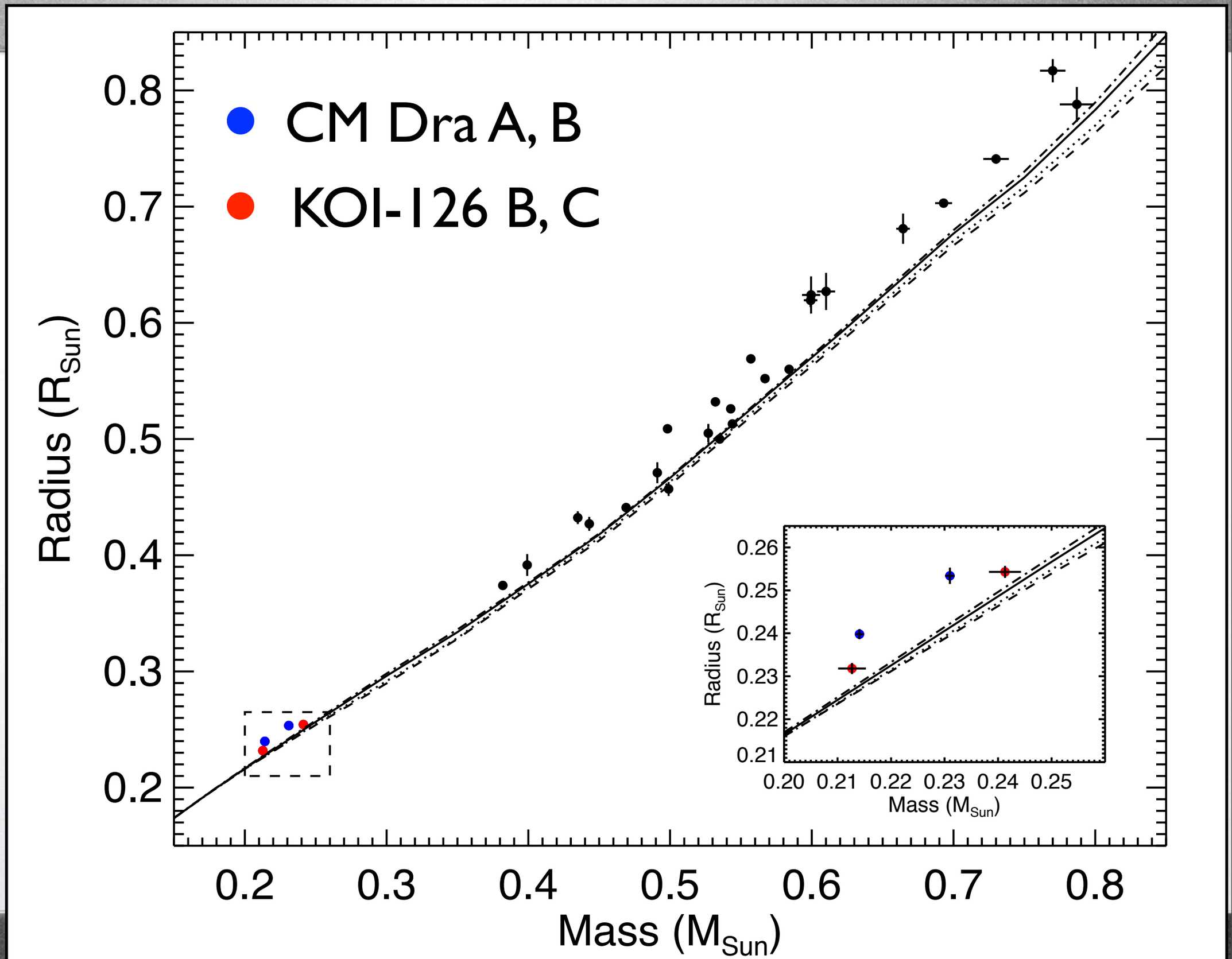
Absolute Dimensions

Parameter	Value
Masses	~2%
M_A	$1.347 \pm 0.032\ M_\odot$
M_B	$0.2413 \pm 0.0030\ M_\odot$
M_C	$0.2127 \pm 0.0026\ M_\odot$
Radii	~0.5%
R_A	$2.0254 \pm 0.0098\ R_\odot$
R_B	$0.2543 \pm 0.0014\ R_\odot$
R_C	$0.2318 \pm 0.0013\ R_\odot$

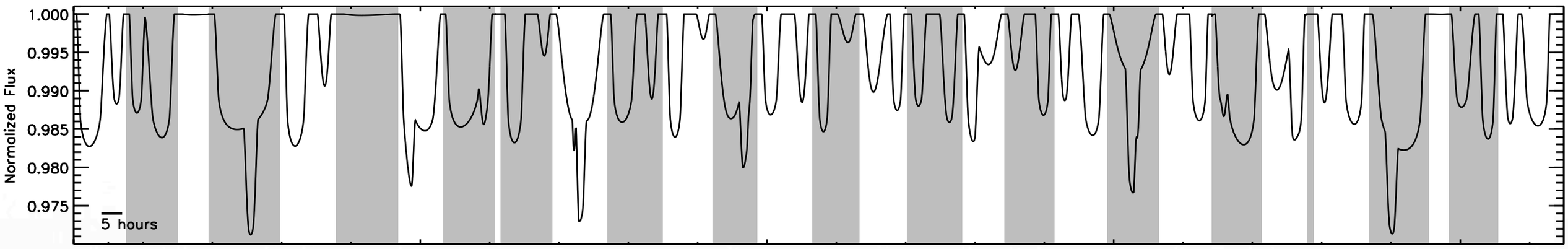
RESEARCH COMPUTING
Harvard University
Faculty of Arts and Sciences

- System metallicity and age courtesy of KOI-126 A:
  - [Fe/H] ~ 0.15
  - Age ~ 4+/-1 Gyr

KOI-126 B,C

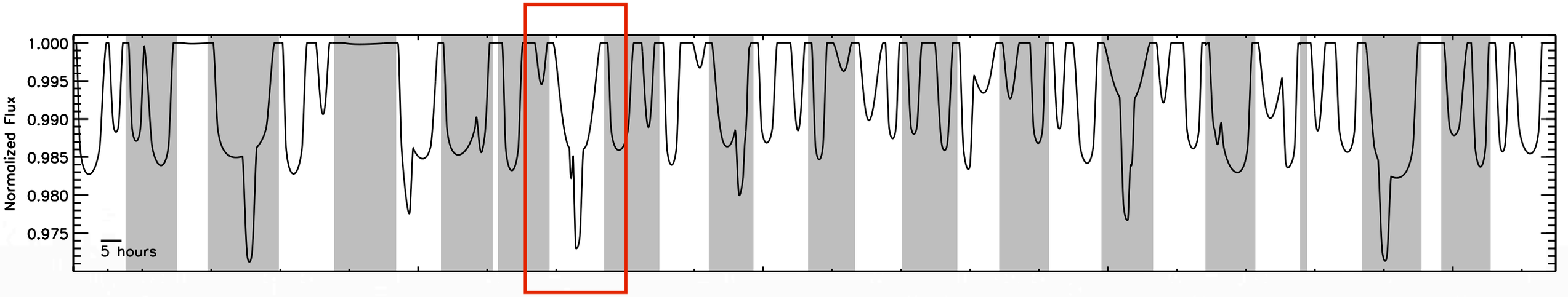

CM Dra A, B
KOI-126 B, C
Radius (R_{Sun})
Mass (M_{Sun})
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Radius (R_{Sun})
Mass (M_{Sun})
0.21
0.22
0.23
0.24
0.25
0.26
0.20 0.21 0.22 0.23 0.24 0.25

KOI-126: More to come



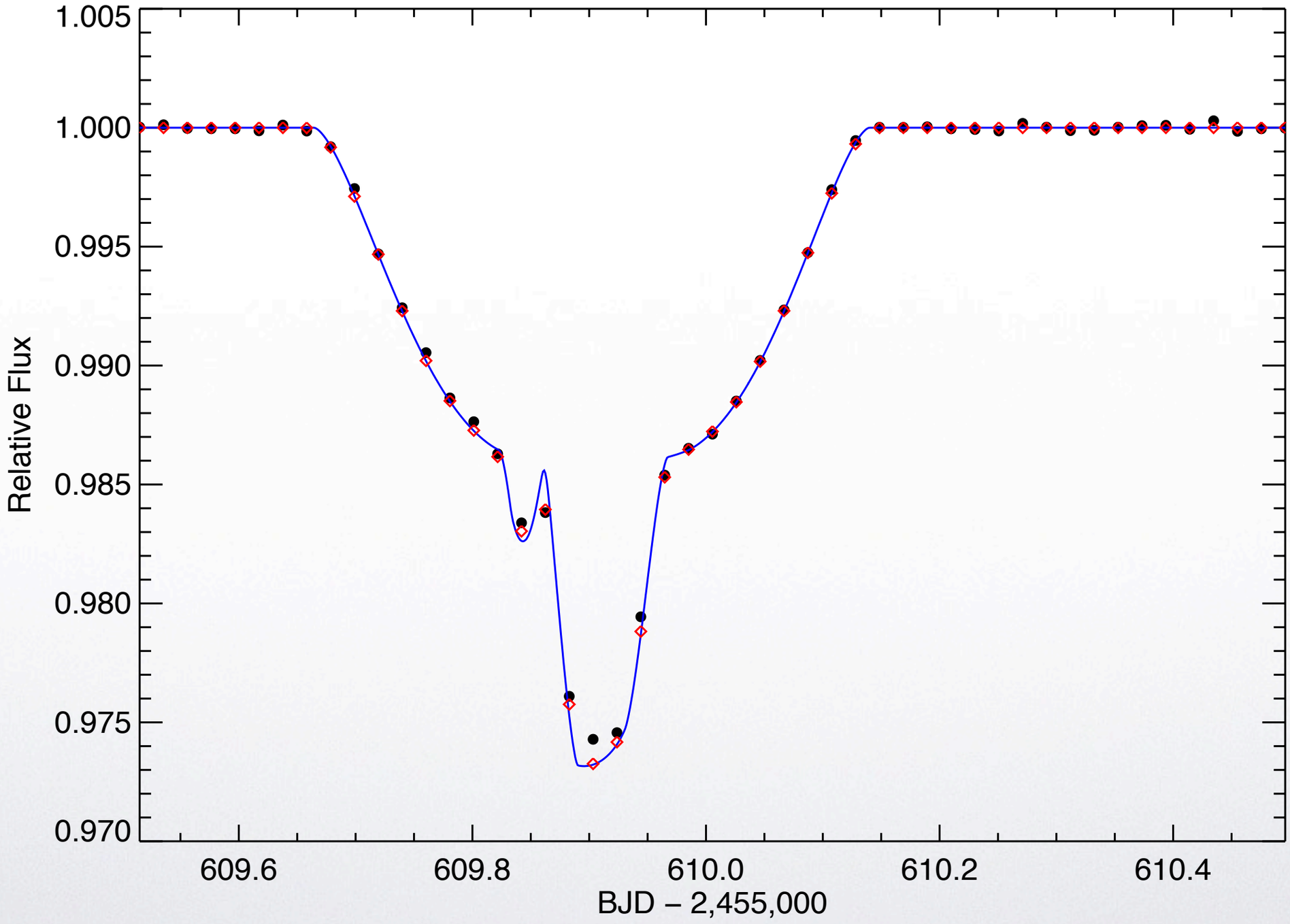
- Mass and radius determinations to better than a fraction of a percent
- $k_2 < 0.6$ @ 95% conf. with current data
- $k_2 \sim 0.1$ measured to ~1% with full mission data.

KOI-126: More to come



- Mass and radius determinations to better than a fraction of a percent
- $k_2 < 0.6$ @ 95% conf. with current data
- $k_2 \sim 0.1$ measured to ~1% with full mission data.

KOI-126: Syzygy! (aka "Mutual Event")



KOI-126

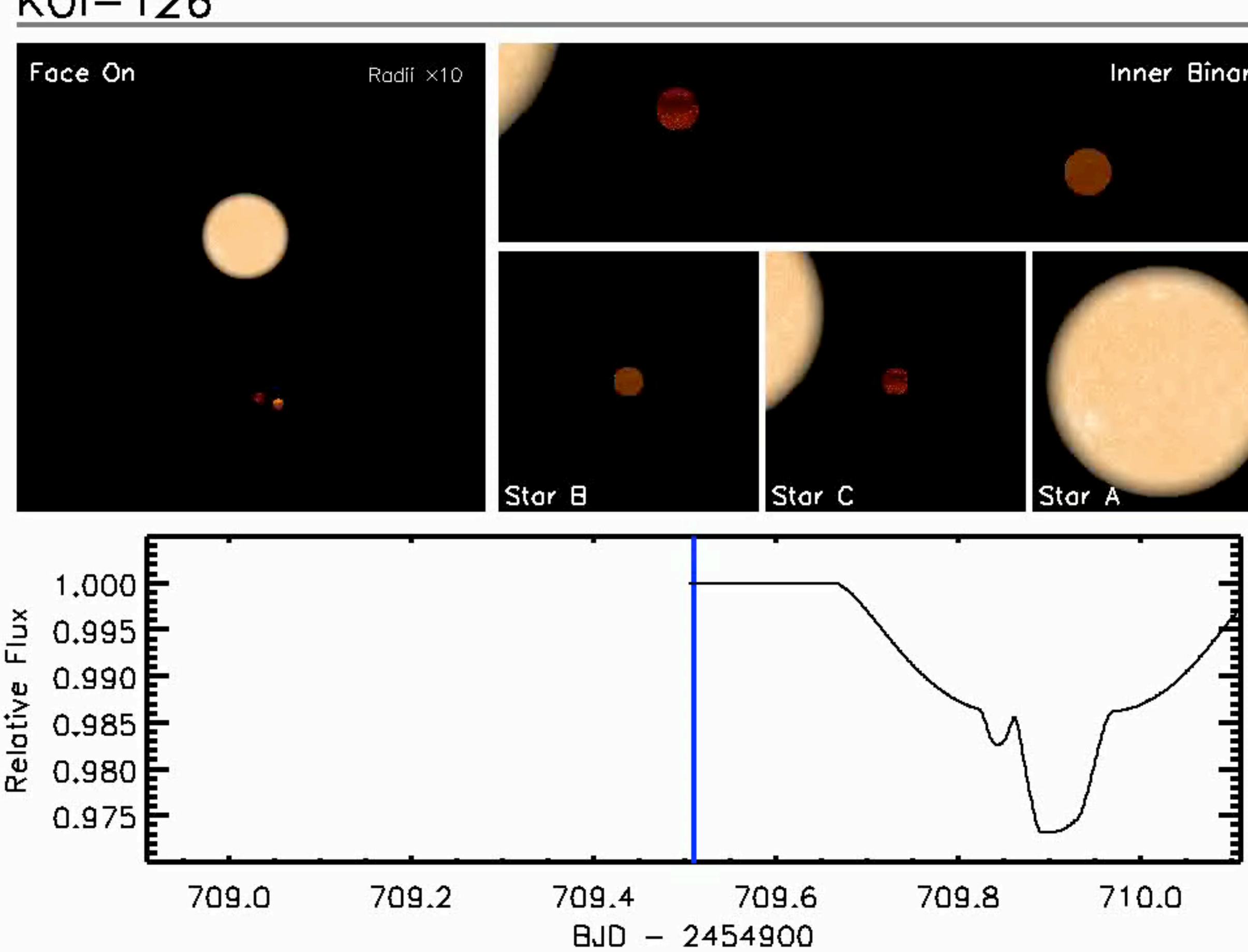
Face On
Radii ×10

Inner Binary

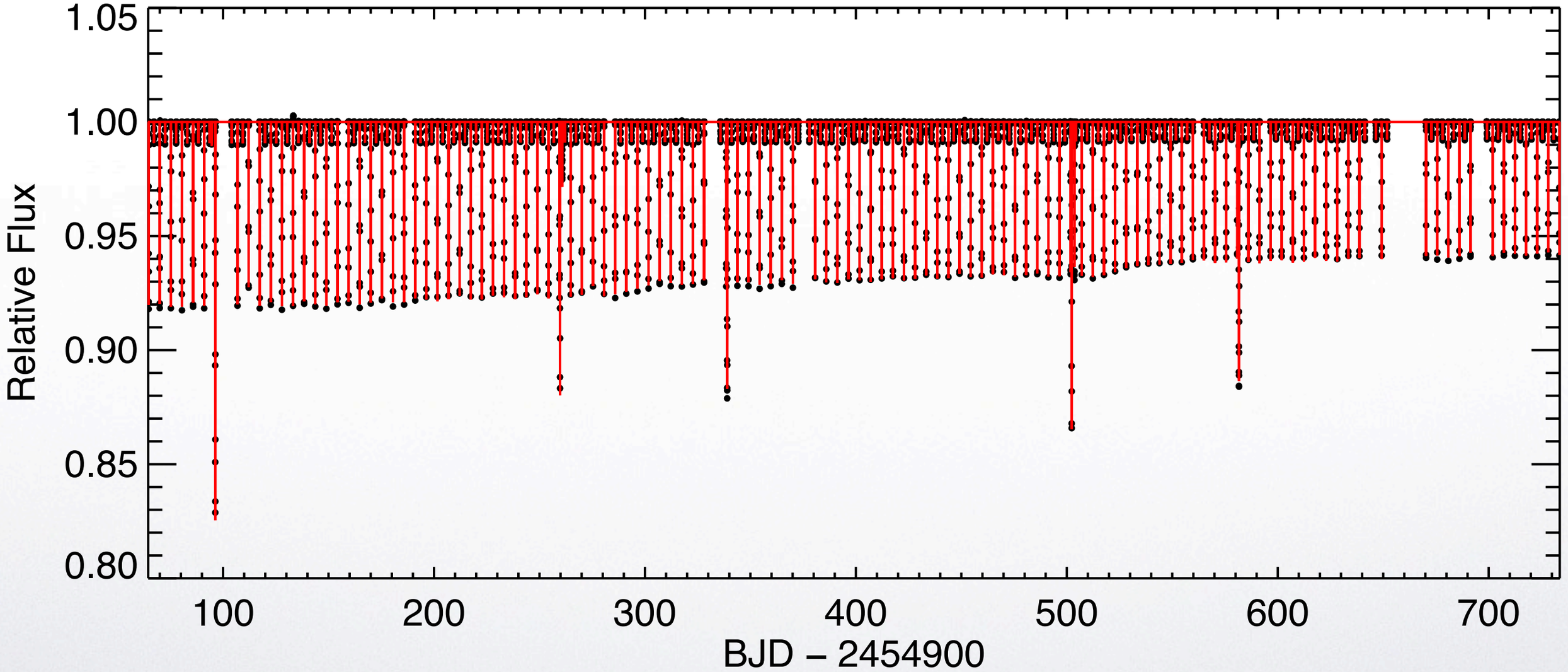
Star B

Star C

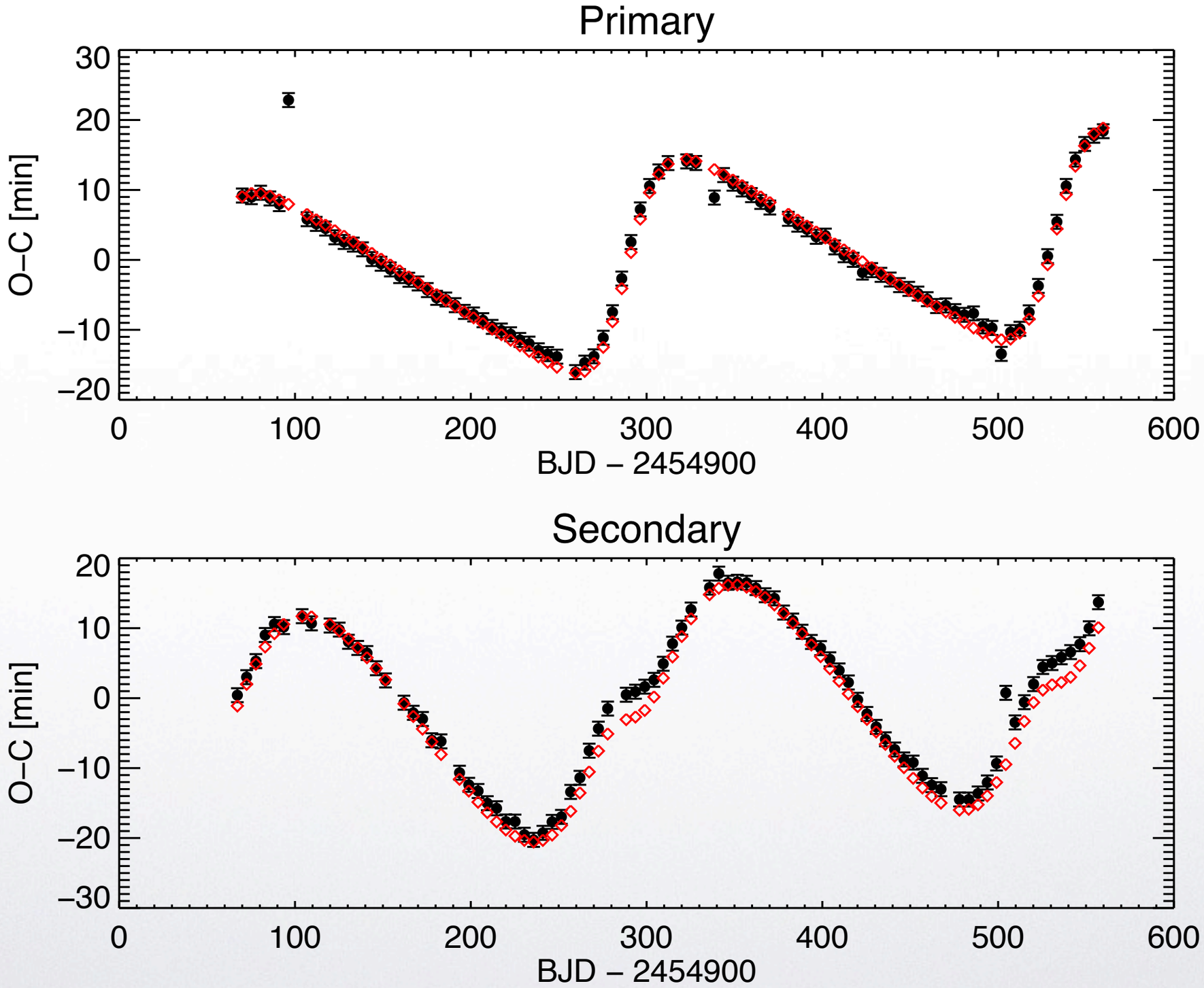
Star A


1.000
0.995
0.990
0.985
0.980
0.975
Relative Flux
709.0
709.2
709.4
709.6
709.8
710.0
BJD – 2454900

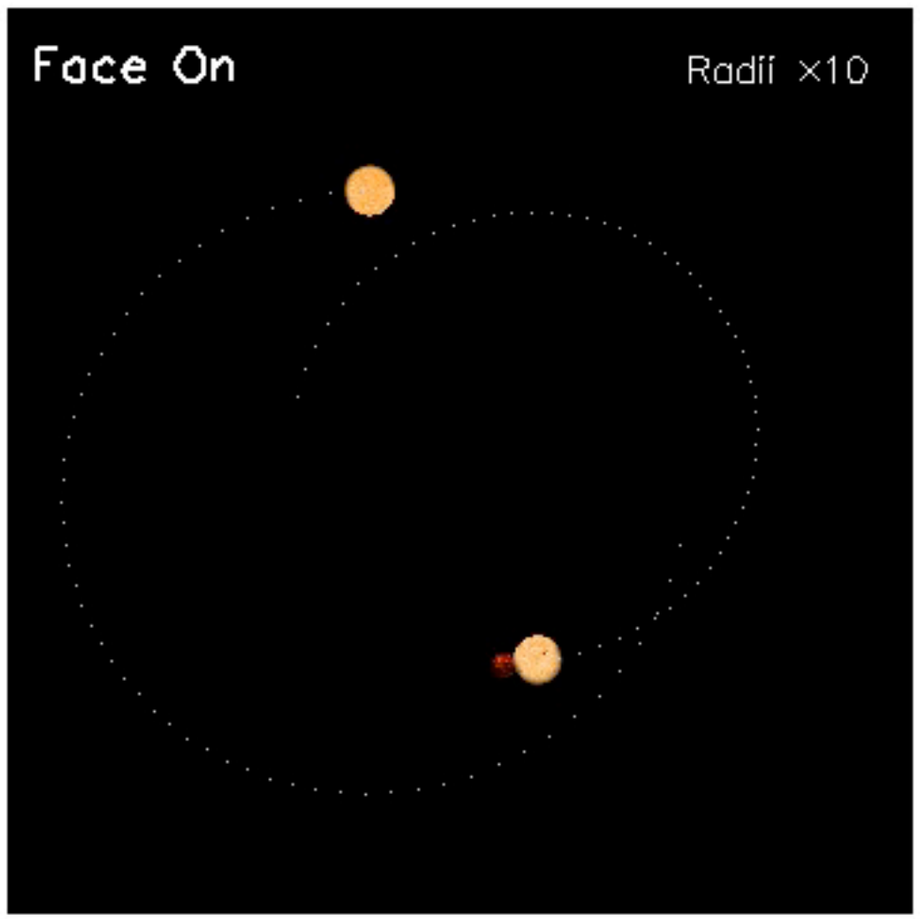
In the works... KIC 7289157



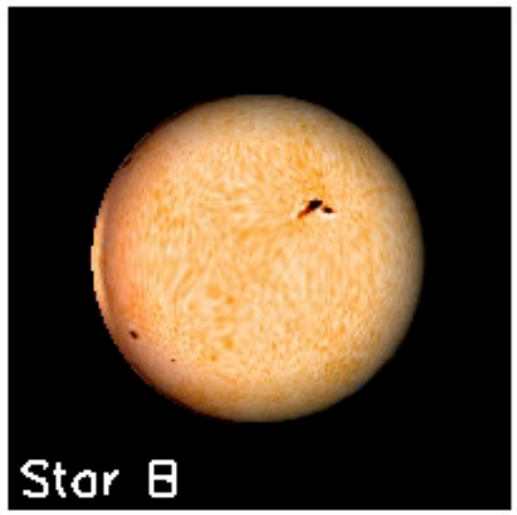
In the works... KIC 7289157

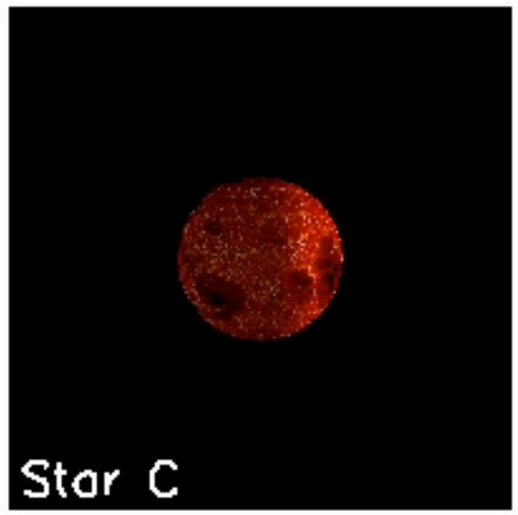


KIC-7289157

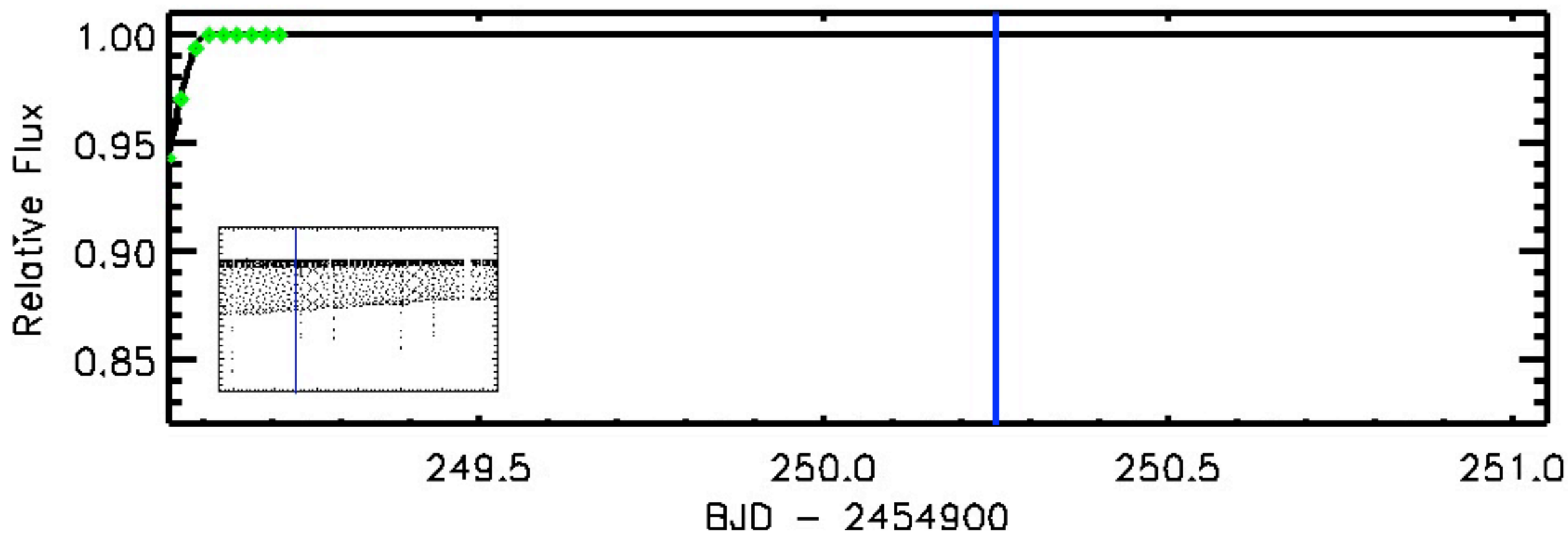

Face On
Radii ×10

Inner Binary

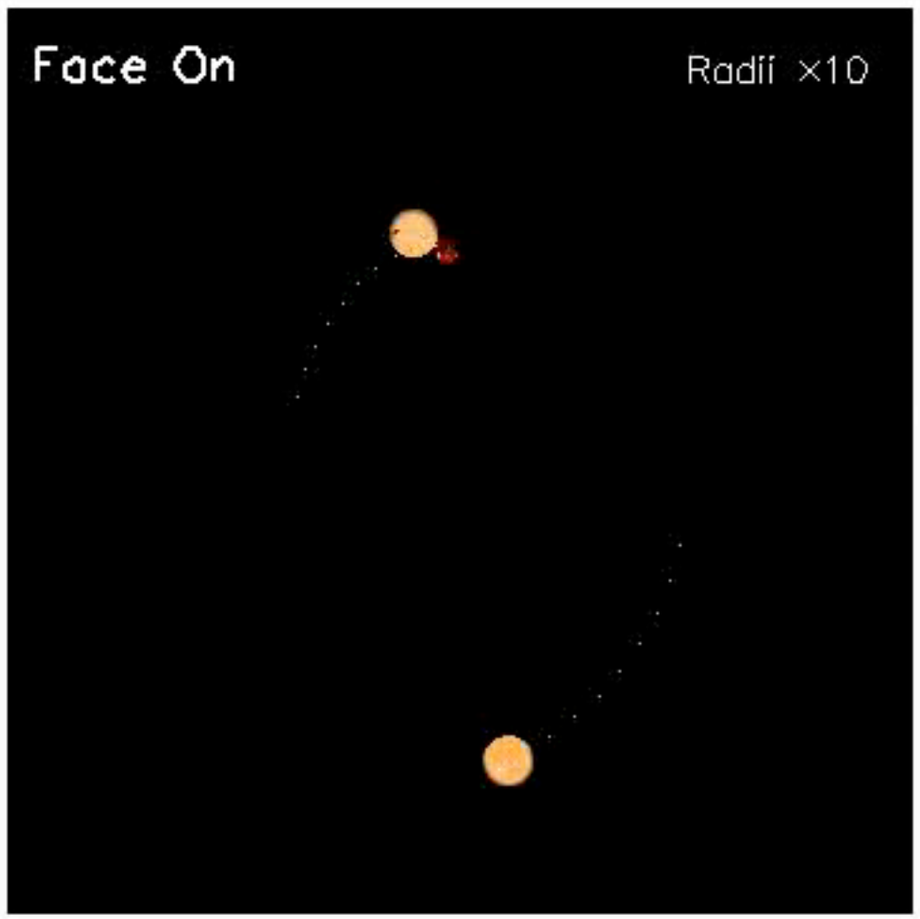

Star B


Star C

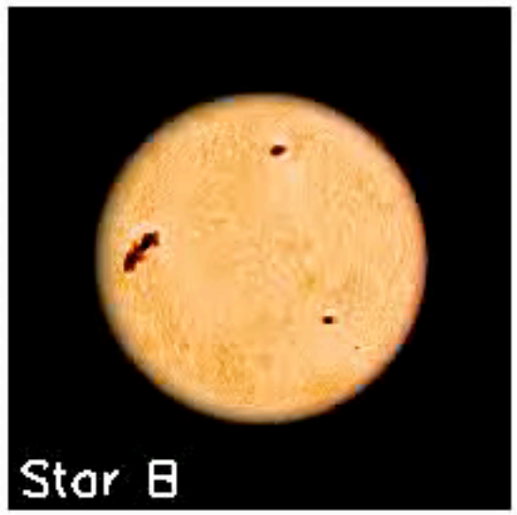
Star A

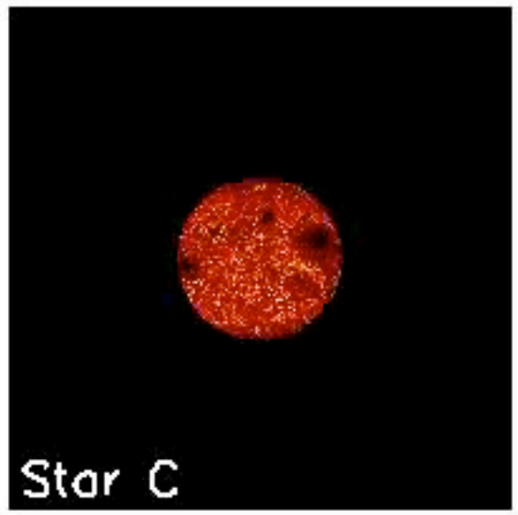

1.00
0.95
0.90
0.85
Relative Flux
249.5
250.0
250.5
251.0
BJD – 2454900

KIC-7289157

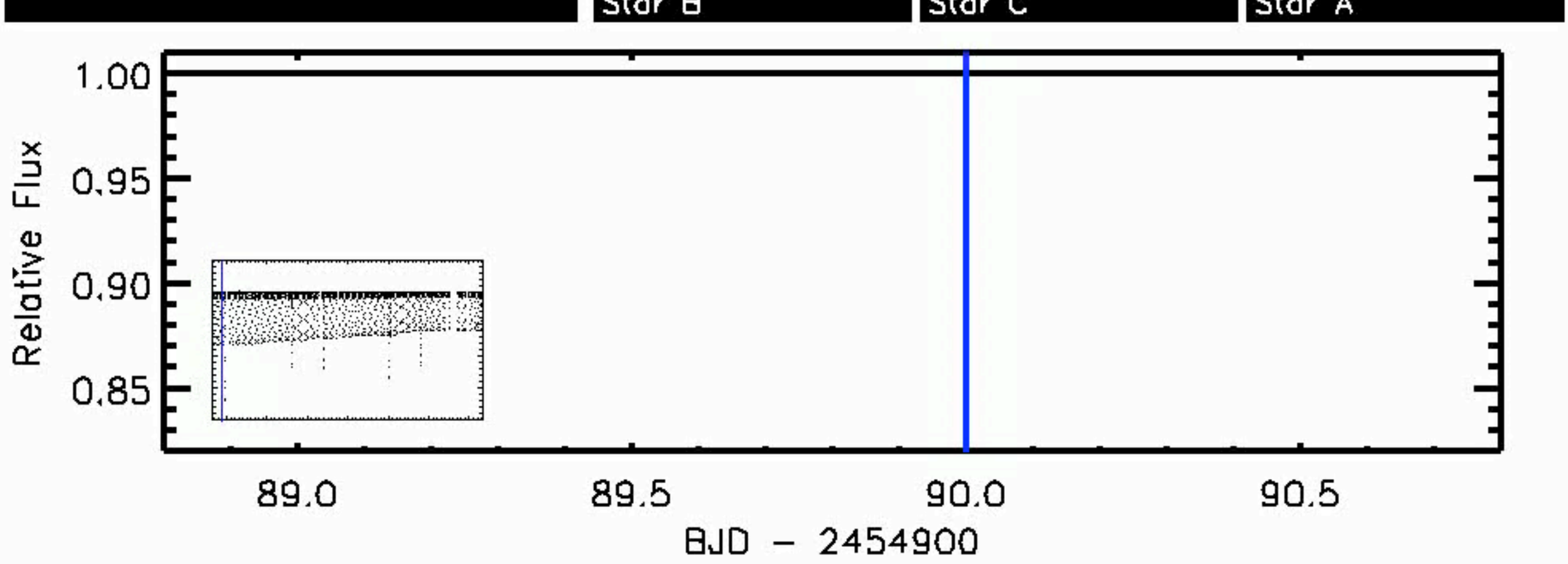

Face On
Radii ×10

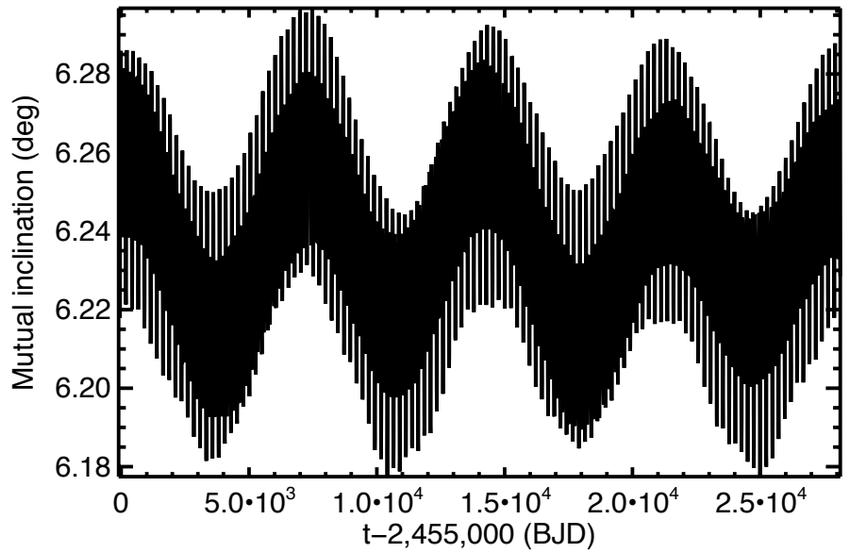
Inner Binary

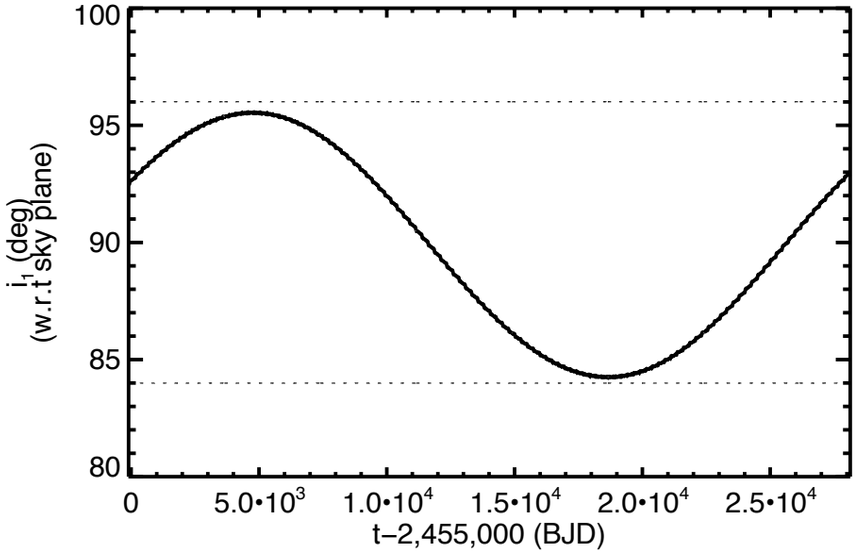

Star B

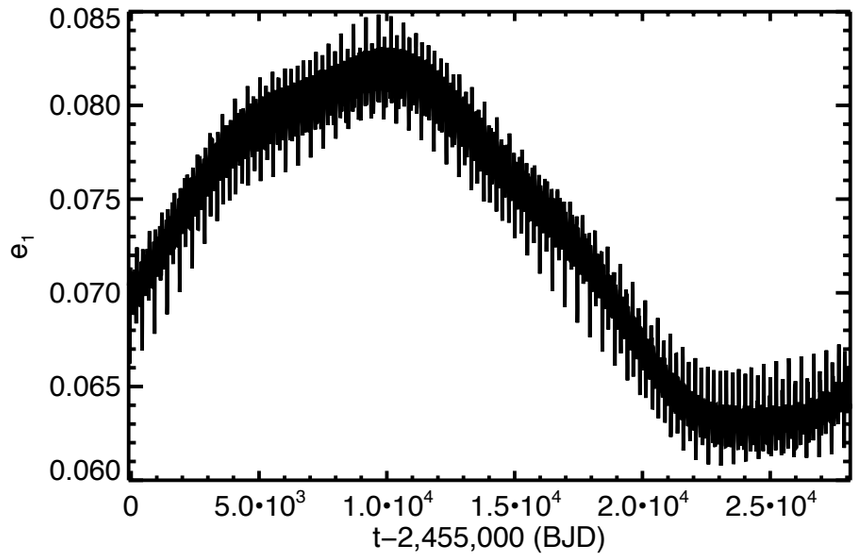

Star C

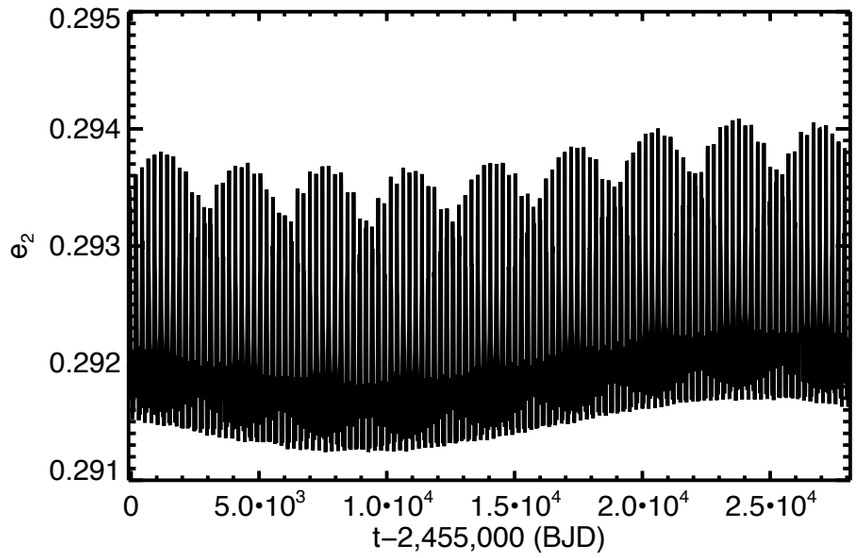
Star A

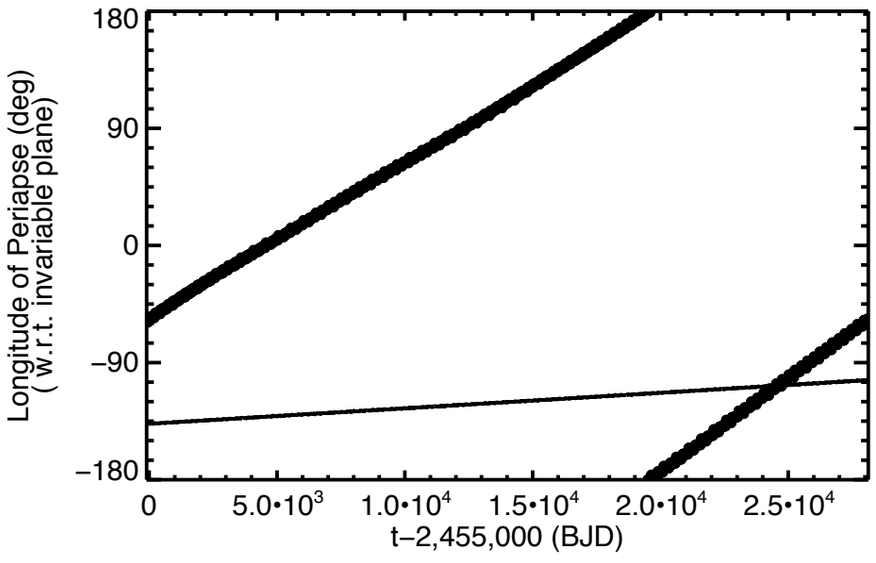

1.00
0.95
0.90
0.85
Relative Flux
89.0
89.5
90.0
90.5
BJD – 2454900

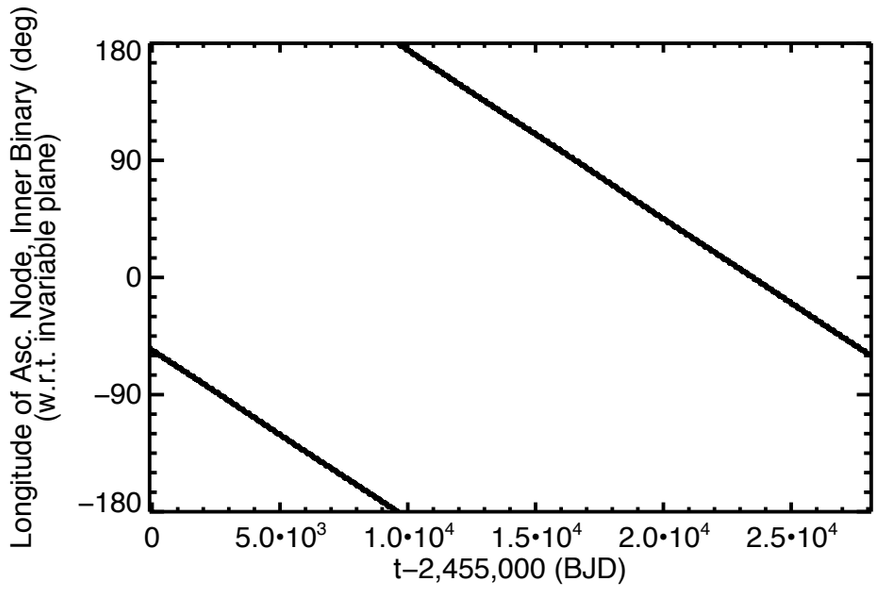

Mutual inclination (deg)
6.28
6.26
6.24
6.22
6.20
6.18
0
5.0•10^3
1.0•10^4
1.5•10^4
2.0•10^4
2.5•10^4
t–2,455,000 (BJD)


i_1 (deg)
(w.r.t sky plane)
100
95
90
85
80
0
5.0•10^3
1.0•10^4
1.5•10^4
2.0•10^4
2.5•10^4
t–2,455,000 (BJD)


e_1
0.085
0.080
0.075
0.070
0.065
0.060
0
5.0•10^3
1.0•10^4
1.5•10^4
2.0•10^4
2.5•10^4
t–2,455,000 (BJD)

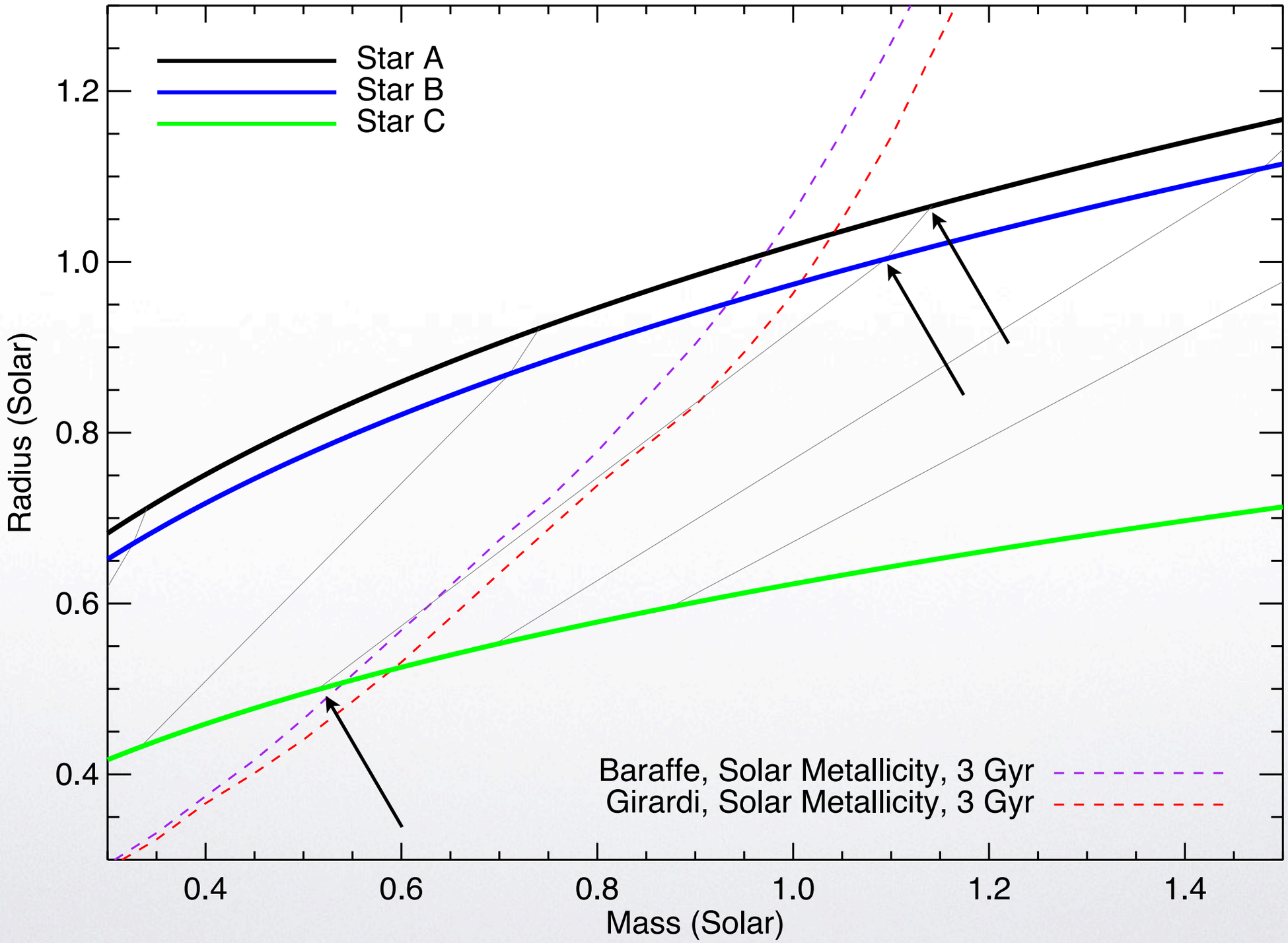

e_2
0.295
0.294
0.293
0.292
0.291
0
5.0•10^3
1.0•10^4
1.5•10^4
2.0•10^4
2.5•10^4
t–2,455,000 (BJD)

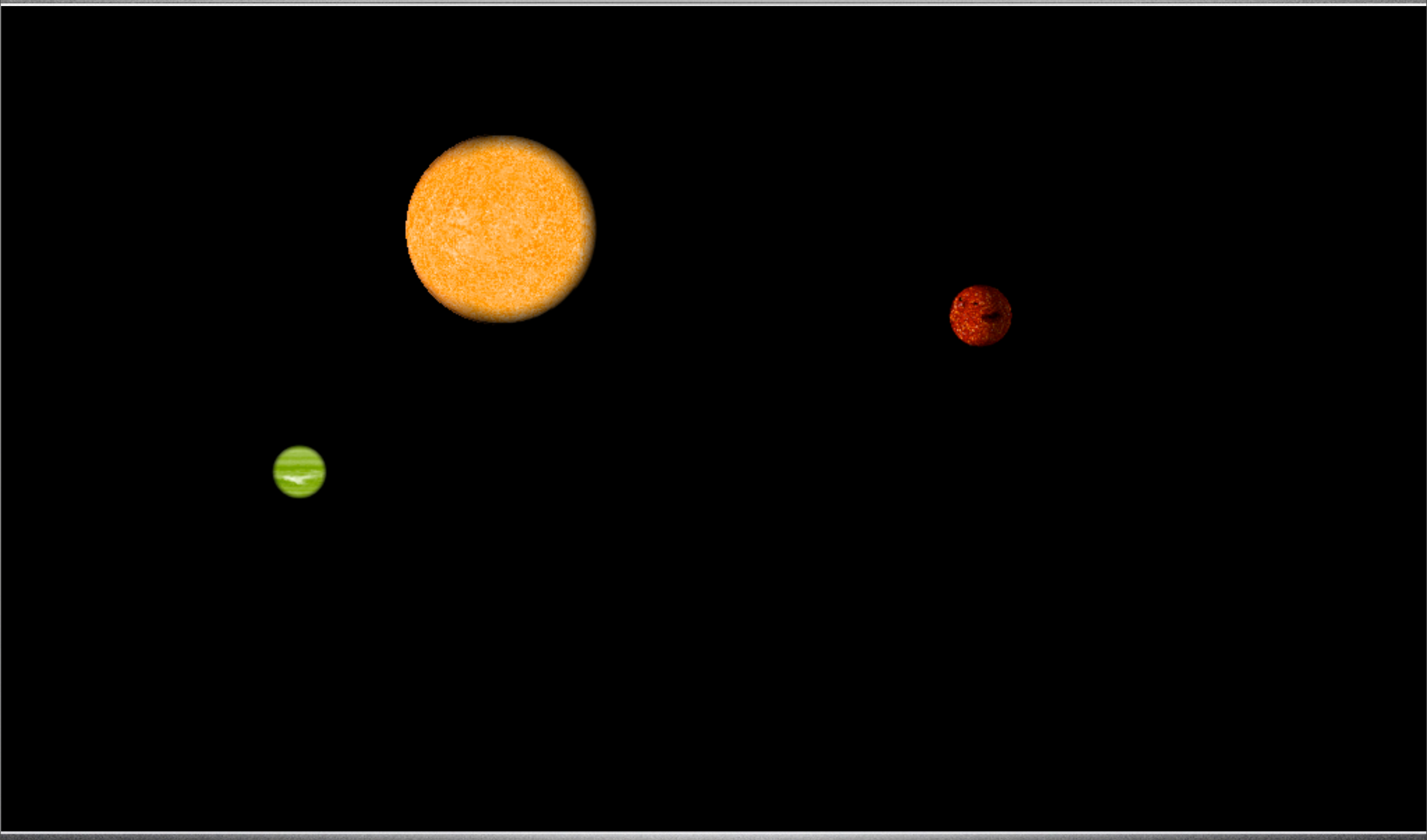

Longitude of Periapse (deg)
(w.r.t. invariable plane)
180
90
0
–90
–180
0
5.0•10^3
1.0•10^4
1.5•10^4
2.0•10^4
2.5•10^4
t–2,455,000 (BJD)

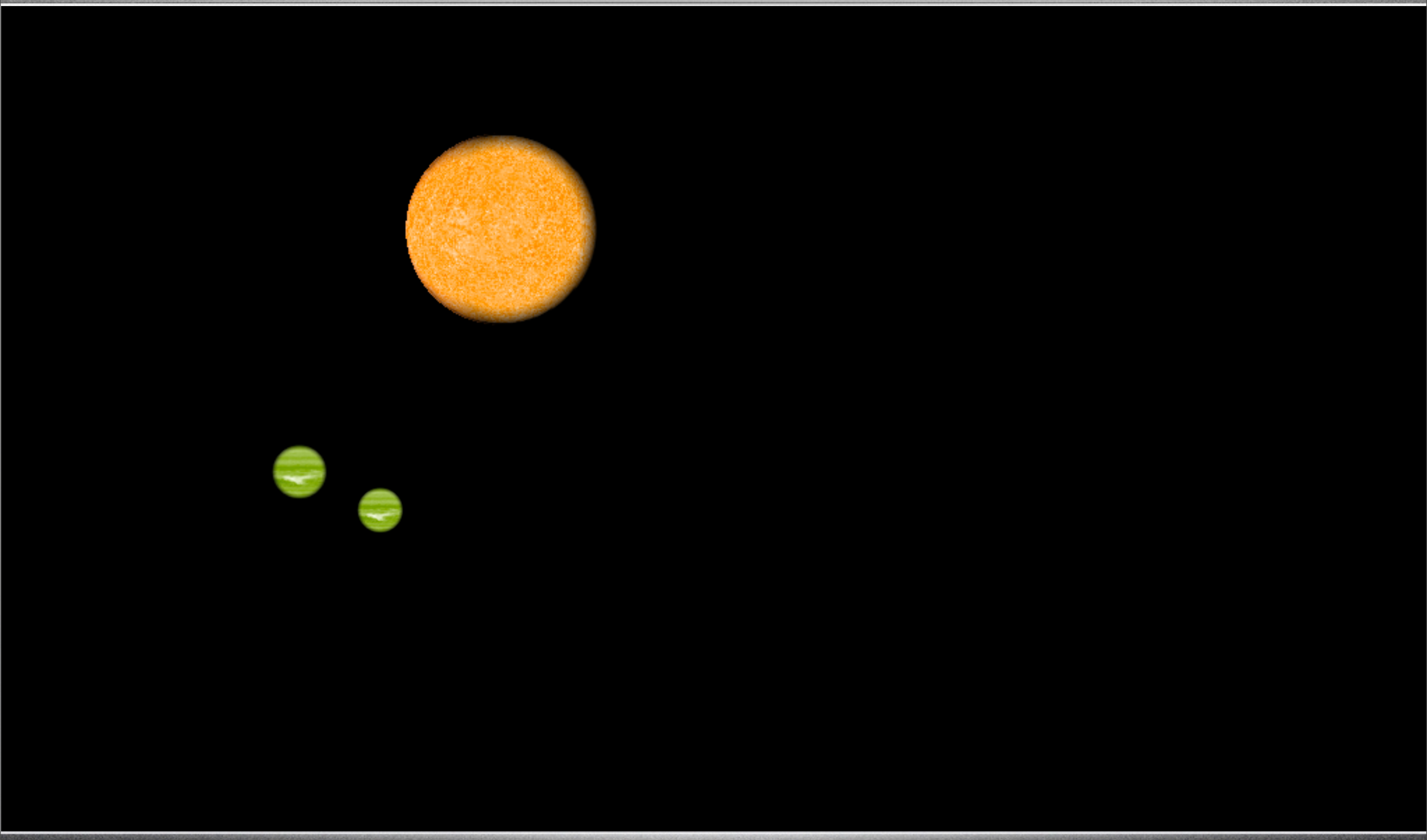

Longitude of Asc. Node, Inner Binary (deg)
(w.r.t. invariable plane)
180
90
0
–90
–180
0
5.0•10^3
1.0•10^4
1.5•10^4
2.0•10^4
2.5•10^4
t–2,455,000 (BJD)

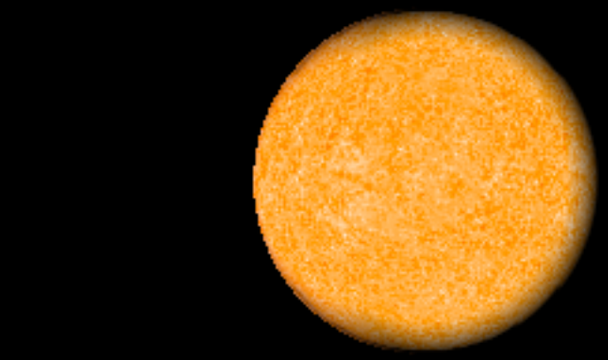
In the works... KIC 7289157

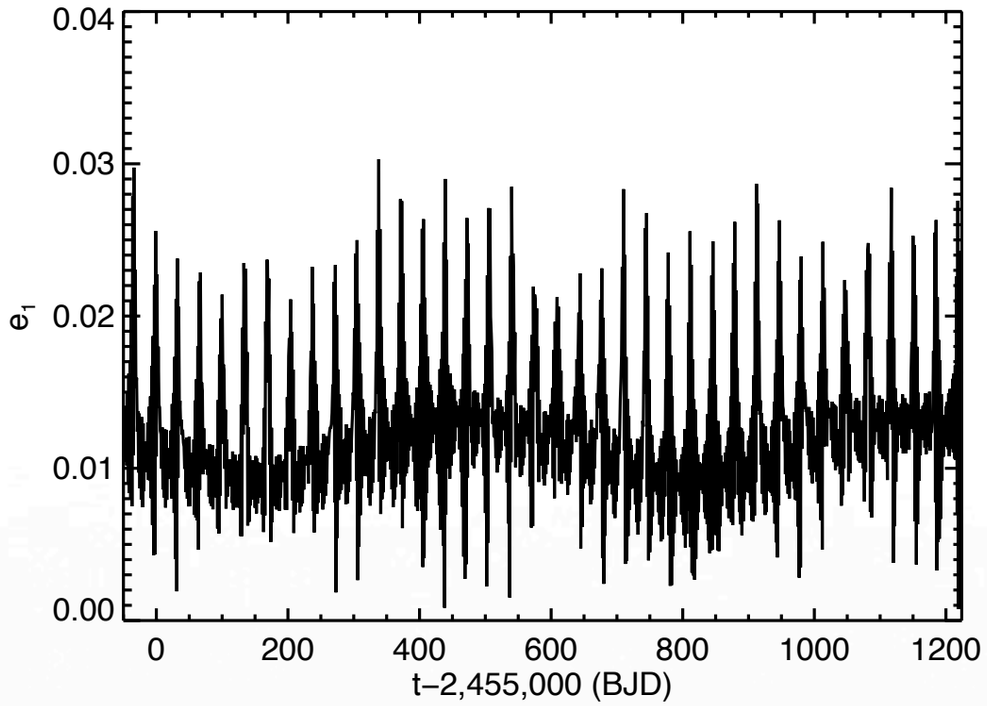
Not quite there yet...

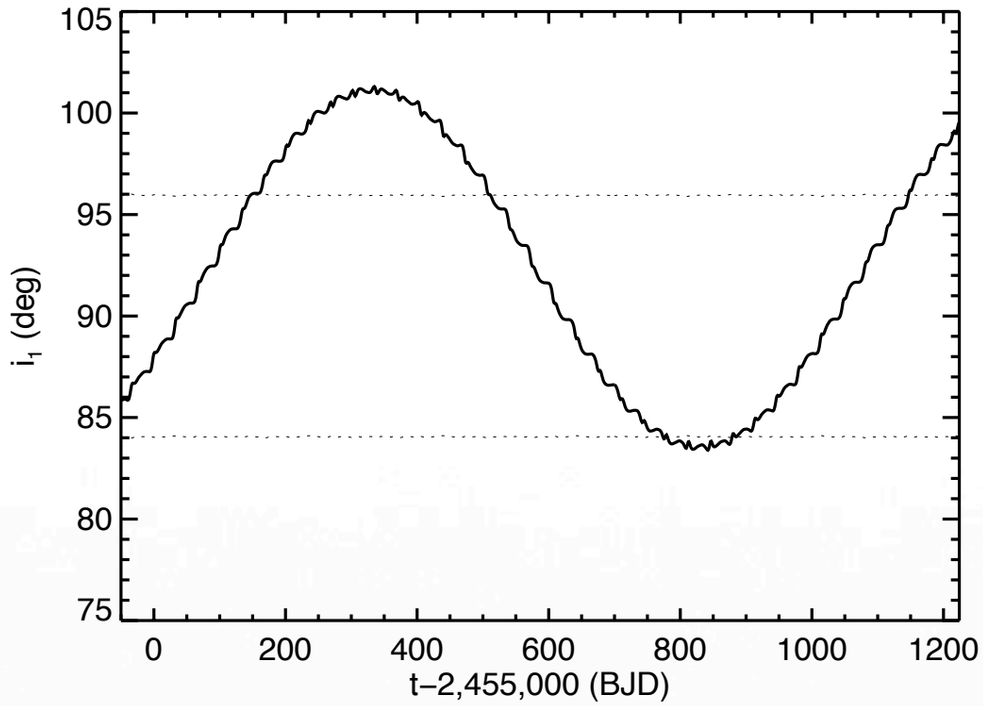


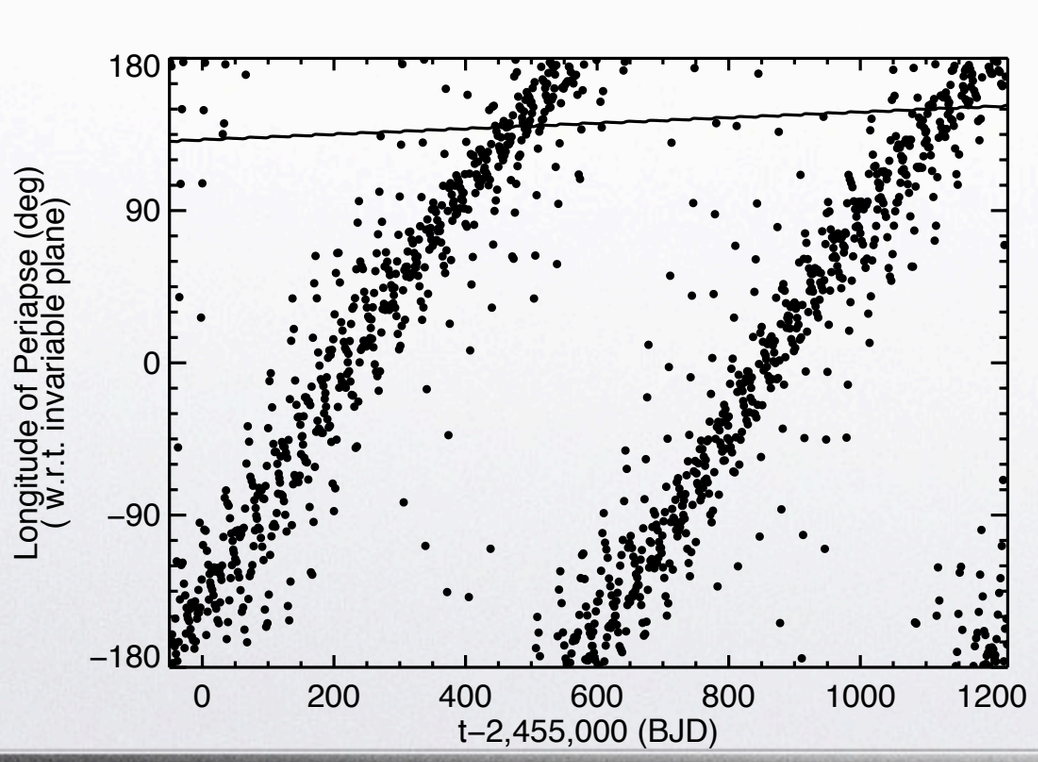


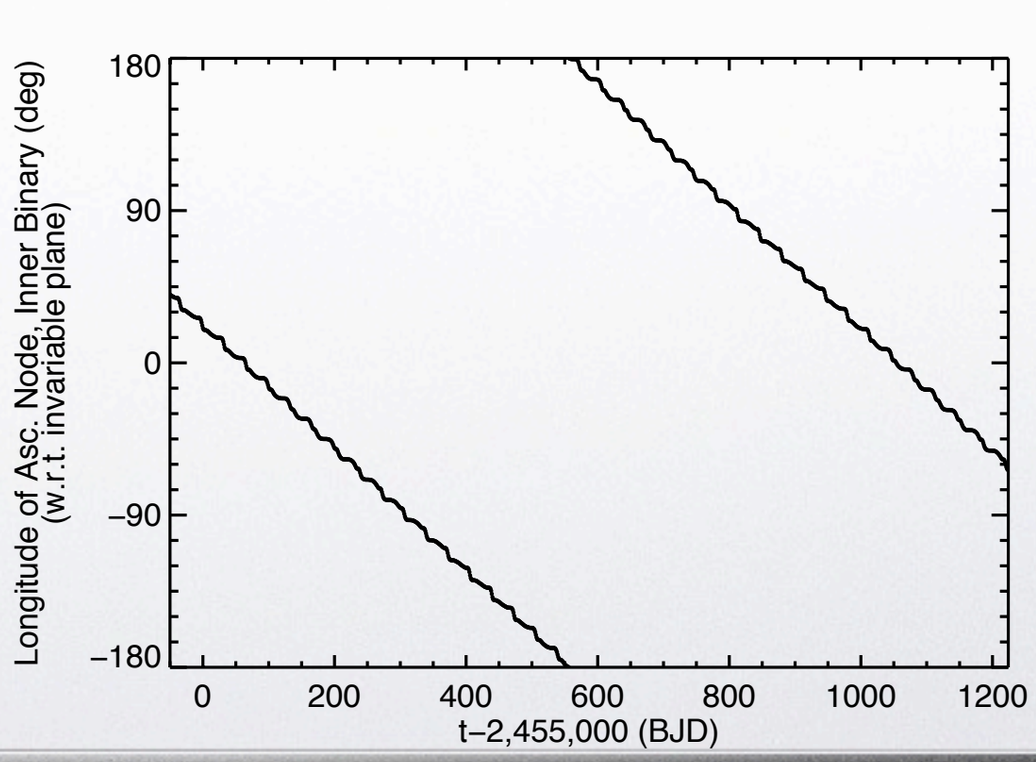


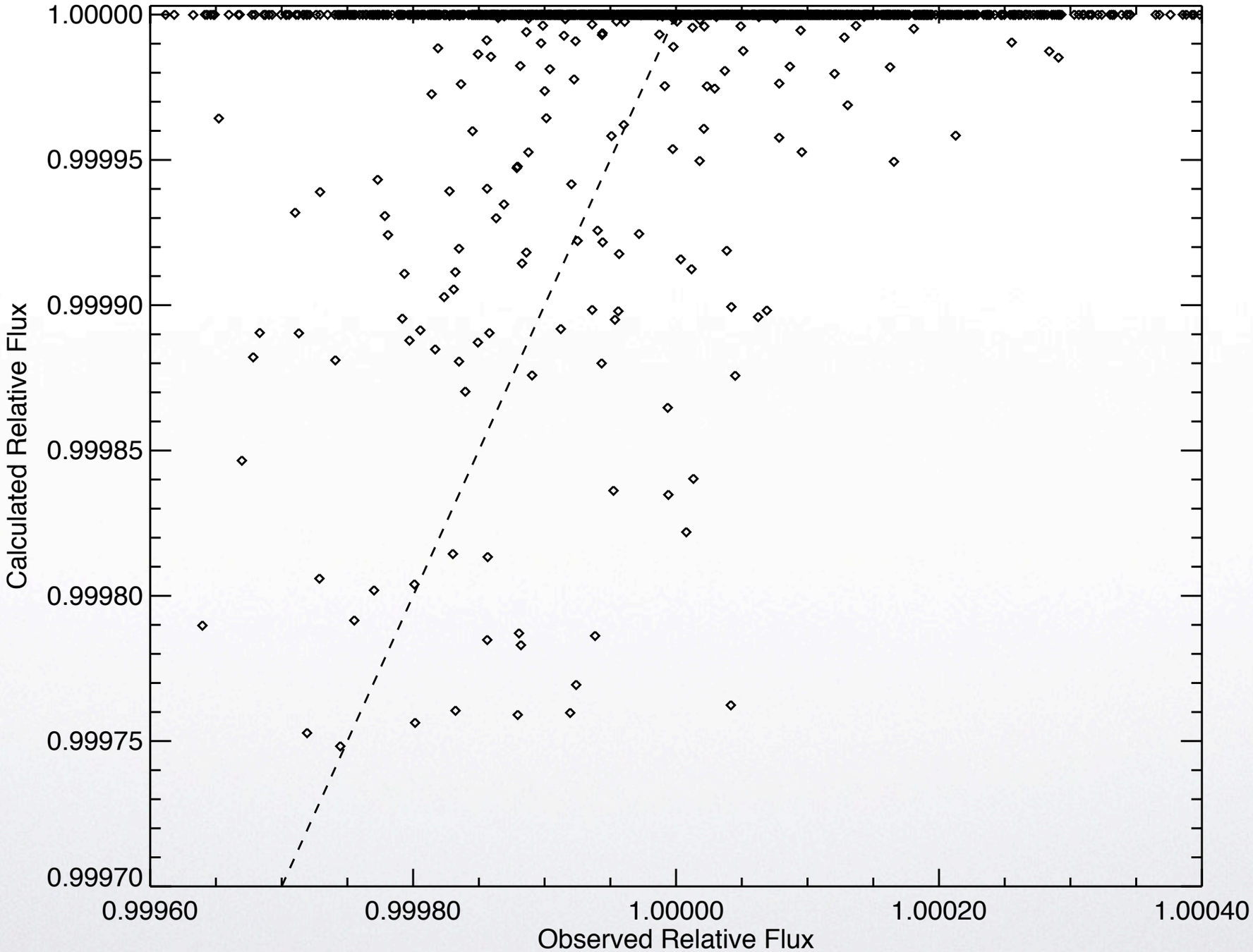


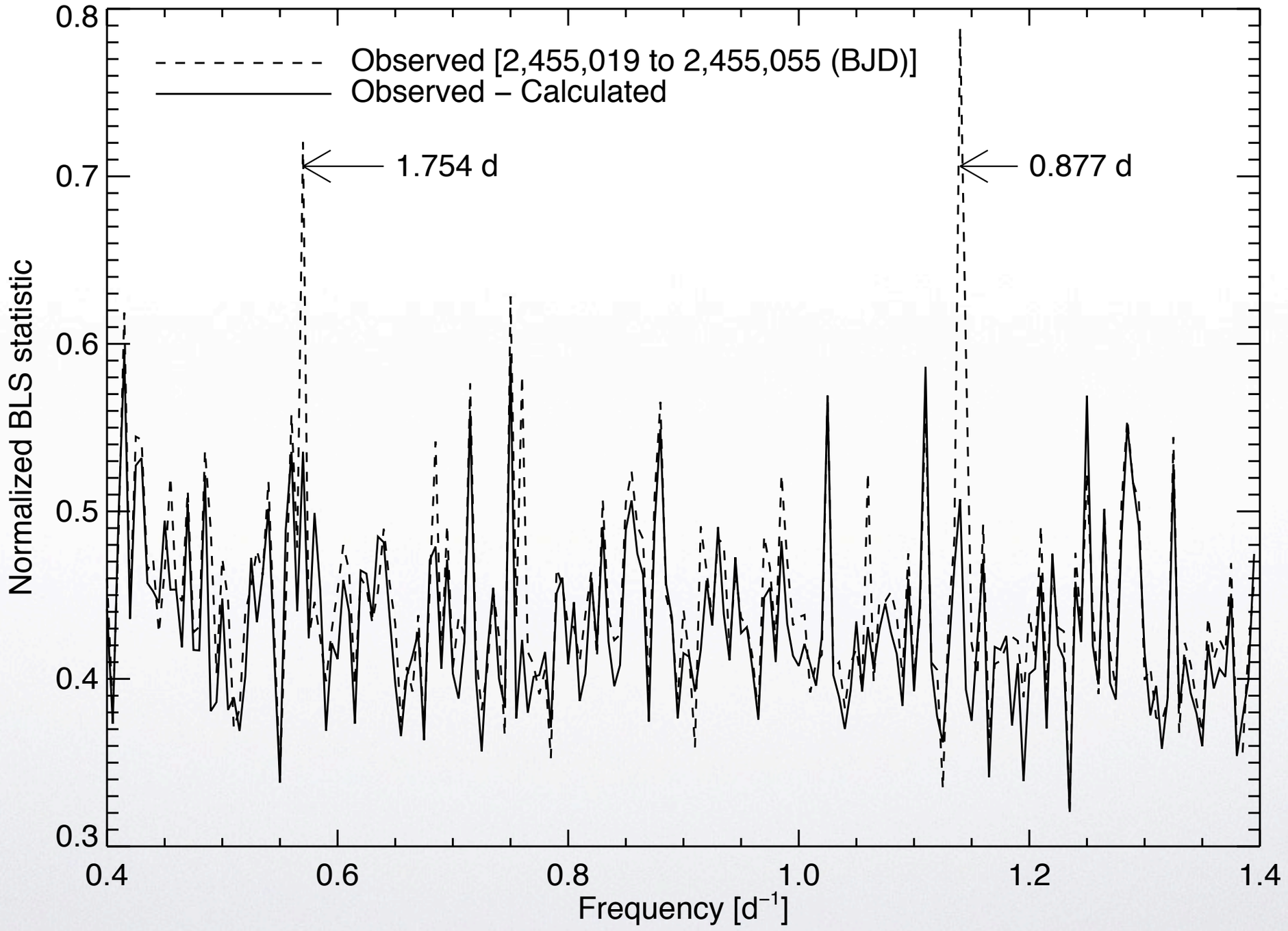

0.04
0.03
0.02
0.01
0.00
e_1
0
200
400
600
800
1000
1200
t–2,455,000 (BJD)

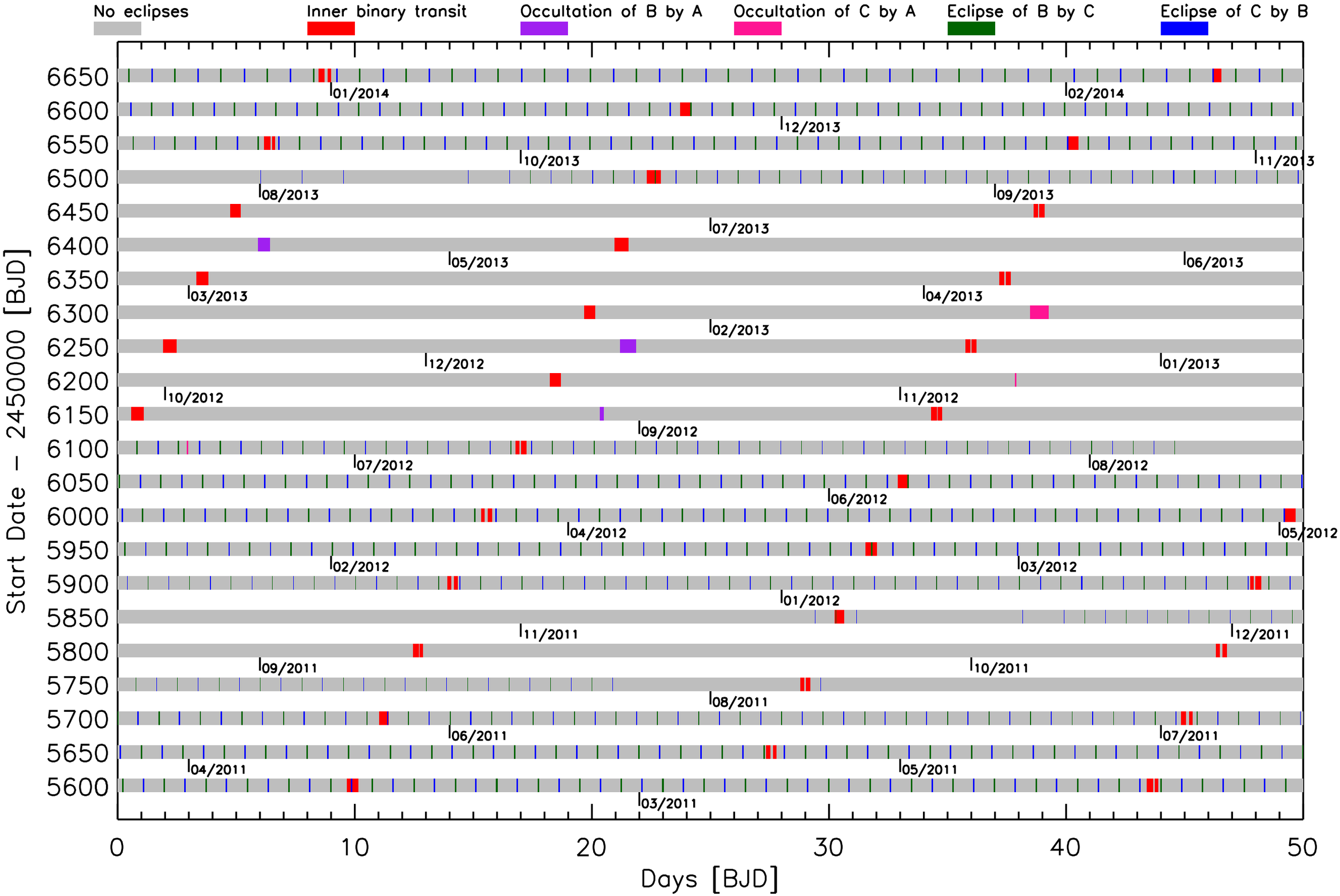

105
100
95
90
85
80
75
i_1 (deg)
0
200
400
600
800
1000
1200
t–2,455,000 (BJD)


180
90
0
–90
–180
Longitude of Periapse (deg)
(w.r.t. invariable plane)
0
200
400
600
800
1000
1200
t–2,455,000 (BJD)

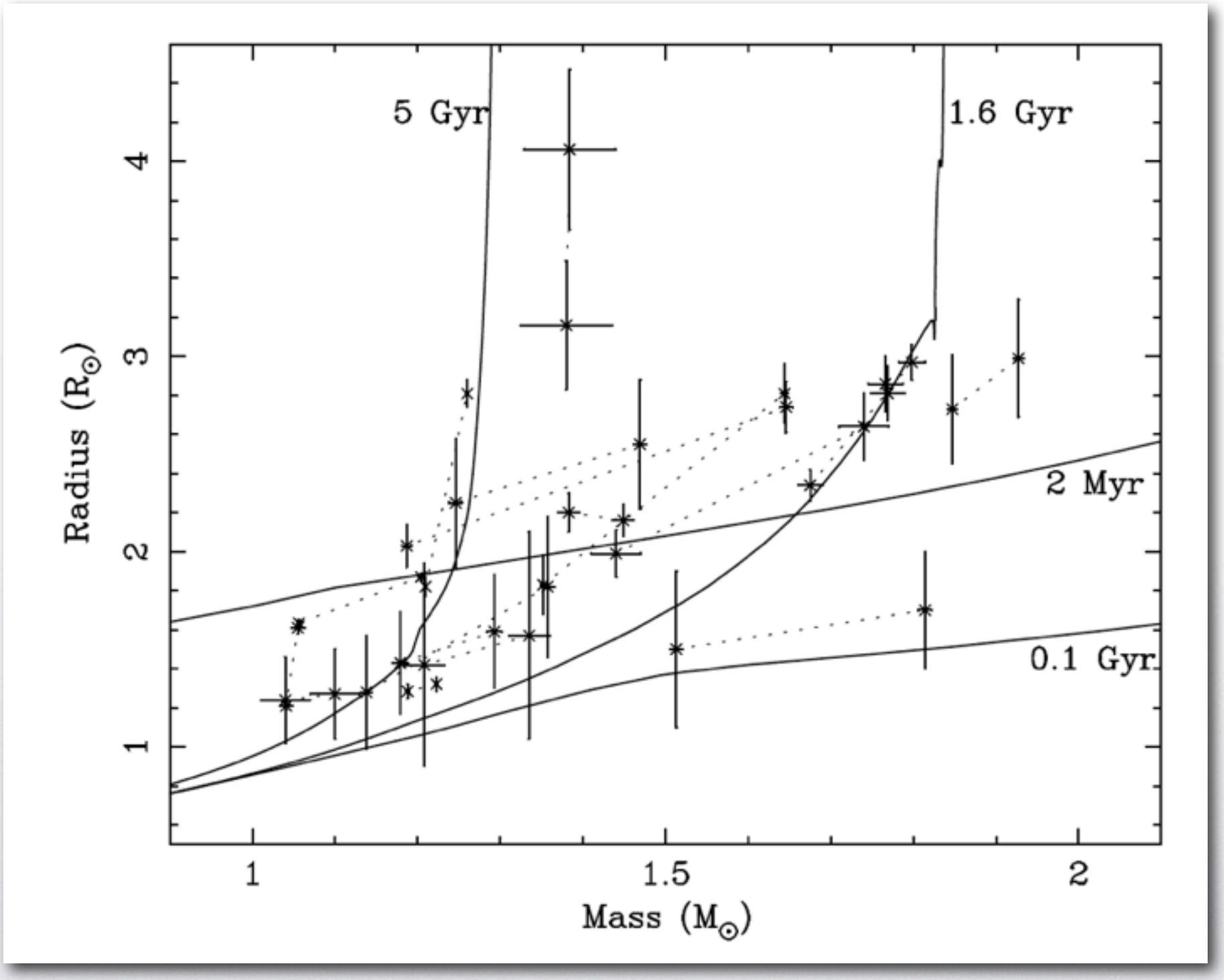

180
90
0
–90
–180
Longitude of Asc. Node, Inner Binary (deg)
(w.r.t. invariable plane)
0
200
400
600
800
1000
1200
t–2,455,000 (BJD)


1.00000
0.99995
0.99990
0.99985
0.99980
0.99975
0.99970
Calculated Relative Flux
0.99960
0.99980
1.00000
1.00020
1.00040
Observed Relative Flux


Observed [2,455,019 to 2,455,055 (BJD)]
Observed – Calculated
1.754 d
0.877 d
Normalized BLS statistic
0.8
0.7
0.6
0.5
0.4
0.3
0.4
0.6
0.8
1.0
1.2
1.4
Frequency [d^{-1}]


No eclipses
Inner binary transit
Occultation of B by A
Occultation of C by A
Eclipse of B by C
Eclipse of C by B
Start Date - 2450000 [BJD]
6650
6600
6550
6500
6450
6400
6350
6300
6250
6200
6150
6100
6050
6000
5950
5900
5850
5800
5750
5700
5650
5600
01/2014
02/2014
12/2013
10/2013
11/2013
08/2013
09/2013
07/2013
05/2013
06/2013
03/2013
04/2013
02/2013
12/2012
01/2013
10/2012
11/2012
09/2012
07/2012
08/2012
06/2012
04/2012
05/2012
02/2012
03/2012
01/2012
11/2011
12/2011
09/2011
10/2011
08/2011
06/2011
07/2011
04/2011
05/2011
03/2011
0
10
20
30
40
50
Days [BJD]

Absolute Dimensions



Hełminiak, Konacki, Ratajczak, Muterspaugh (2009)

Slawson et al. (2011)

Kepler Eclipsing Binary Catalog

Revision: 1.96

Date: 2011-06-15

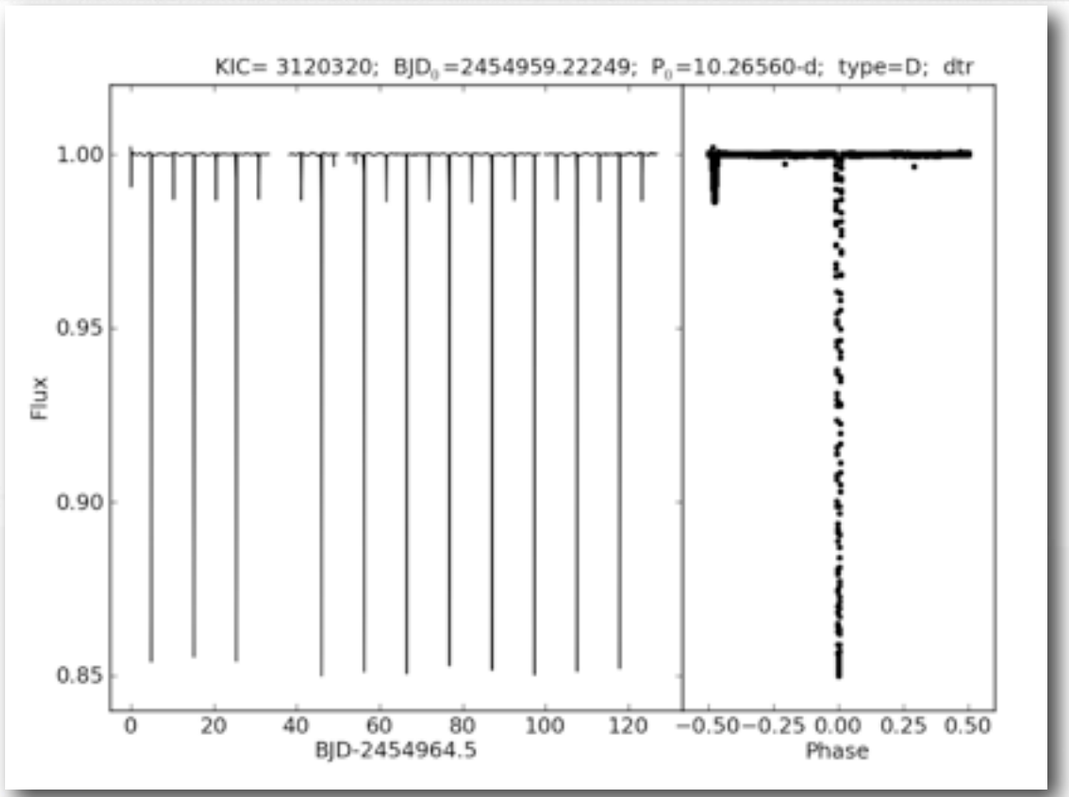
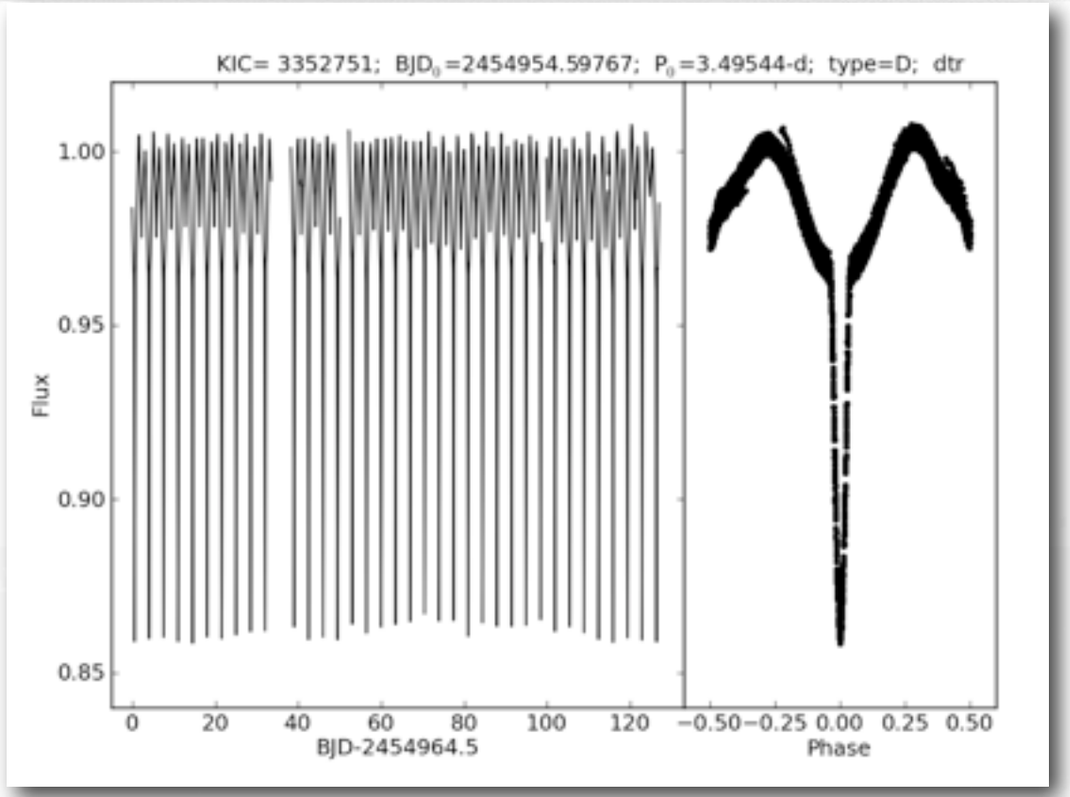
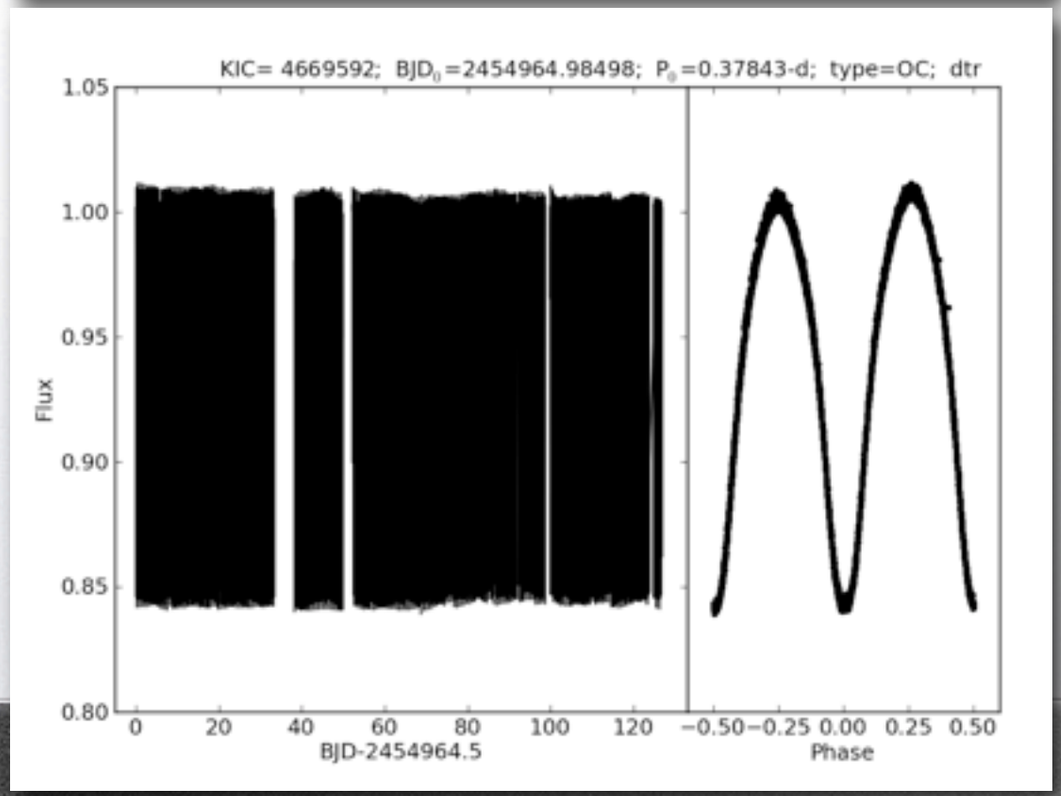
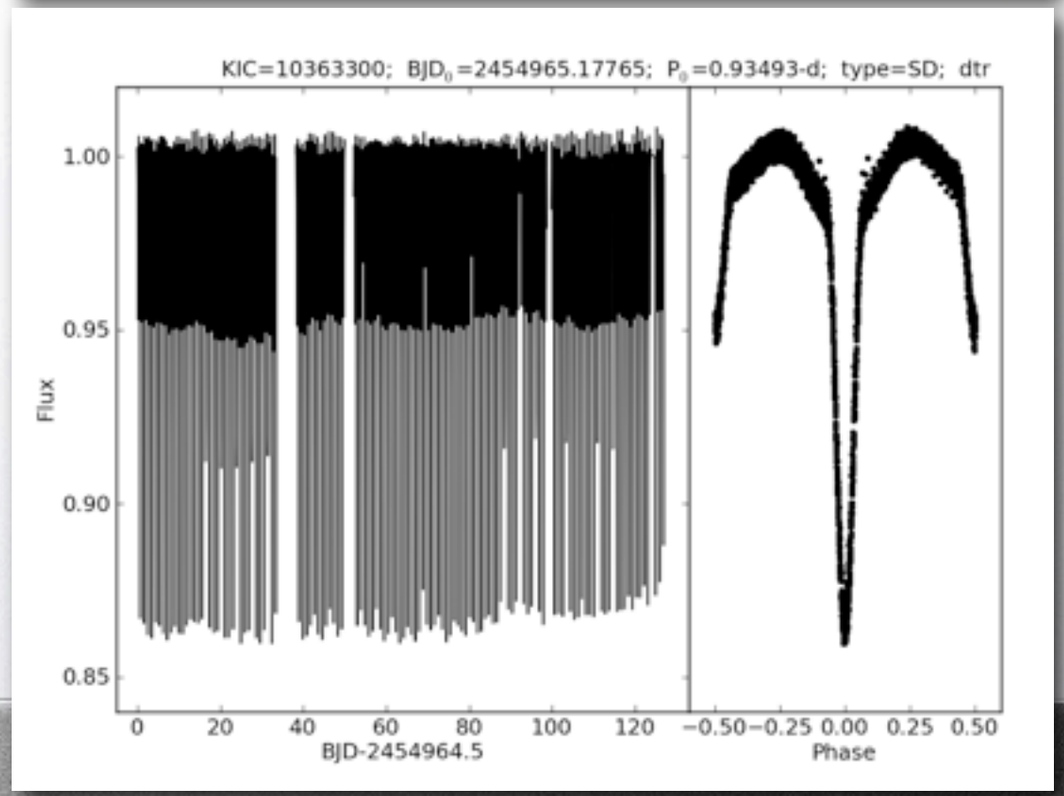
IMPORTANT NOTICE: This is a second revision of the Eclipsing Binary catalog; it follows up the first paper in the series, Prsa et al. (2011), AJ 141, 83. It includes Q0, Q1 and Q2 data. The results are *preliminary* and may change before the paper is accepted for publication in the Astronomical Journal. The pre-print of the paper may be downloaded here: Slawson et al. (2011), submitted.

IN PROGRESS: Catalog-wide manual detrending is being performed. The updates are made to this page in real time. The official catalog (V2.0) will have all data detrended.

The table fields are: Kepler Input Catalog (KIC) identifier; morphology type -- detached (D), semi-detached (SD), overcontact (OC), ellipsoidal (ELV) and uncertain (?); barycentric ephemerides (BJD_0, P_0); Kepler magnitude (Kmag); principal parameters (temperature ratio T_2/T_1, sum of fractional radii $\varrho_1+\varrho_2$, orthogonalized eccentricity e sin ω, e cos ω, mass ratio q, fillout factor FF and sin i; the last column contains links to three figures: raw light curve (raw), detrended light curve (dtr), and polyfitted phase curve (fit). Do not trust parameters if the polyfit curve looks bad!

You can access the initial version of the catalog (V1.0) here.

The table below is sortable. Click on the column header to sort by that column.

KIC:	TYPE:	BJD_0	P_0	Kmag	T_2/T_1	$\varrho_1+\varrho_2$	q	e sin ω	e cos ω	FF	sin i	Figures
01026032.00	D	54966.773843	8.460438	14.813	0.85956	0.12451	N/A	0.05515	0.01308	N/A	0.99687	raw dtr fit
01026957.00	D	54956.011753	21.762784	12.559	0.49053	0.18848	N/A	-0.06237	-0.07830	N/A	0.98538	raw dtr fit
01433962.00	D	54965.325203	1.592691	15.470	0.78423	0.11622	N/A	-0.12883	0.07820	N/A	0.99716	raw dtr fit
01571511.00	D	54954.506187	14.021624	13.424	0.82928	0.13522	N/A	-0.10259	-0.02367	N/A	0.99416	raw dtr fit

Eclipsing Binaries