2012 Sagan Exoplanet Summer Workshop

Hands-on Session
“Transit Timing Variations”

Presenters

- Dan Fabrycky
  - Hubble Fellow at UC Santa Cruz (UCSC)
  - Assistant Professor at University of Chicago in fall
- Darin Ragozzine
  - Postdoctoral Researcher at University of Florida with Eric Ford
- Both Dan and Darin have expertise in working with Transit Timing Variations from Kepler as active members of Kepler's TTV/Mulitples Working Group

Other support and Thanks

- Stefano Meschiari (UT Austin McDonald Fellow)
- Josh Carter (SAO Hubble Fellow)
- Eric Agol (UW Professor)
- Carolyn Brinkworth (NExScI Science Affairs)
- Technical Support from IPAC/NExScI
- Sagan Workshop Organizers

Get some files to follow along…

- Open up a web browser within the VNC viewer (world and mouse icon at the top), and navigate to:

  http://www.ucolick.org/~fabrycky/saganws/

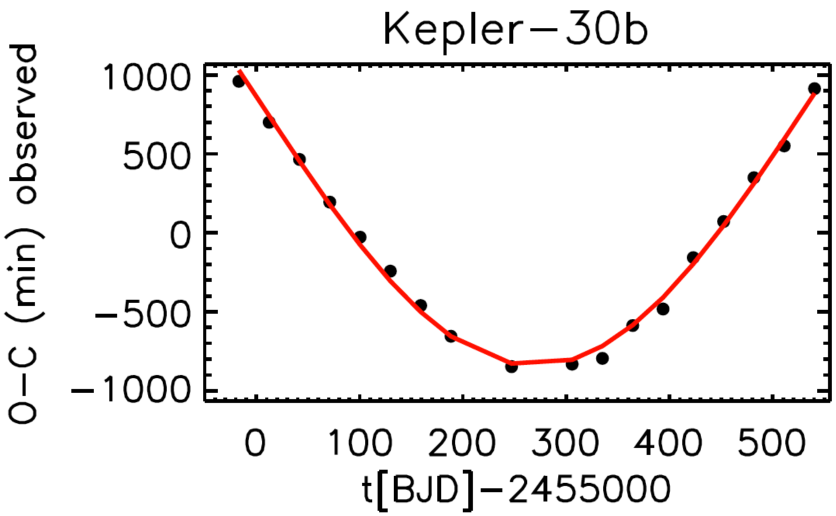
-- You can get TTV_handson.pdf, to follow along this presentation.

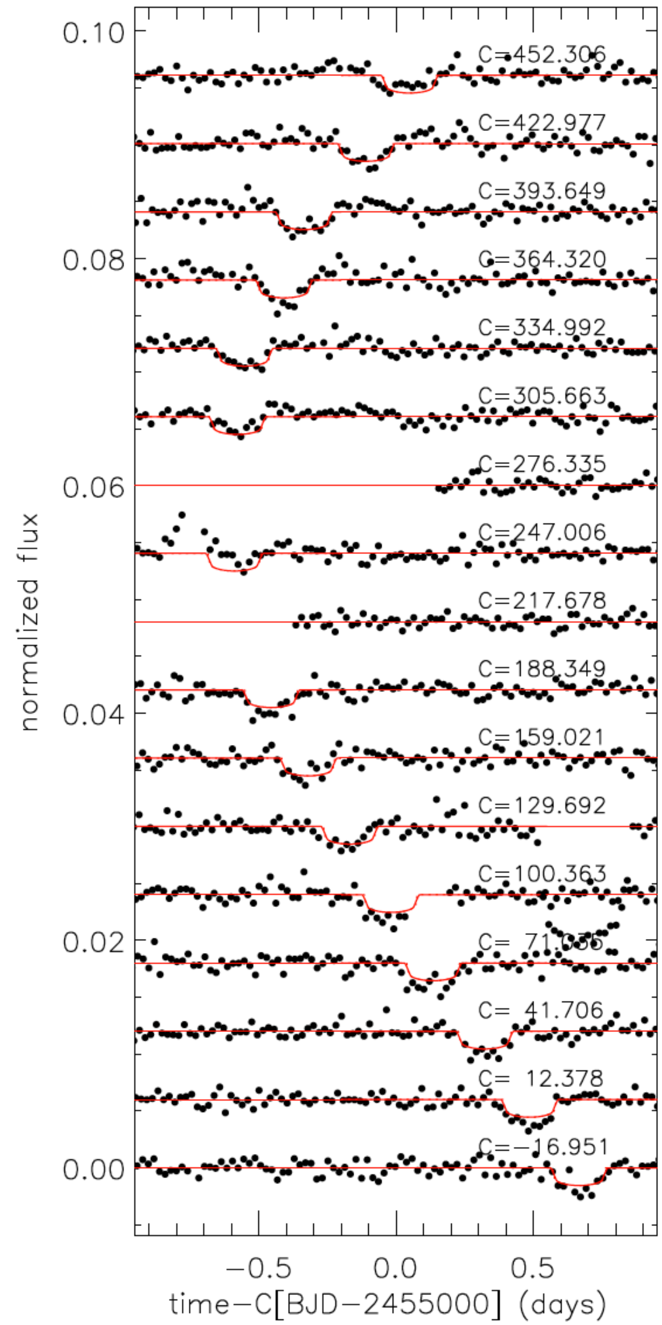
-- Open up QATS_notes.txt which we'll use later.

Review: Transit Timing Variations

- An idealized star+planet system undergoes perfectly periodic ("Keplerian" or two-body) motion
  - The times of transits are perfectly periodic
  - The times of transits follow a linear ephemeris: $T_N = T_0 + N*P$
  - No significant deviations from a best-fit line
  - Even with ultra-precise, continuous, long-duration measurements from Kepler, the majority of planets have periodic transits
- Planet-planet gravitational interactions induce:
  - Non-periodic, non-linear transit times
  - Variations remain after subtracting best-fit period
- Transit Timing Variations = TTVs

Strong Example





Power of TTVs

- Already present in Kepler data
  - ~10% of Kepler candidates (Ford et al. 2012)
  - 100+ planets and growing fast!
- Can be used to confirm candidates (currently most numerous method for Kepler) or detect new planets
- Measures interacting planets and hence **MASSES**:
  - Complementary to radius measurements
  - Allows for density measurements, yielding insights into Composition, Formation, and Dynamics
  - *Currently best method for small planets*
- Best used in systems with more than one transiting planet = Multi-Transiting Systems (MTSs). ~900 such valuable systems already known from Kepler

Some TTV References

- Prediction of Method and Theory (Miralda-Escude 2002; Agol et al. 2005; Holman & Murray 2005; many others)
- Early Detections (Kepler-9, Holman et al. 2010; Kepler-11, Lissauer, Fabrycky et al. 2011; etc.)
- Planet Confirmations (Ford et al. 2012a; Fabrycky et al. 2012a; Steffen et al. 2012a)
- Non-Transiting Planet Detection (Ballard et al. 2011; Nesvorny et al. 2012)
- Planet Discovery issues (Garcia-Melendo & Lopez-Morales 2011; Carter & Agol 2012; etc.)
- **TTV Data** and Statistical Studies (Ford et al. 2011; Ford et al. 2012b; Steffen et al. 2012b,c; Rowe et al. 2012)

Main Goal for this Session

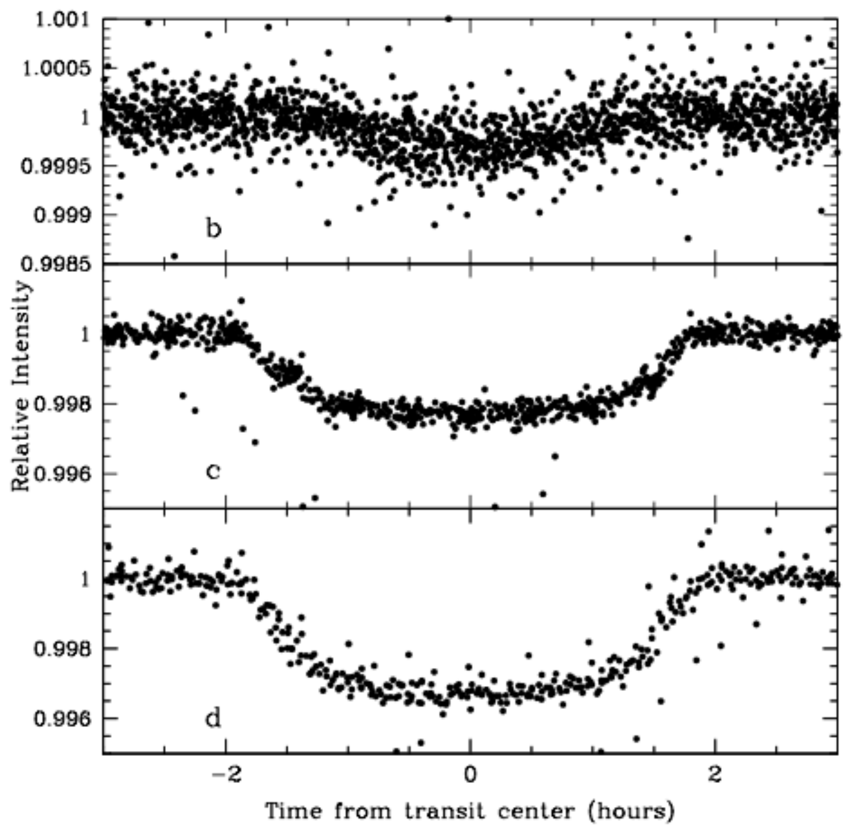
- **Analyzing transit times from a Kepler Multi-Transiting System to measure planet masses**
- Assumed starting point:
  - Individual transit times and errors for each planet
    - Other hands-on sessions
- *This is a very ripe area for research!*
  - 3 more quarters of Kepler data (Q7-Q9) are going public in a few days, very useful for TTVs
  - Kepler team regularly comes out with TTV data catalogs and identification of interesting systems
- (Note: for planets with transits too small to measure individual times, you need a different method, such as a photodynamical model (e.g., Kepler-36).)

Main Goal for this Session

- Reproducing mass measurements for Kepler-18c and Kepler-18d (Cochran et al. 2011 = C+11)
- Check that everyone is logged in and ready
- Let us know if you have any questions!
- At the end, we will use a non-linear transit search method (QATS) to search for the planets of Kepler-30

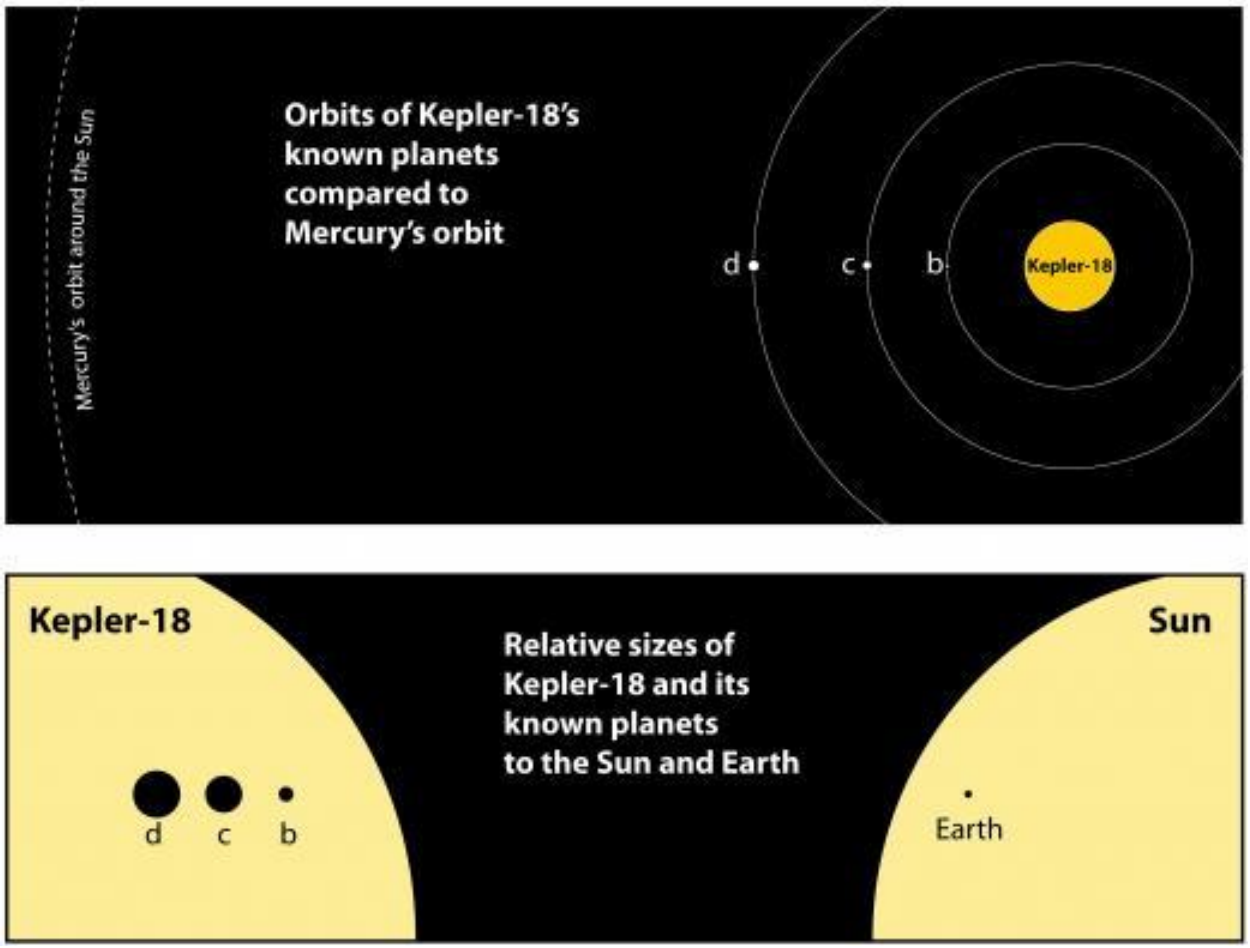
Kepler-18 (C+11 Fig 2)

- Kepler pipeline detected 3 planets



Kepler-18 Architecture

- System with Tightly-packed Inner Planets



Analysis using the Systemic Console

- Written by Stefano Meschiari and collaborators
  - Available at www.stefanom.org
- Extension from Console seen on Greg Laughlin's excellent exoplanet blog (www.oklo.org)
- Organized and efficient Java GUI
- Can fit a variety of datasets in flexible ways, very useful for fitting and studying TTVs.
- See Meschiari et al. 2009; Meschiari et al. 2010

Thank You Stefano!

Console Input Files

- Systemic keeps different datasets in individual column-delimited ASCII text files.
  - Transit timing data in “TDS” file.
- Investigate data for Kepler-18c
  - *more ~/datafiles/k18c.tds*
- At the top is JD epoch (subtracted from all subsequent times)
- Also planet number (Kepler-18c is the 2nd planet)
- First column is transit time (since JD epoch) in days
- Second column is error (in days)
- Third column is 1 for primary or 2 for secondary eclipse.

Questions for Discussion

- What is the approximate period of this planet?
  - 7.5 days, just subtract two adjacent times
- What is the difference between Transit Times and TTVs?
  - TTVs have the “average period” subtracted (O-C)
- What is the approximate period of planet d (*k18d.tds*)?
  - 15 days
- What is the typical TTV error in minutes for this planet?
  - 1 minute (from 0.0006 days and 1440 mins/day)
- What are the main factors in determining TTV errors?
  - SNR of single transit: depth and star brightness; ingress/egress timescales compared to cadence
  - K18c/d are large and K18 bright: excellent precision

Simultaneous Data Fitting

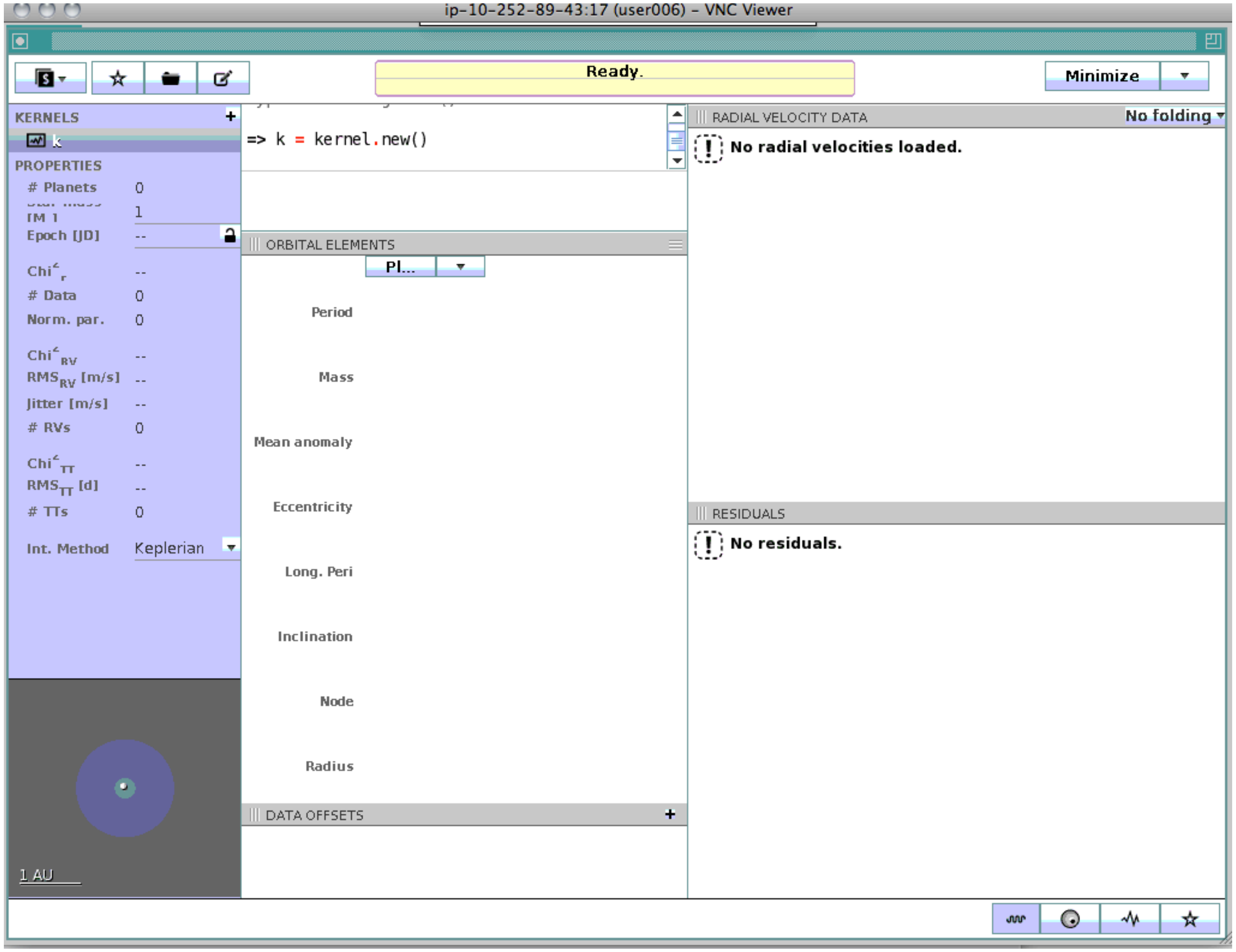
- Systemic can bundle multiple datasets together for simultaneous fitting by using a **.sys* file
- Kepler-18 datasets:
  - *more ~/datafiles/k18.sys*
- TD means transit data
  - We'll be fitting both *k18c.tds* and *k18d.tds*
- Kepler-18 also has RV measurements (*k18.vels*) that we'll be fitting as well
- *k18.sys* also includes the mass of the star and “Epoch”
  - In dynamically interacting systems, the orbital properties of the planets *change as a function of time*. Therefore, we choose a specific epoch at which time we will determine the orbits.

Load Systemic Console

- Get a terminal (from Applications, select '*xterm*')
- Load the Systemic Console Java GUI
  $ *java -jar SystemicGui.jar*
- Resize the window to fill the screen.
- Let us know if you have any trouble loading this up.
- For this workshop, we will be using Systemic v1.8.
  - Versions for various systems are available, e.g. Mac.
  - http://www.stefanom.org/?systemic for the latest version, tutorials, etc.

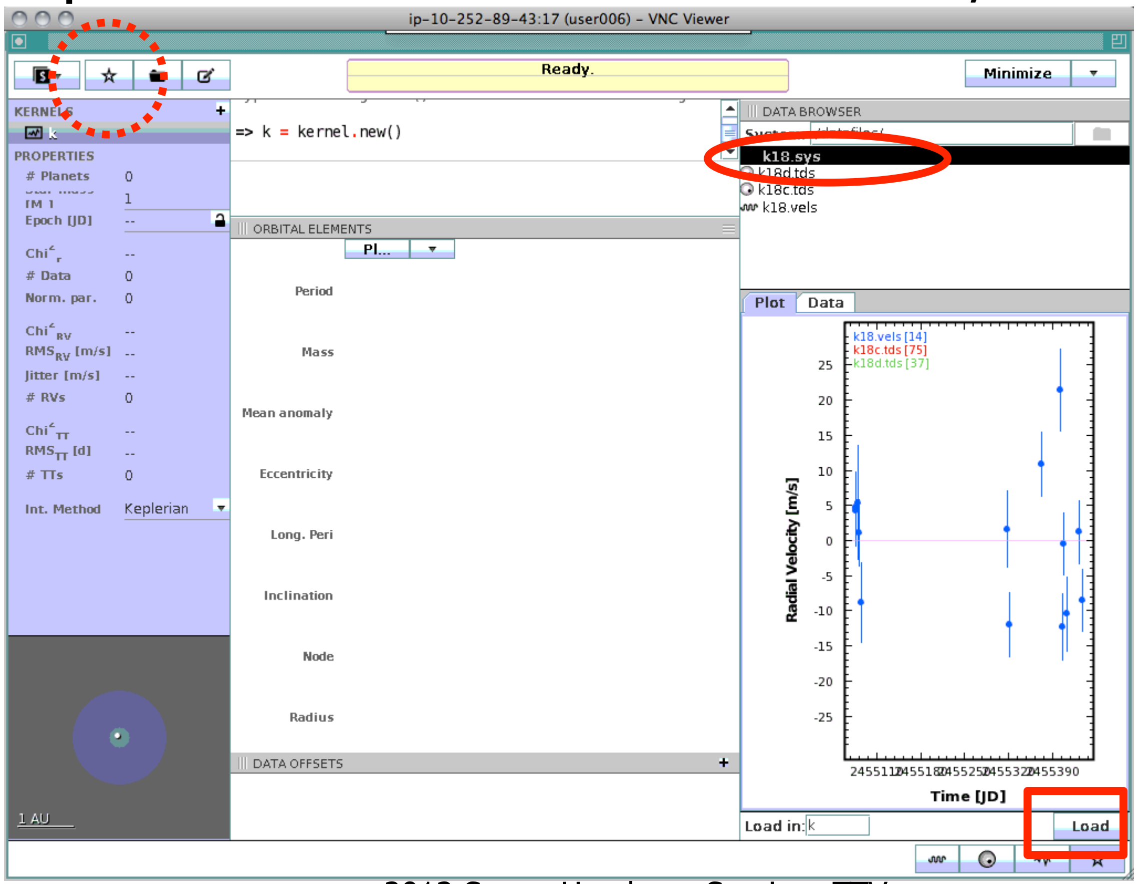
Introduction to the Console

- Panels ("left", "center", "right"); drag subpanels to resize



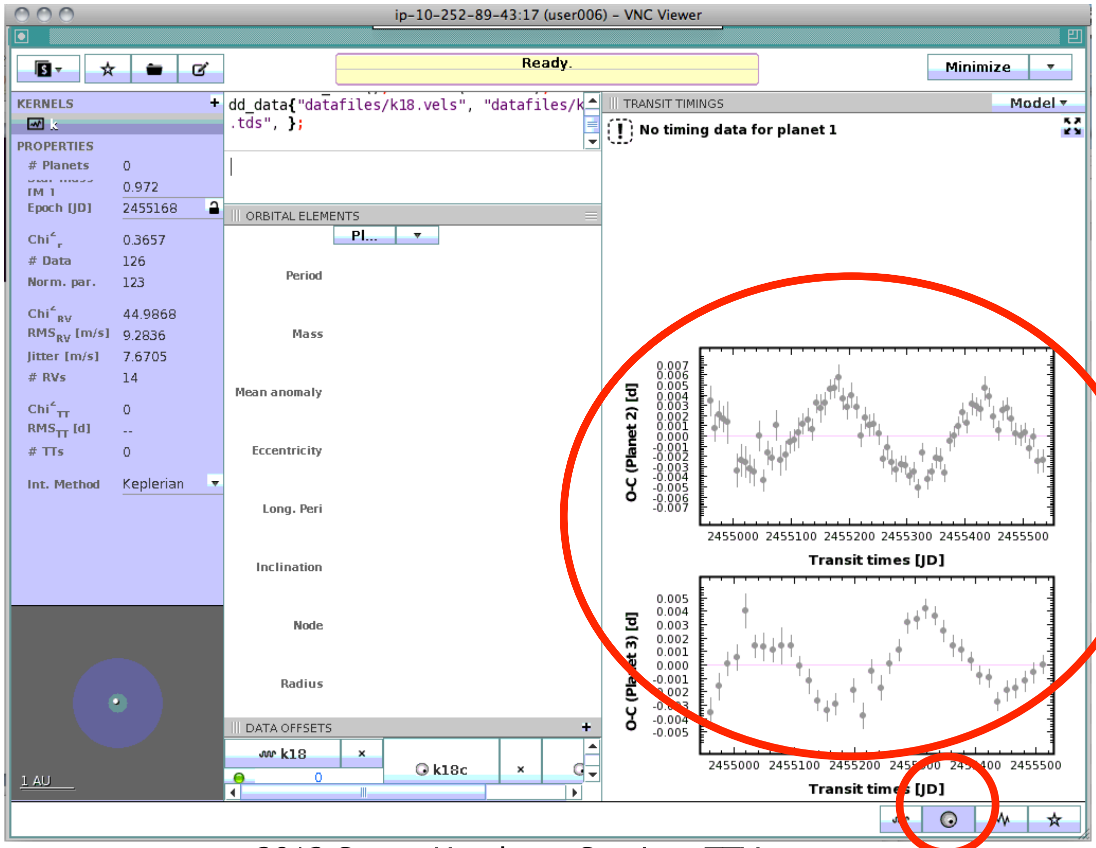
Load Kepler-18 datasets

- Click on the star in the upper left or lower right
- Right panel shows filenames and data; “Load” *k18.sys*



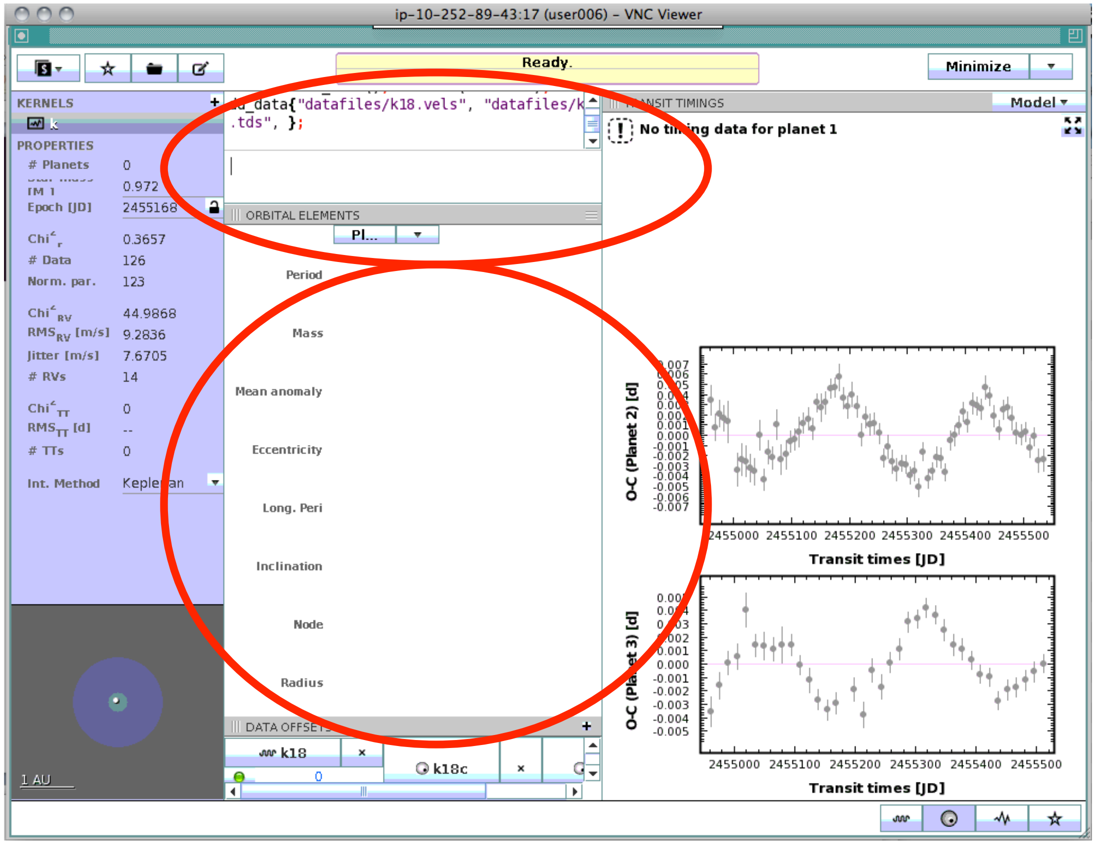
Look at TTV curve

- Click on transit symbol in lower right
- TTV data with best-fit period subtracted is shown



Center Panel

- Top subpanel: terminal echoing commands; we'll ignore
- Middle subpanel: Set planets' parameters: *SCIENCE!!*

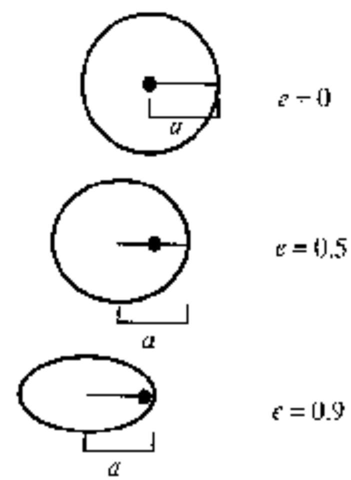


Planet Parameters

- Physical parameters: mass and radius
- Orbital parameters: period, mean anomaly, eccentricity, longitude of periapse ("long. peri."), inclination, longitude of the ascending node ("node")
  - In combination with stellar mass, these completely describe the position and velocity of the planet
  - Coordinate System: polar (radius, angle from reference line); centered on star; reference plane is the plane of the sky; reference line (in reference plane) is Astronomical North

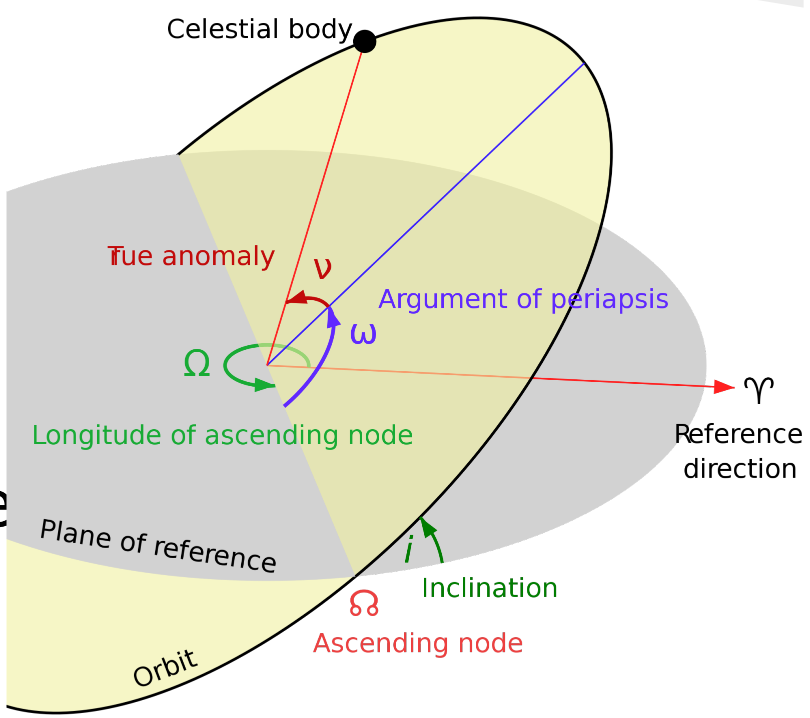
Orbital Elements: Size and Shape

- Period *(P)*: time to make one complete revolution
  - If the masses are known, Kepler's Third Law directly relates the period to the semi-major axis *(a)*, the physical size of the orbit (usually measured in AU)
  - Since we measure times and don't know masses perfectly, better to solve for periods
- Eccentricity *(e)*: a measure of how circular an ellipse is
  - Transiting planets give very weak constraints
  - TTVs can help a lot!



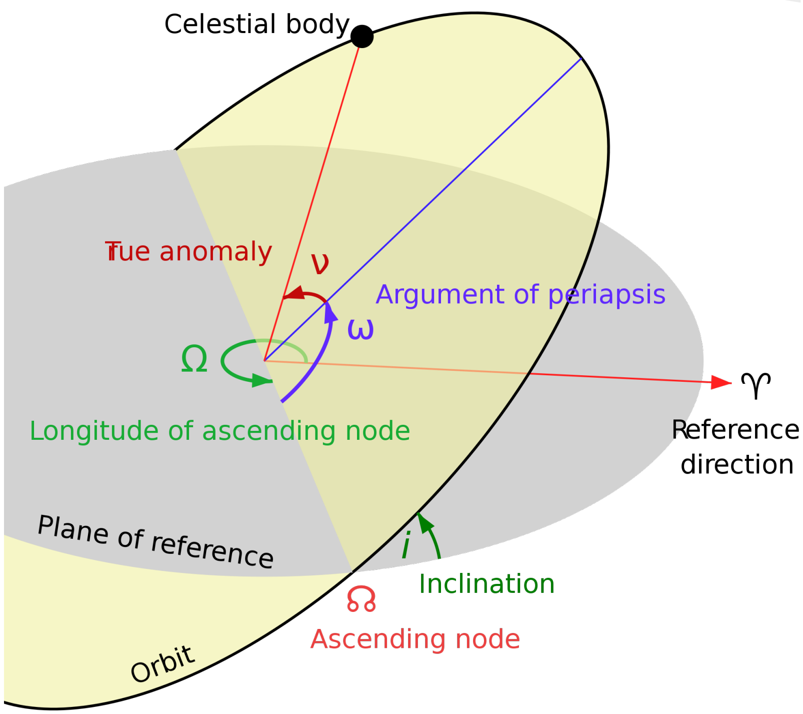
What do we need to know?

- Inclination *(i)*: angle relative to sky plane
  - Edge-on (transiting) = 90°
- Longitude of the Ascending Node *(Ω)*: usually not measurable (except for relative nodes between planets)
- Argument of periapse *(ω)*: angle in plane of the orbit from nodal line to periapse
- Longitude of periapse *(ω̃)*: $\Omega+\omega$



Orbital Elements: Orientation Angles

- True Anomaly *(ν or f)*: Angle in plane from periapse to current position of planet
  – Non-uniform as a function of time due to Kepler's 2nd Law
- Mean Anomaly *(MA)*: An averaged angle from periapse directly related to the true anaomly by Kepler's Equation
  – Uniform as a function of time
- Etc.

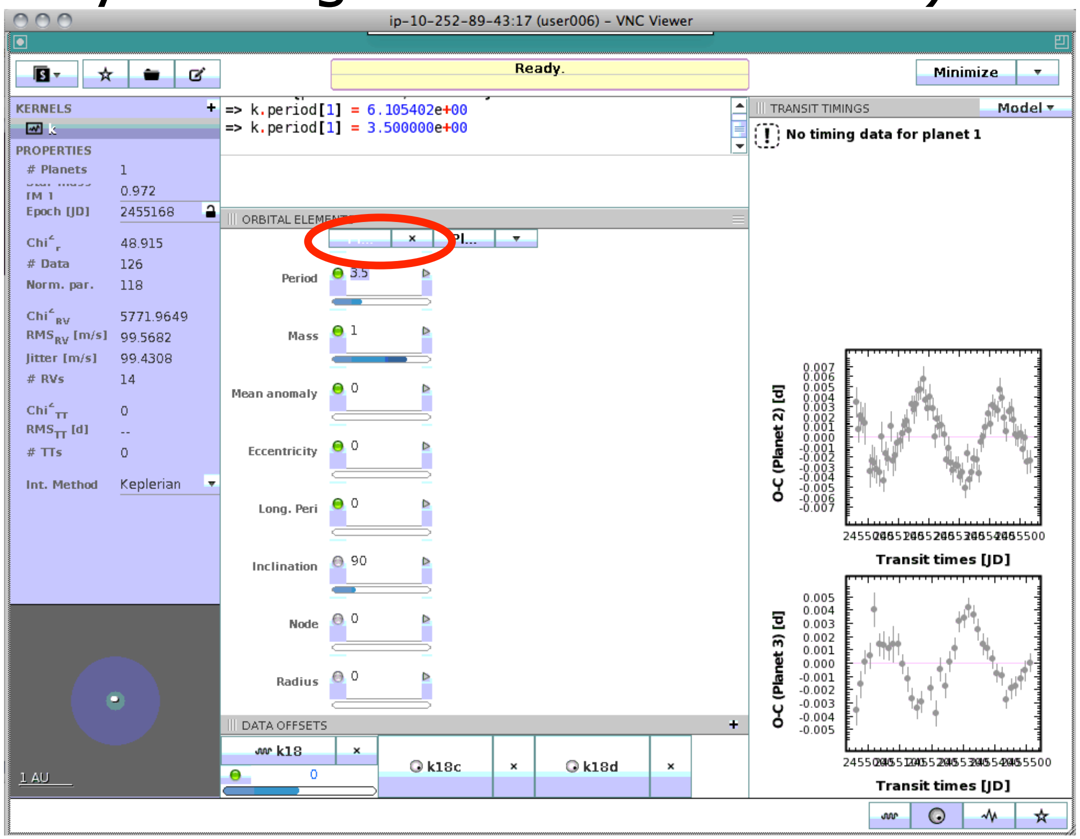


What do we need to know?

- Mean Anomaly (*MA*) is like orbital phase and is directly related to the time of transit
  - Regardless of TTVs, to get transit times right, we must have very correct values of *P* and *MA*
- Even in the geometrically simple case of circular motion, changing some elements (e.g., Ω) can change the geometric meaning of other elements (e.g., *MA*), sometimes in non-intuitive ways. Basically, *MA* (and often *P*) should always be left as a free parameter.
- We'll start with circular, coplanar, edge-on (i=90°) planets, a very good approximation for Kepler-18 (C +11)

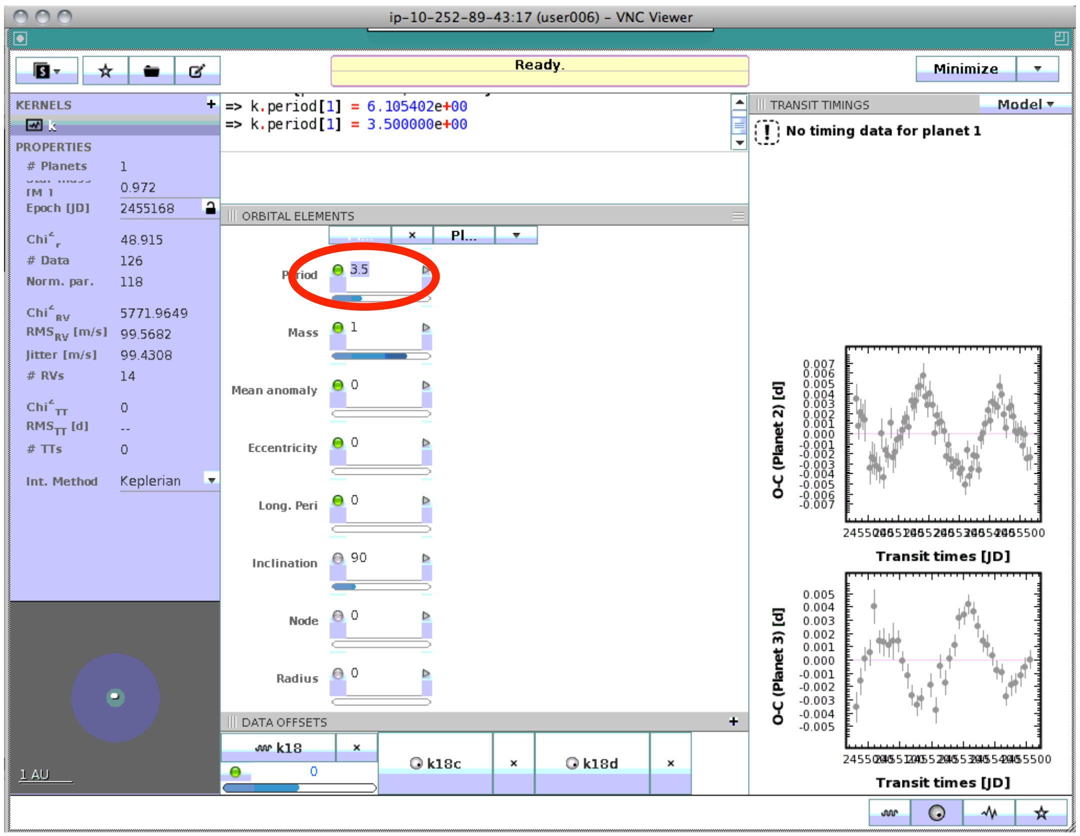
Console: Add Planet

- Add a planet by clicking on the “Planet N” button
- (Delete by clicking *x* next to the name.)



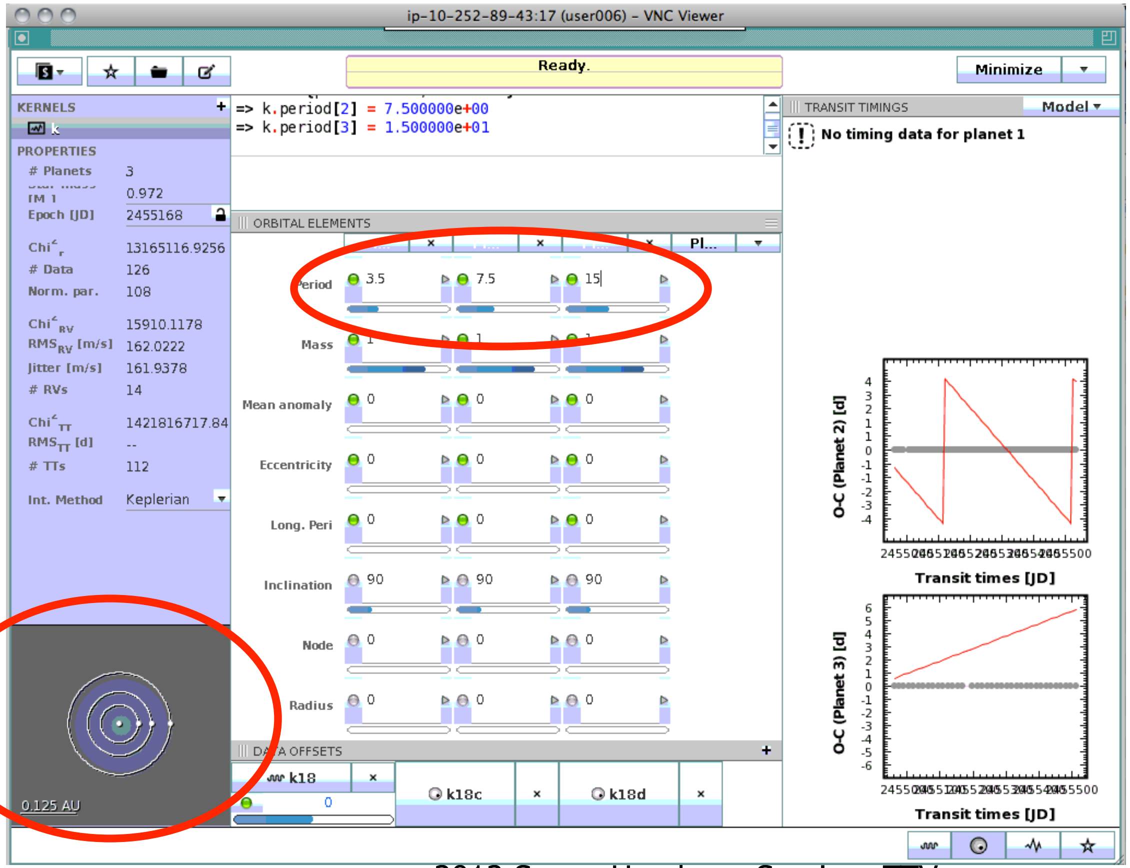
Console: Change Planet Parameters

- Click on text, edit, and hit enter
- Can also use slider underneath text



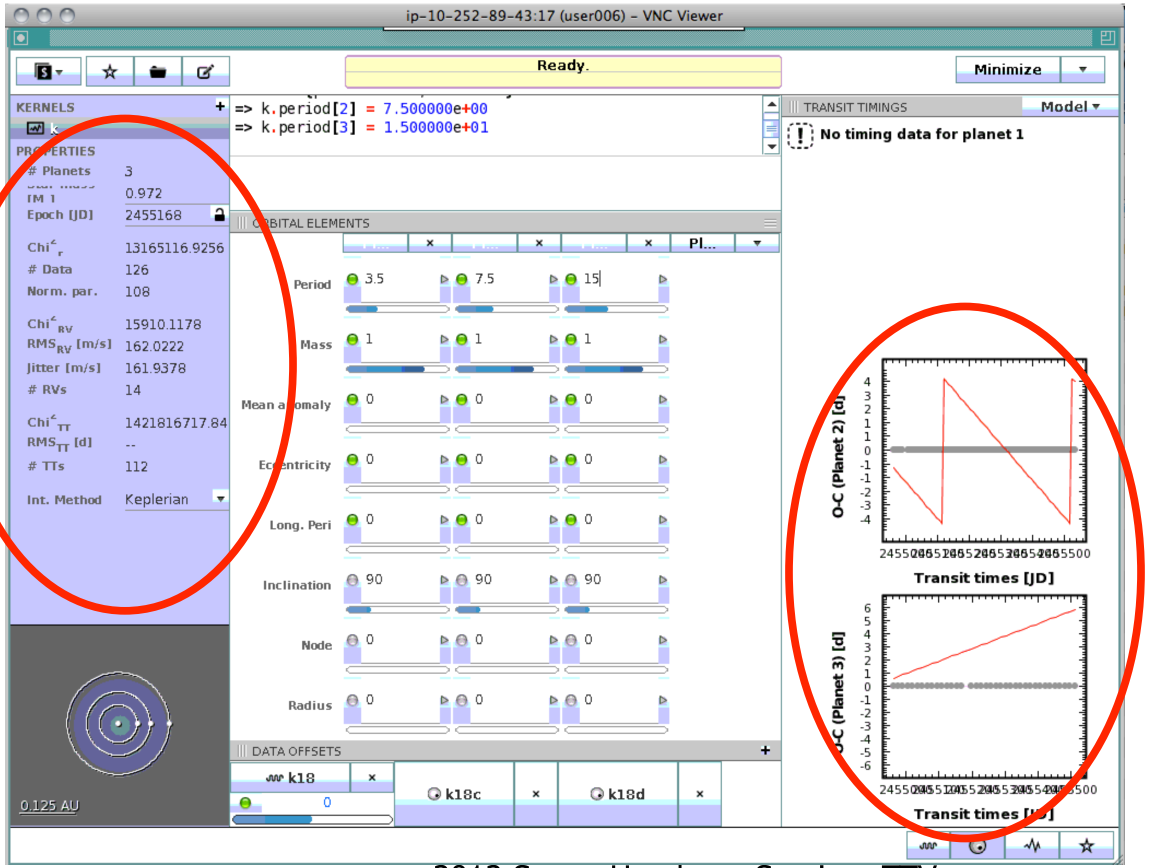
Console: Add Kepler-18 Planets

- Type approximate periods: 3.5, 7.5, and 15 days; “enter”.
- Lower left subpanel: orbit diagram; manipulate with mouse



Console: TTV Model

- Right panel auto-updates: shows current model as red line
- Left panel auto-updates: shows current goodness of fit (χ^2)

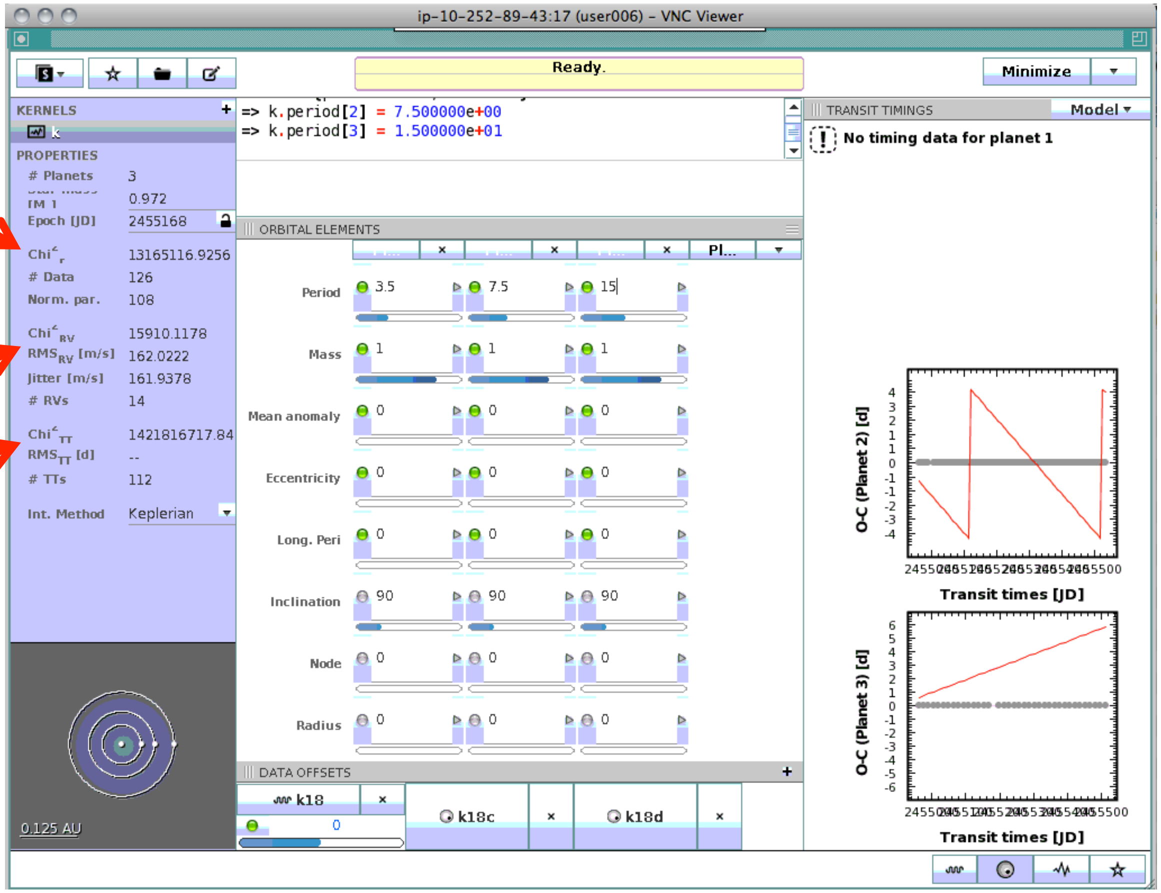


Console: Built in Minimizer

- Console has built-in minimizers to automatically improve fit

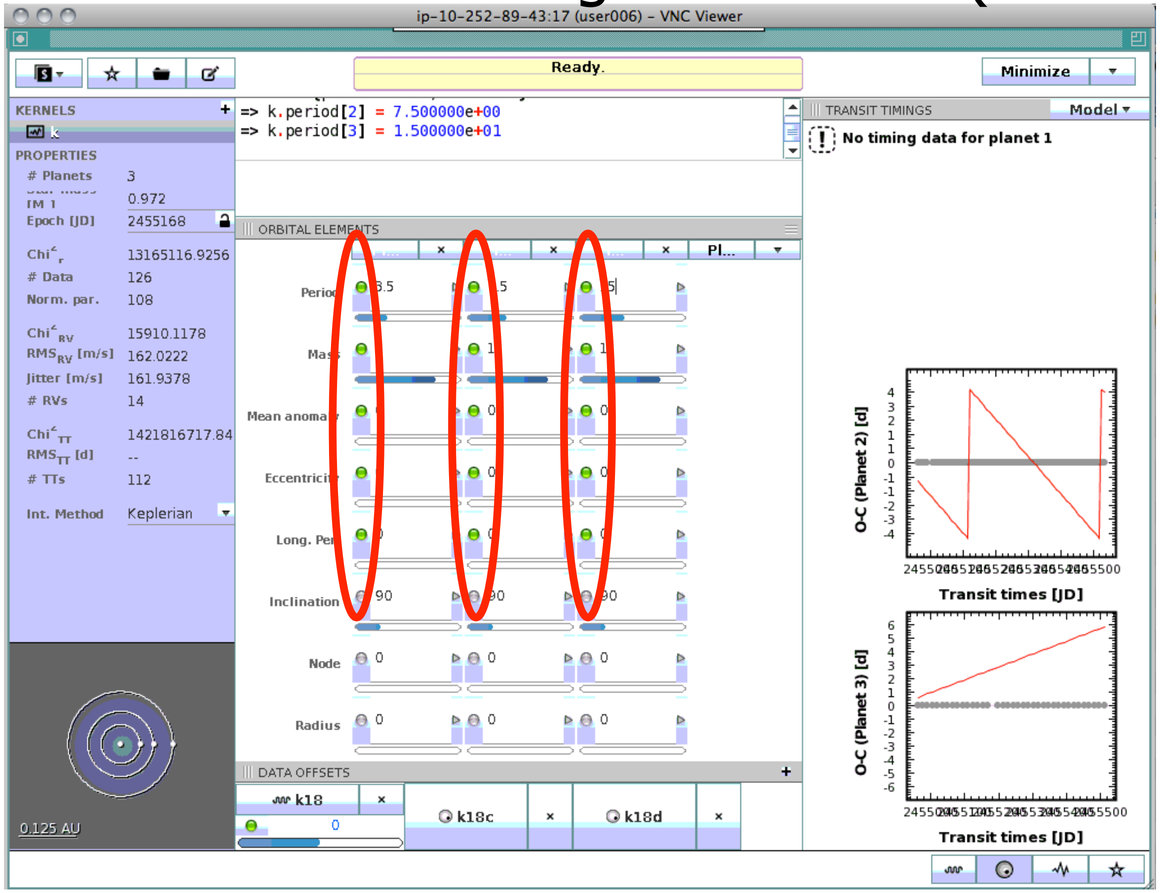
Figure of merit is reduced chi-square (Chi^2_r), ~1="good fit"

Chi^2_{RV} : RV
Chi^2_{TT} : Transit times



Console: Built in Minimizer

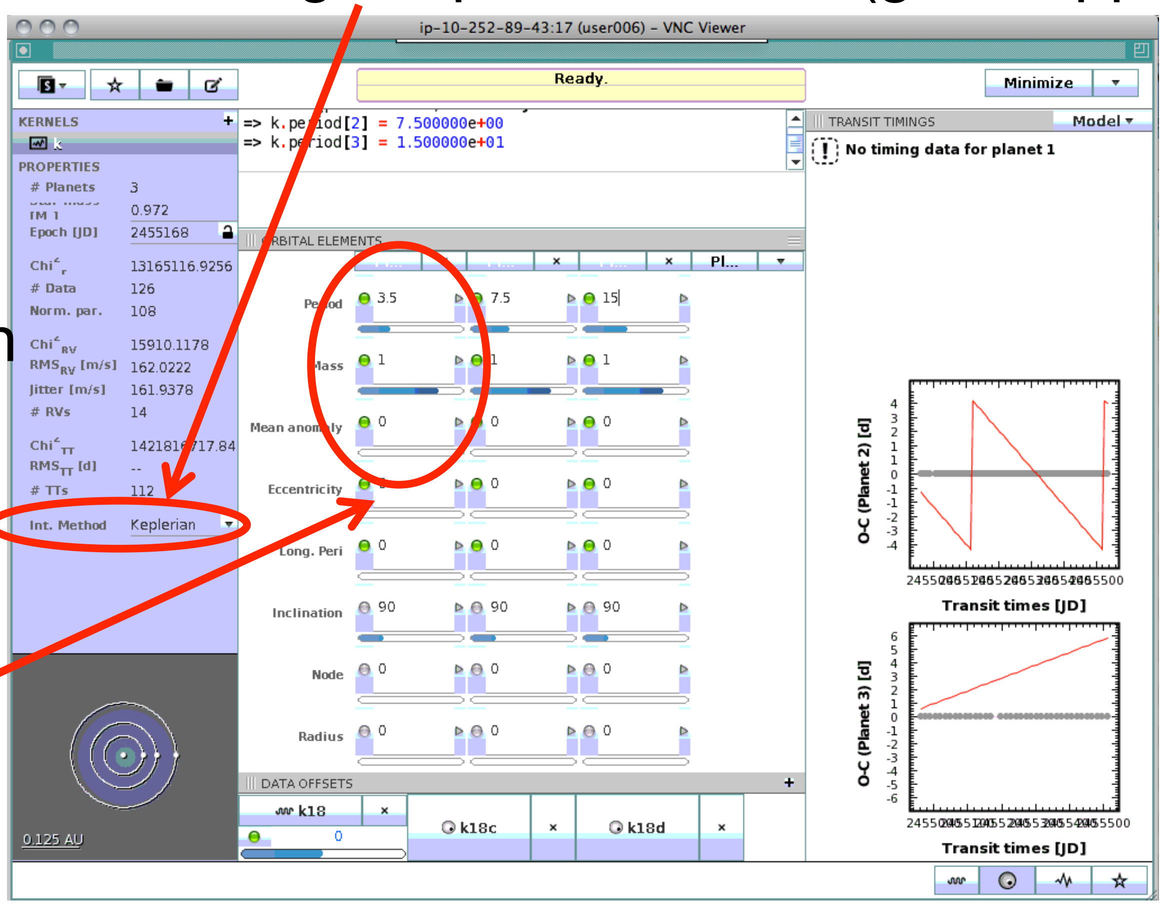
- Radio buttons near parameters determine what is included in the multi-variate minimization: green = “on” (included)



Console: Start Slowly, and fix b

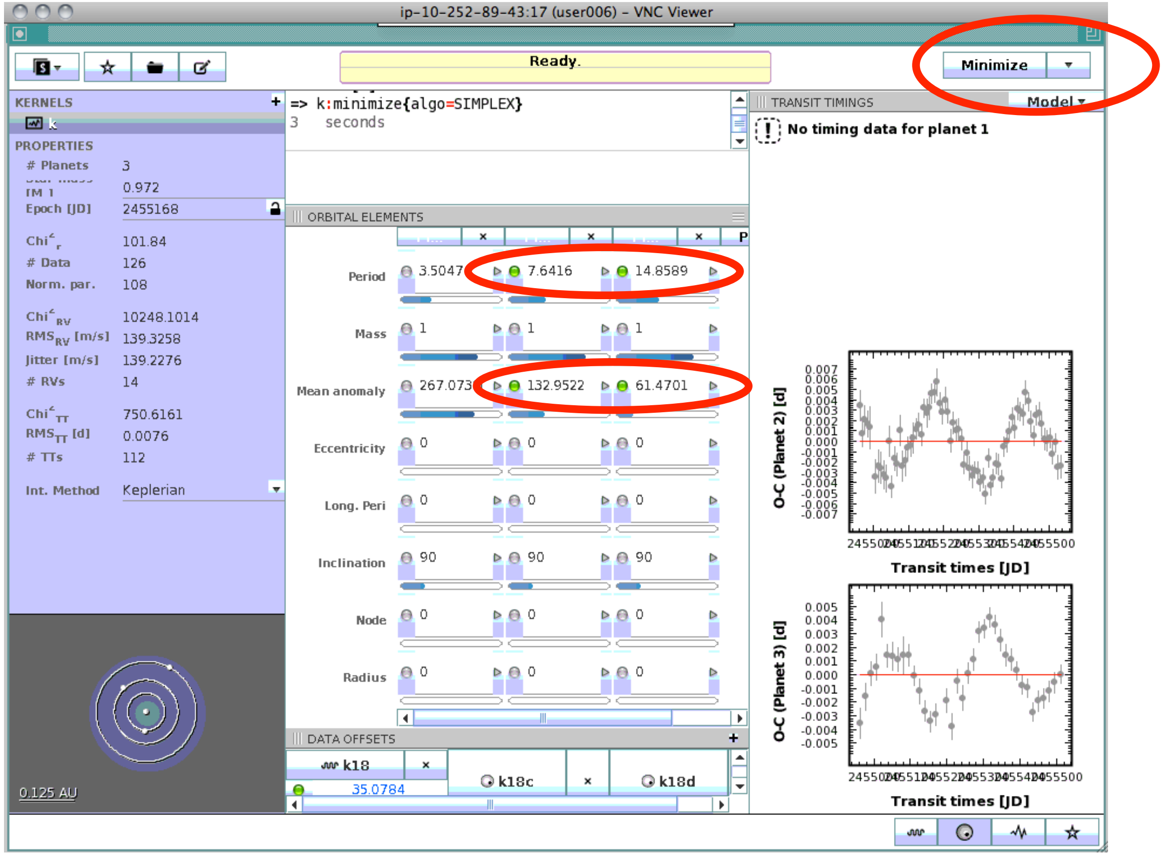
- Minimizers need a good initial guess to converge correctly
- Start with non-interacting “Keplerian” orbits (good approx.)

- Planet b is not our focus, use properties known from transit:
  - *P*=3.504725 and *MA*=267.0738



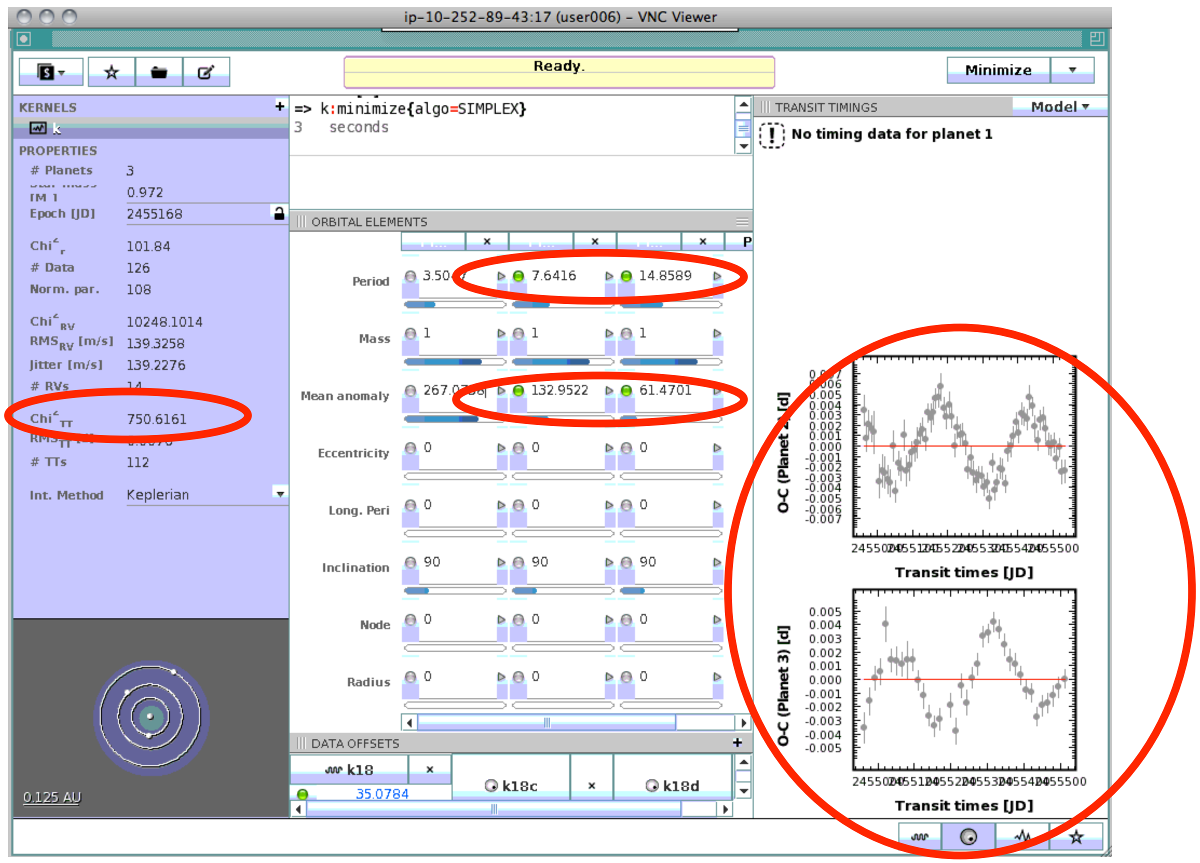
Console: Better Periods and Phases

- Deselect all buttons for minimization except Period and Mean Anomaly of Planets 2 and 3. Hit "Minimize"!



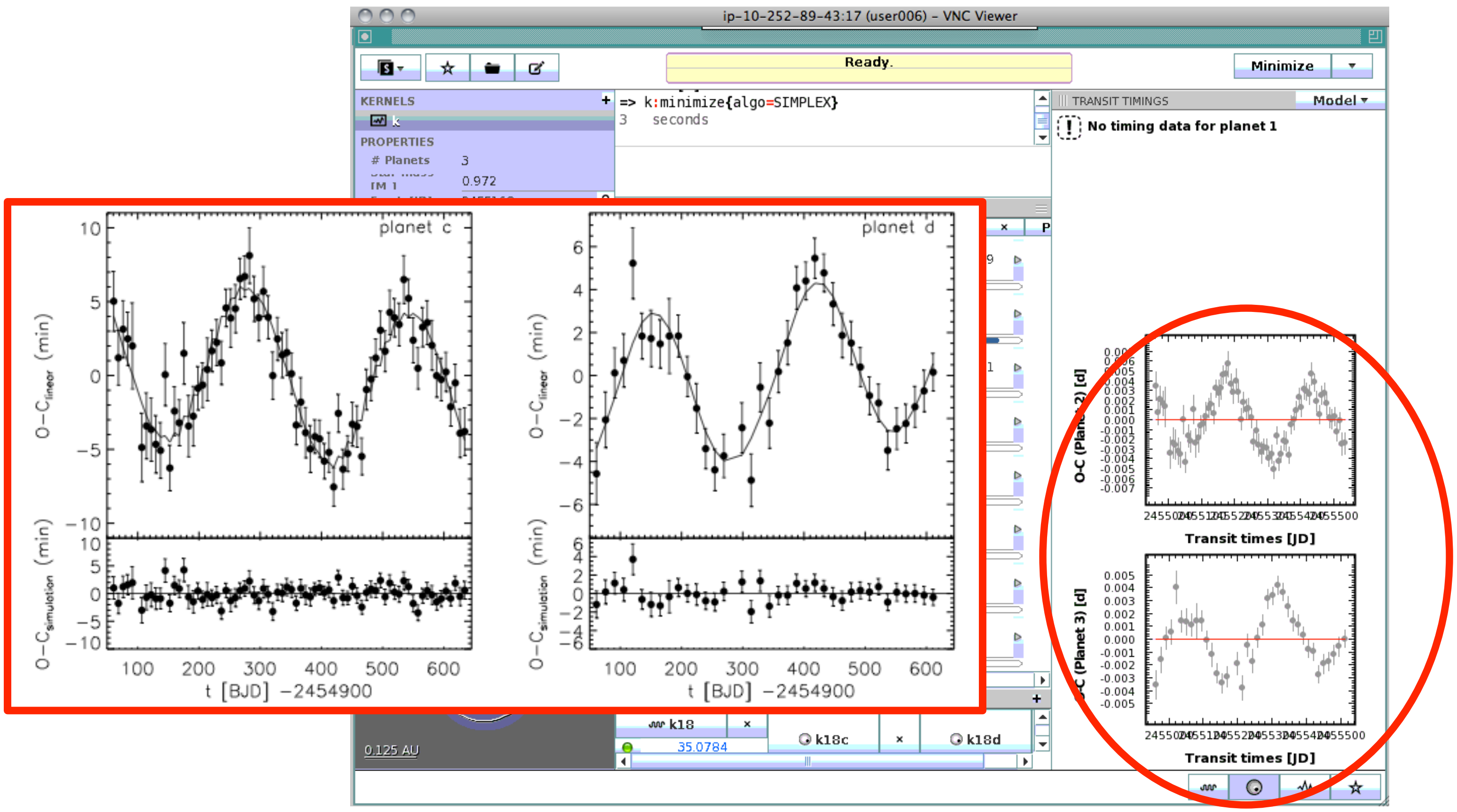
Console: Better Periods and Phases

- Systemic determined best-fit periods and phases.
- Red model line and Chi^2_{TT} are much much better.



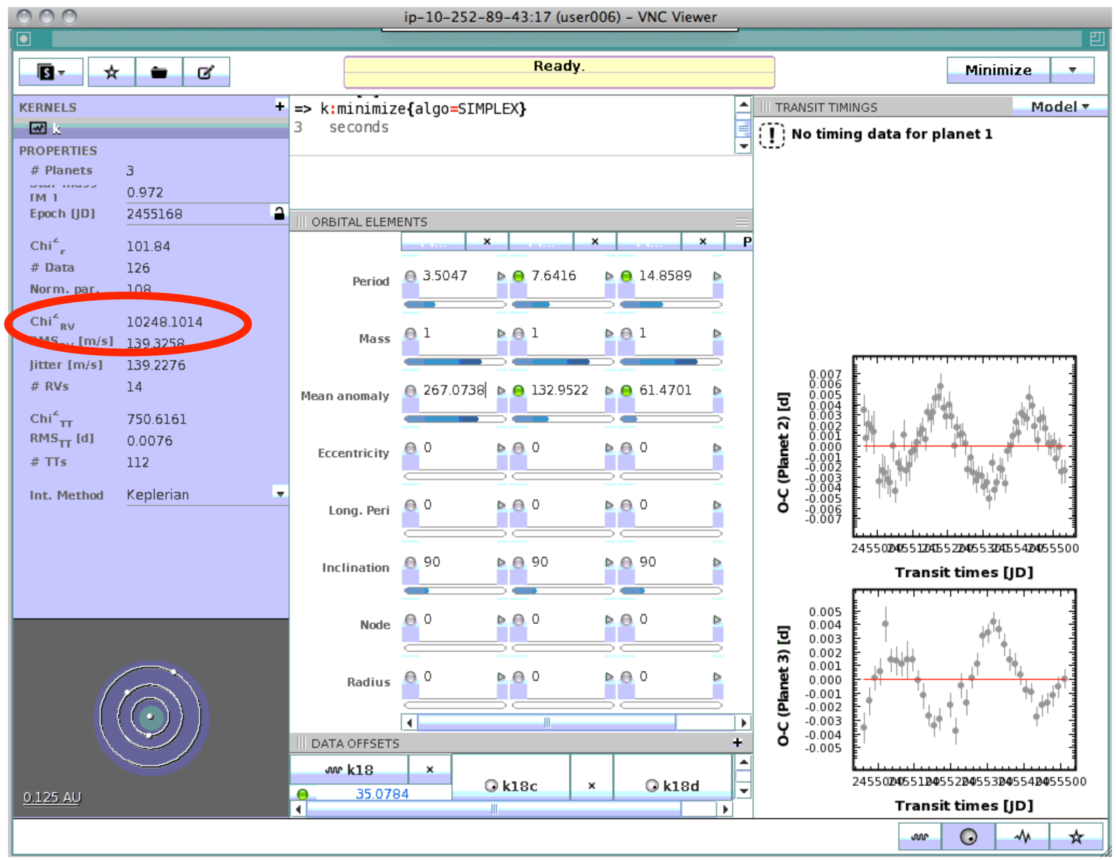
Compare to C+11 Values

- TTV (or O-C) is now similar to C+11 Figure 7
- C+11 Periods: 7.64159 and 14.85888 (Table 4)



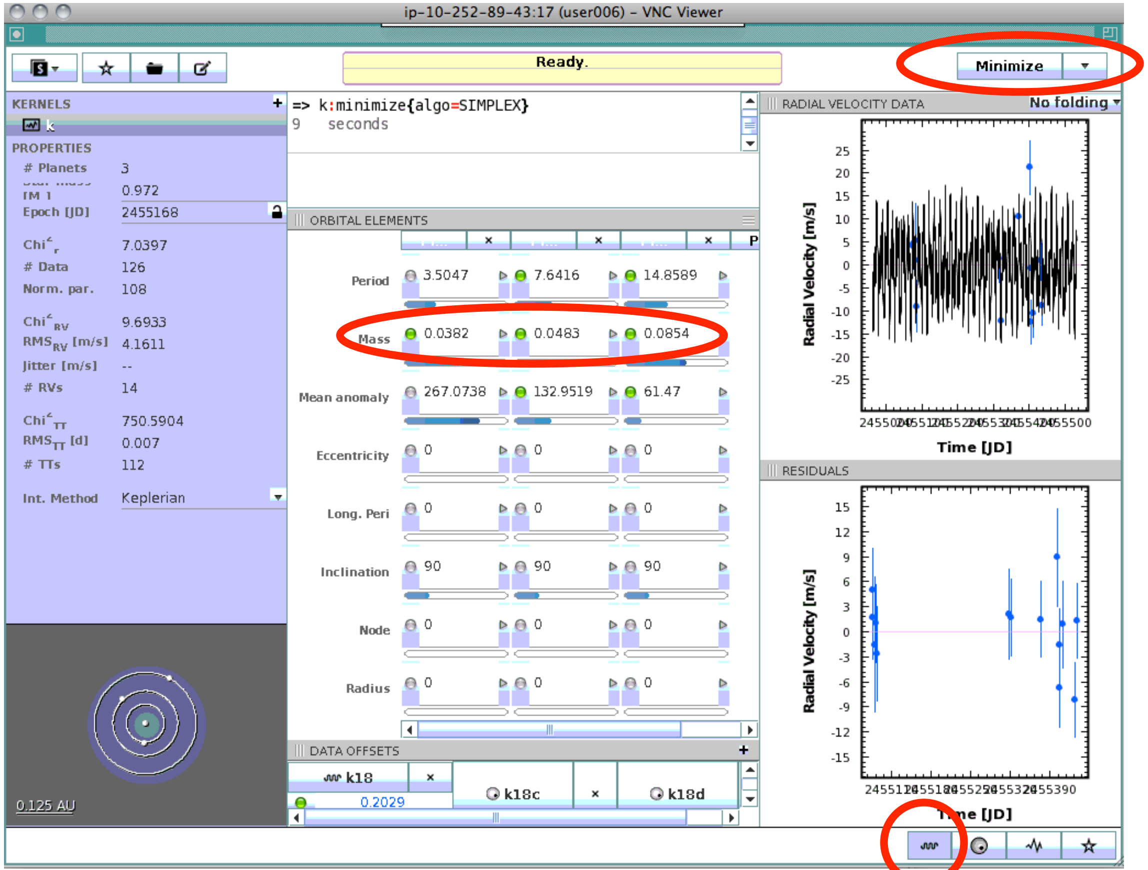
Console: Radial Velocities

- Both data (Chi^2_{RV}) and typical planet densities suggest that 1 Jupiter mass is way too big for these planets (2, 5.5, and 7 Earth radii).



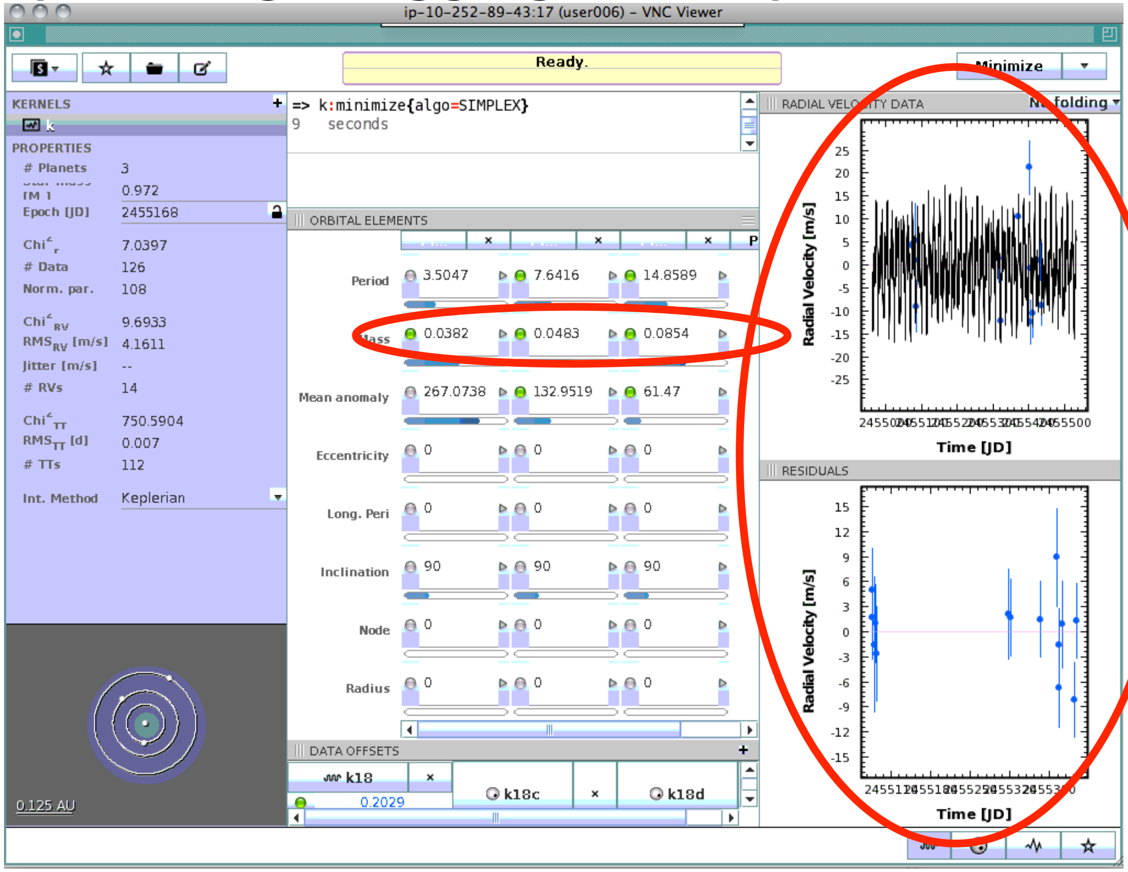
Console: RVs to estimate masses

- Add all 3 masses to minimizer by clicking their green buttons on. Hit the sine-curve button to view the data. “Minimize”!



Console: Better mass estimates

- New masses are more reasonable (0.01 Jup ~= 3.2 Earths)
- Zoom in and out by clicking/dragging on RV panel.
- Note that TTVs will also determine masses



Effect on TTVs?

- Click the transiting planet button. With our new mass estimates, is the TTV fit (Chi^2_{TT}) improved? Why or why not?

Interpreting TTV Curves

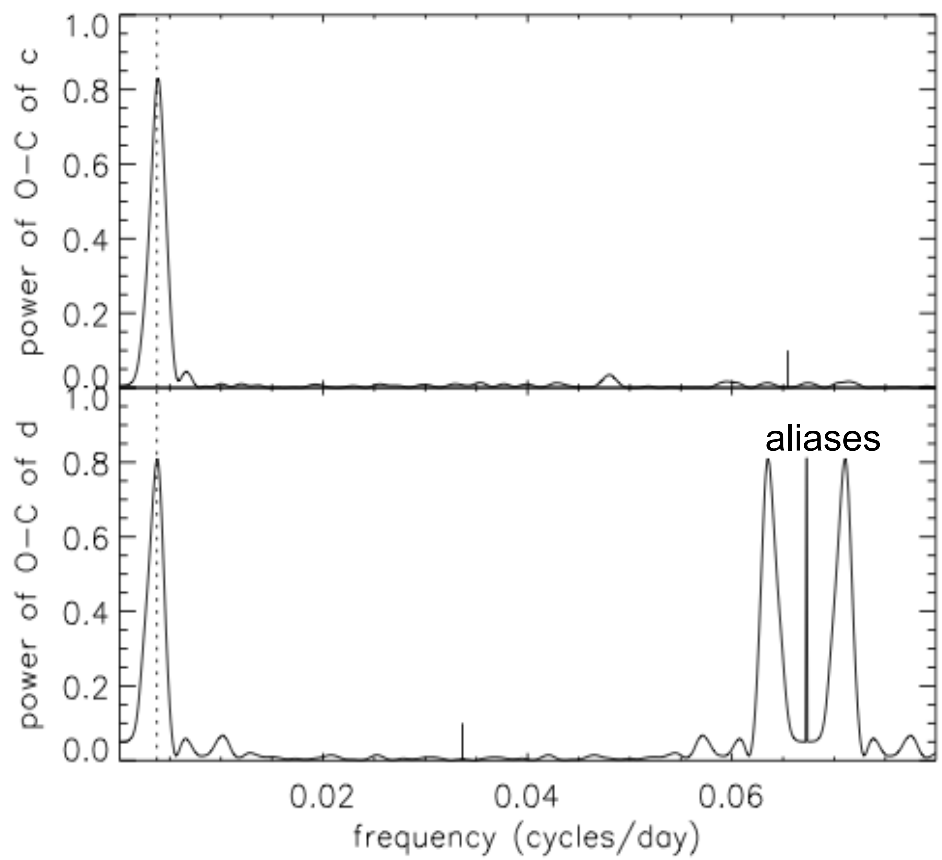
- The ratio of the period of the planets is 1.944
  - Near a ratio of small integers, i.e., a commensurability or (mean motion) resonance
  - At/near resonances, interactions can add coherently
  - May or may not be actually in resonance
- Near (but not deep in) resonance has predicted timescale:

$$\mathbf{P_{TTV} = 1/(2/P_d - 1/P_c) = 268\ days}$$

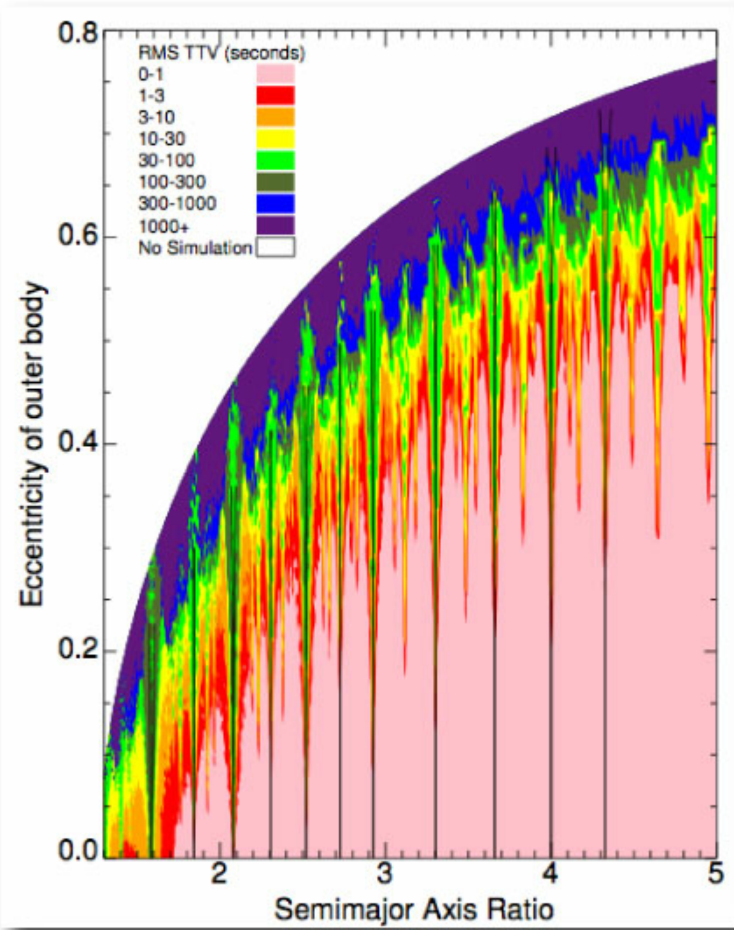
- (Period of the sweeping of the "line of conjunctions" across the line of sight)
- Ratio of amplitudes is related to ratio of planetary masses (smaller planets get pushed around more)

TTVs at Expected Period

- C+11 Figure 8 shows a power spectrum of the TTV signals for both planets and a dashed line at the predicted period



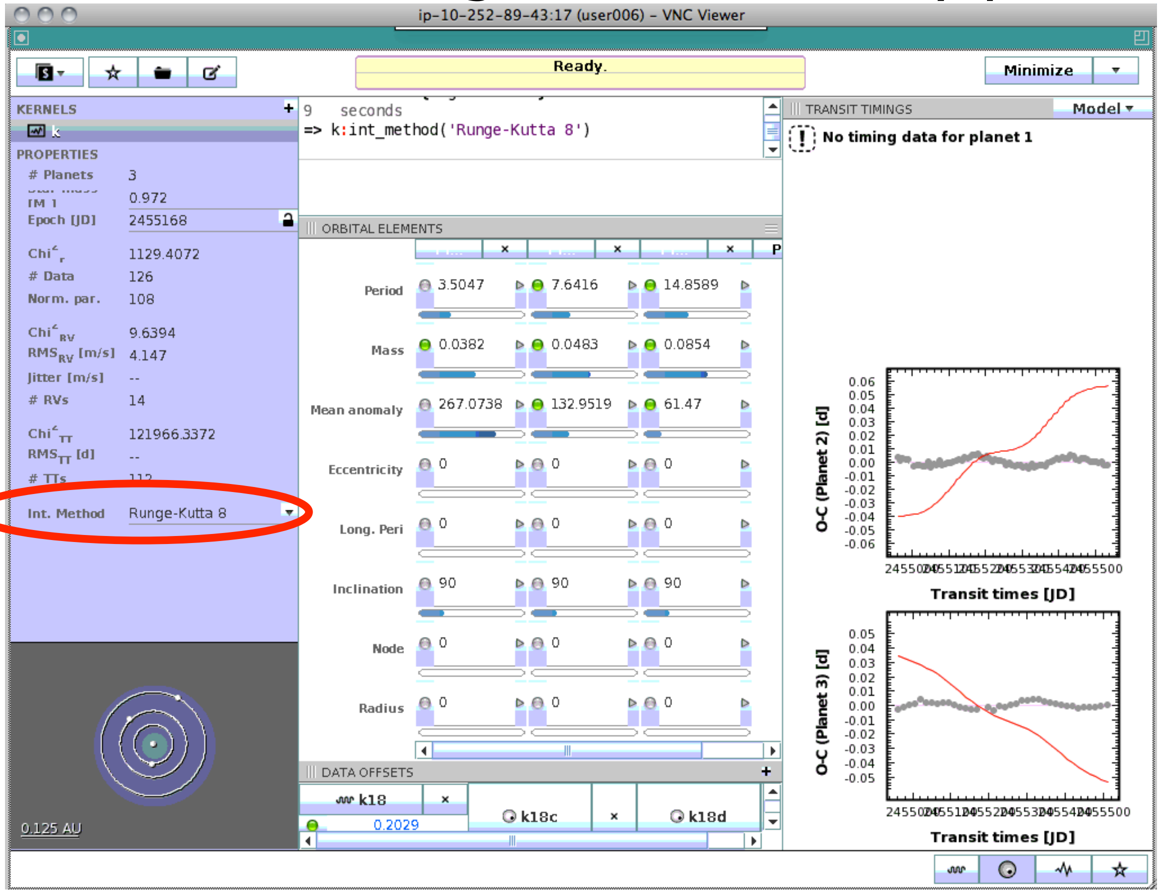
TTV Amplitudes



- Amplitude of TTV signals is very sensitive to various orbital parameters, particularly period ratio (e.g., Veras et al. 2011, left)
- Especially when the perturbing planet is non-transiting it can be *difficult to impossible to determine the properties of the perturber* from TTVs alone (Meschiari et al. 2010, Ballard et al. 2011, but see Nesvorny et al. 2012).

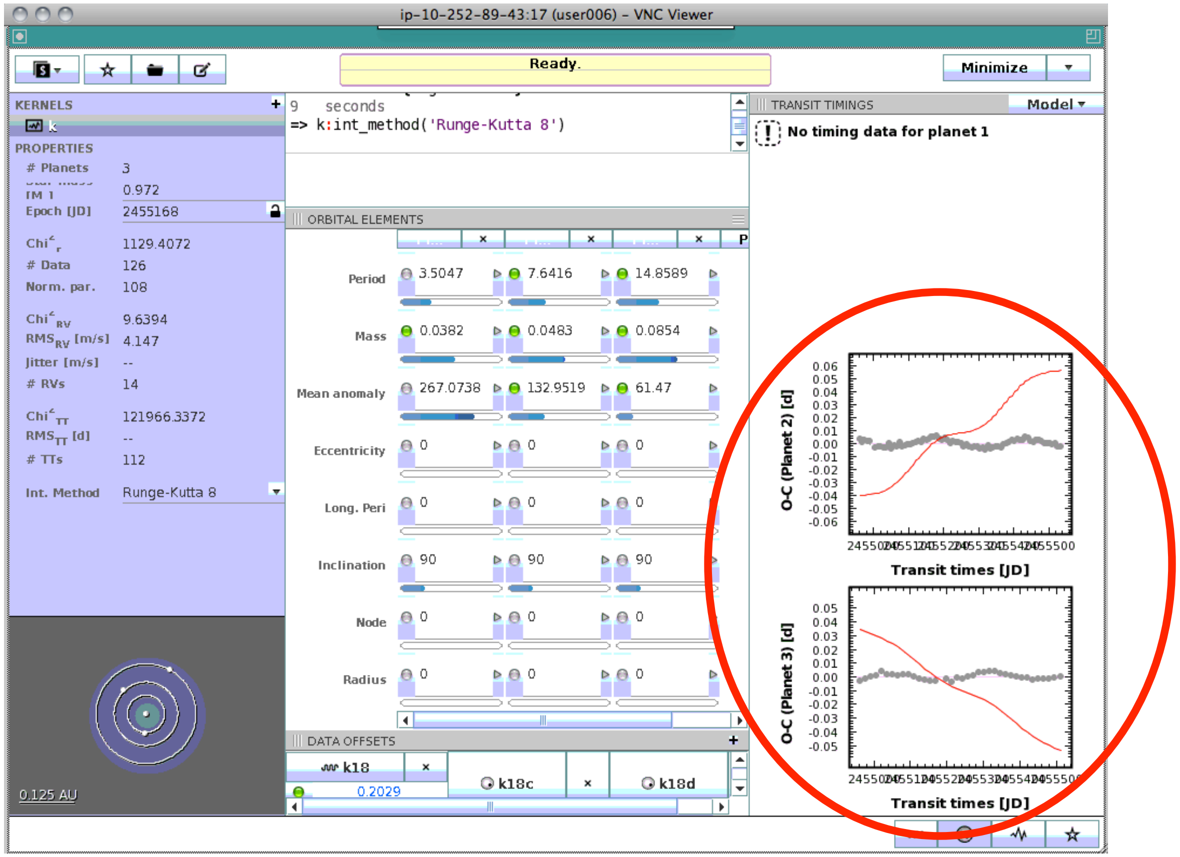
Console: Interacting Planets

- In the middle of the left panel, change the "Int. Method" to "Runge-Kutta 8": this integrates the 4-body problem



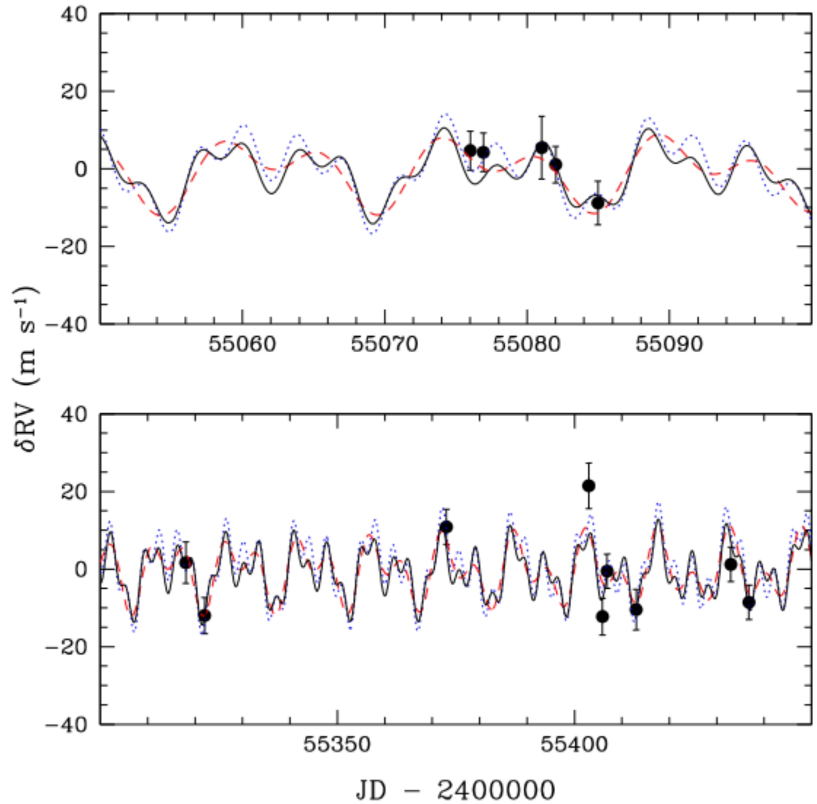
Console: Interacting Planets???

- The red model line is now curved, indicating non-Keplerian
- What happened to our nice TTV plot? (Why?)



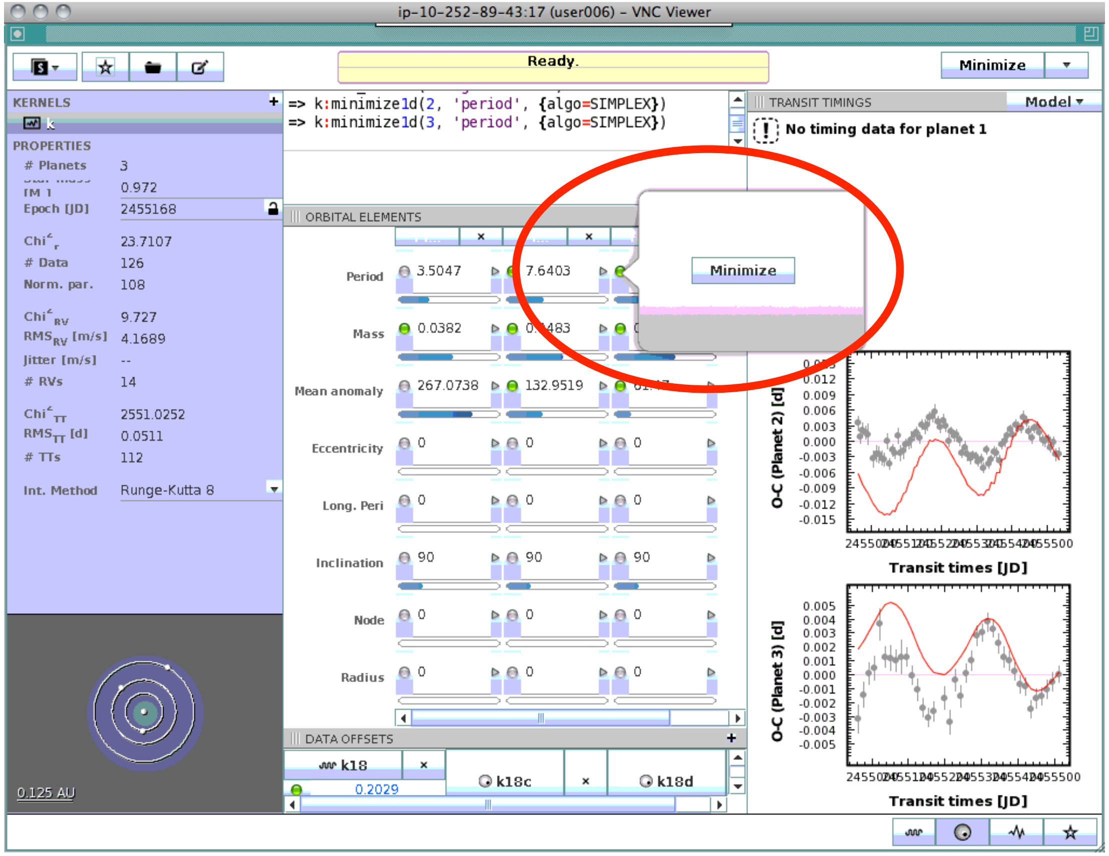
RVs of Interacting Planets

- Are the RVs any different for interacting planets?
- C+11 Figure 4: Keplerian = dashed red, interacting = black



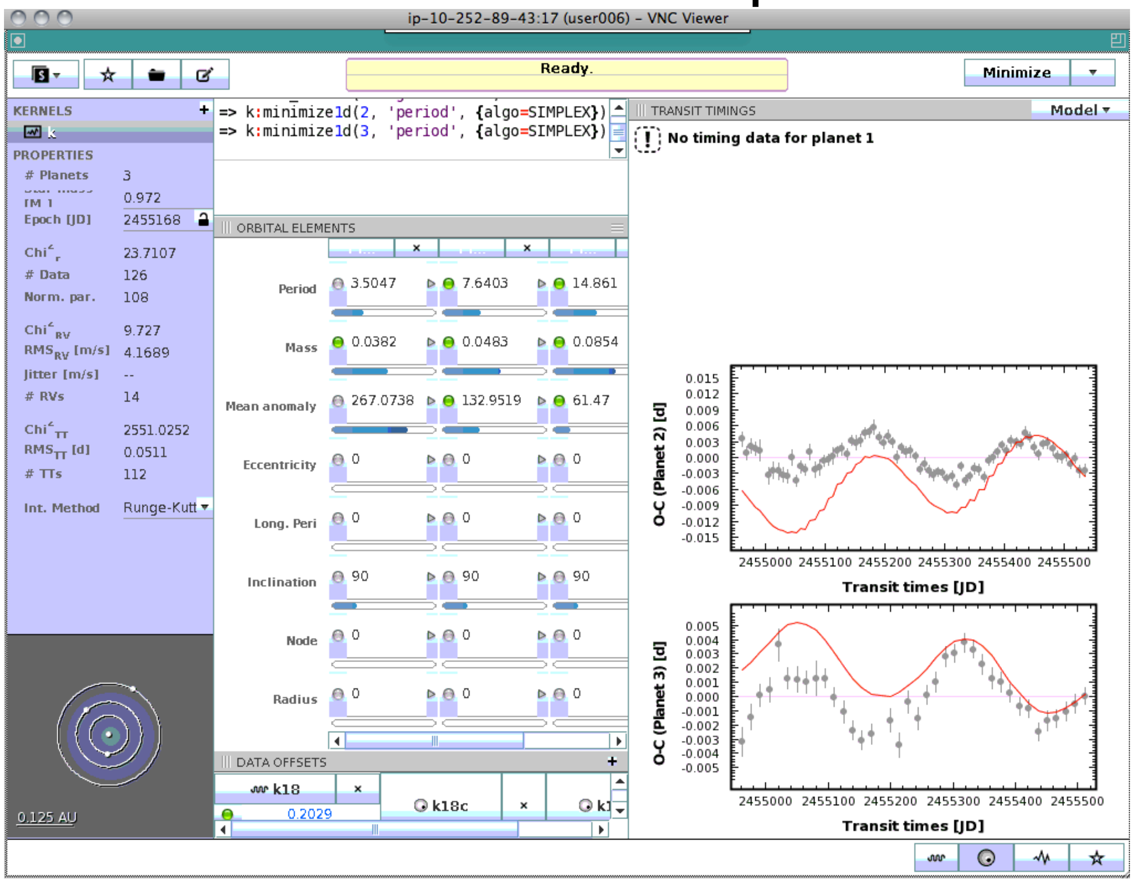
Console: Single parameter minimizer

- Click on the arrow (▶) to the right of Period of Planet 2
- Hit "Minimize"! Do the same for Period of Planet 3



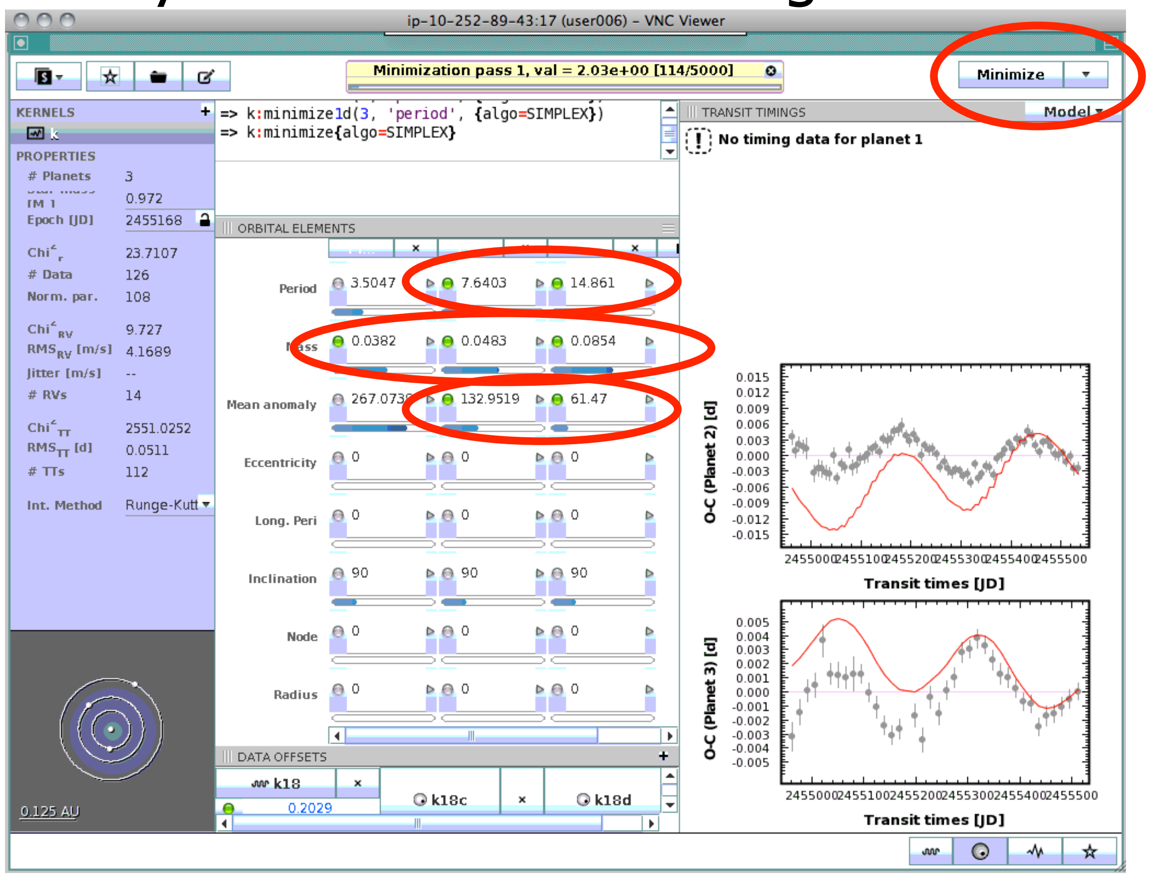
Console: Single parameter minimizer

- Improved average period estimate a lot.
- Single parameter minimization helps refine initial guess



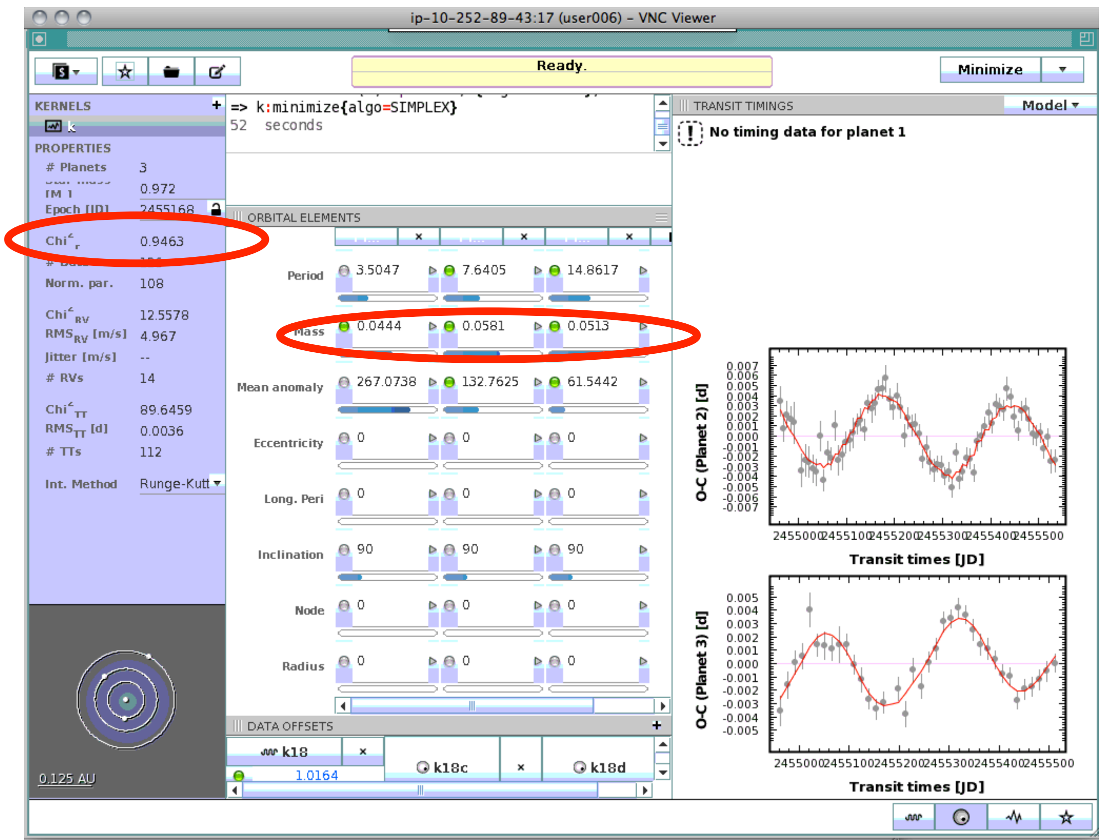
Console: Fit the TTVs!

- Activate masses of all 3 planets and *P* and *MA* of 2 and 3.
- Hit Minimize! Why does this take so long?



Console: Final Fit!

- Chi^2_r ~= 0.94 suggests we have an excellent fit!
- C+11: 0.022 +/0.011, 0.054 +/- 0.006, 0.052 +/- 0.004

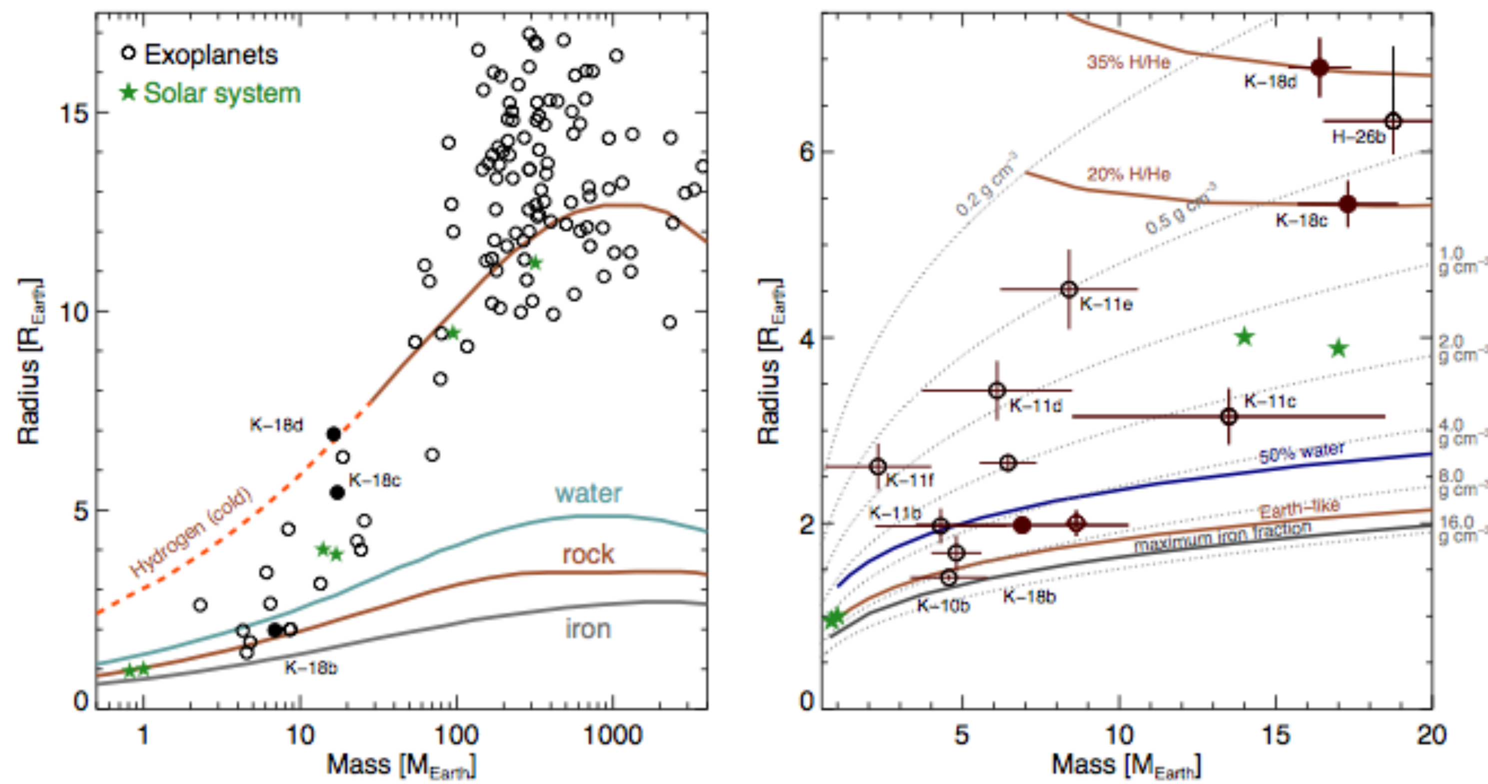


Thoughts on the final fit

- Minimizers often go to local minima instead of global minima. Even slight differences in the ordering of fitting can lead to different results: you may have different reduced chi-square or masses. For well-posed problems, the differences will usually be within the noise, unless you've gotten stuck in the wrong local minimum (usually due to a poor initial guess).
- Note also that C+11 had some small differences in analysis
- With practice, you can measure masses and other properties due to TTVs rapidly and efficiently.

Thoughts on the final fit

- We just measured the masses of two extra-solar planets!
- Now we can put our results on a mass-radius diagram
  - Kepler-18c and d must have significant fractions of H/He!



Additional Exercises

- Play with (or read about) other aspects of the Console (e.g., saving kernels, other minimizers, etc.)
- Fit for planet masses without RV data
- Fit for eccentricities and longitudes of pericenter for Kepler-18 c and d
- Determine upper limit on mutual inclination from TTVs (Hint: use sky-inclination determined by lightcurve shape, which are published)
- Think about how to use the Console to measure errors
- Fit your favorite TTV data! Fill in the small planet Mass-Radius plot!
- Publish results!

Discovering planets with TTVs

- New algorithms:
  - Widen the duration and use BLS
  - Others in development (non-linear ephemerides)
  - **Quasiperiodic Automated Transit Search (QATS) Carter & Agol**
    - Ready for general use
    - Already discovered Kepler-36b (Carter, Agol, and the Kepler Team 2012)
    - *Let's use it today!* **(Thanks to Josh Carter!)**

Pre-QATS

- Compiled in your directory: C++ code with an IDL wrapper
- We'll apply it to Kepler-30 ("Strong Example" above)
- Before running QATS: cleaned, detrended data (provided for you in *~/qatscpp/koi806data.sav*)

Run QATS!

- *cd ~/qatscpp/*
- Start IDL by typing '*IDL*' at the command prompt
- *.compile searchQATS* (prepares the IDL file to be run)
- *restore, 'koi806data.sav'* (loads in Kepler-30 data)
- *searchQATS, x, sigma=robust_sigma(f), pmin=250, pmax=22000, fraction=[0.025], q0=1.08d0, ql=0.75, qr=1.25, deltabg=[2], threshold=7.1d0, output='KOI806test', header=['KOI-806test'], tstart=min (time), dt=0.0204335d0, maxDetect=6*
- See also:

http://www.ucolick.org/~fabrycky/saganws/QATS_notes.txt

QATS options

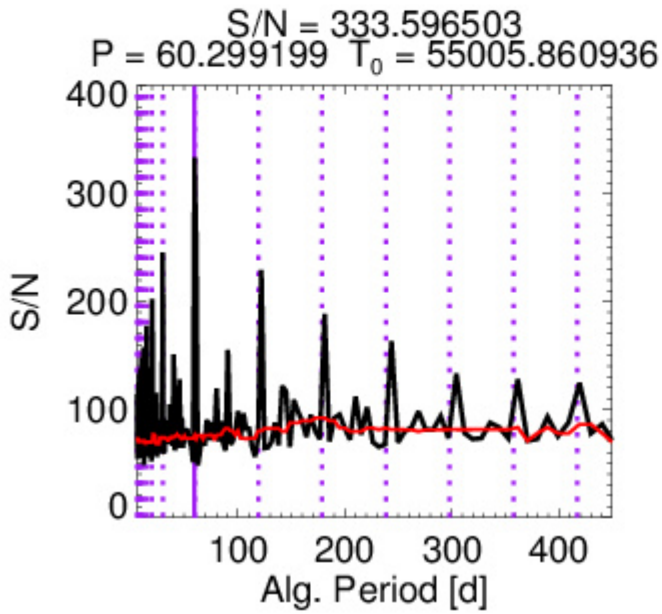
- *pmin=250, pmax=22000*: min and max periods searched (in cadences)
- *fraction=[0.025]*: transit-to-transit slop in orbital period
- *q0=1.08d0, ql=0.75, qr=1.25*: specifies transit durations
- *tstart=min(time), dt=0.0204335d0*: cadence length in days
- *output='KOI806test', header=['KOI-806test’]*: for the plot
- *deltabg=[2], threshold=7.1d0*: measures of significance
- *maxDetect=6*: how many signals to propose as planets

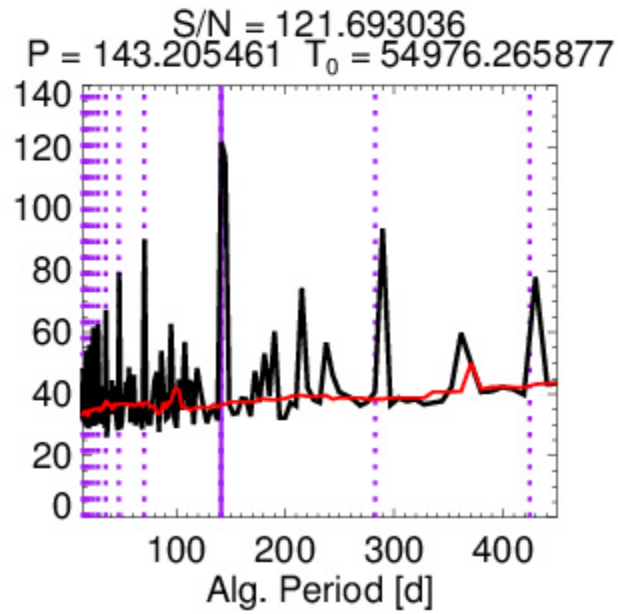
Investigate QATS Results!

- QATS gives some command line output from which we see that 4 planets were detected with varying periods and significances
- QATS also returns a results and diagnostics file: *KOI806test_QATS_0.eps* (or a similar filename)
- Let's take a look at this: *gv KOI806test_QATS_0.eps*
- Each column corresponds to a single candidate and has four main parts: spectrum, “river plot” (with TTVs), and co-added transit plot
- (Additional informative text about the file and thresholds, etc. not belonging to any column)

QATS Report: Spectra

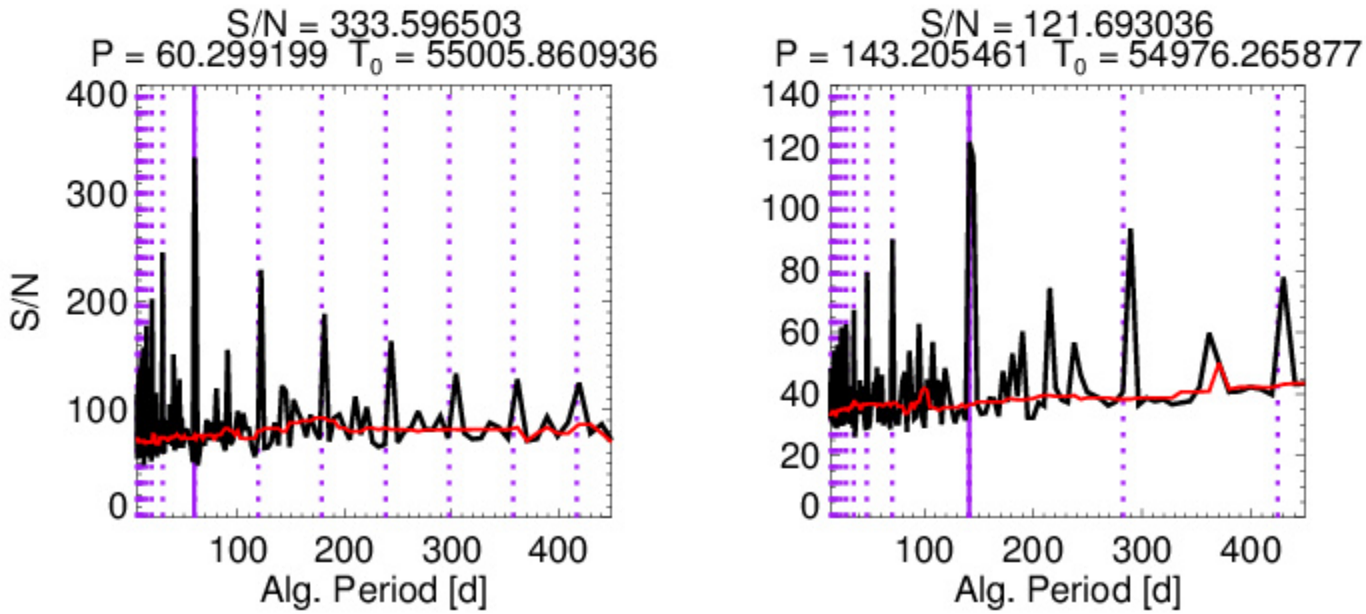
- Plot: Signal/Noise vs. Algorithm [~average] Period
- Black line is the "spectrum" of power detected by QATS
- Solid purple vertical line is best-fit period; dotted vertical lines are aliases (with a predictable pattern)
- Red line is "Stochastic background", i.e., the noise floor



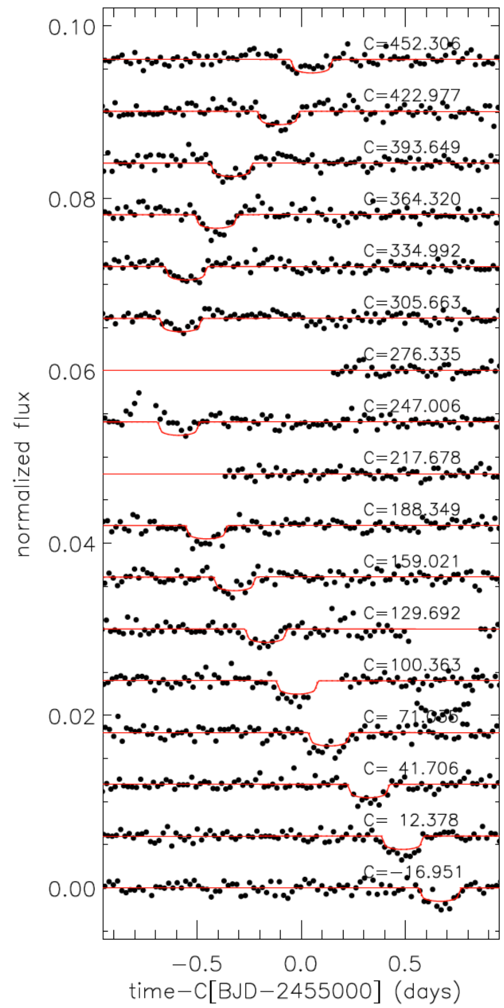


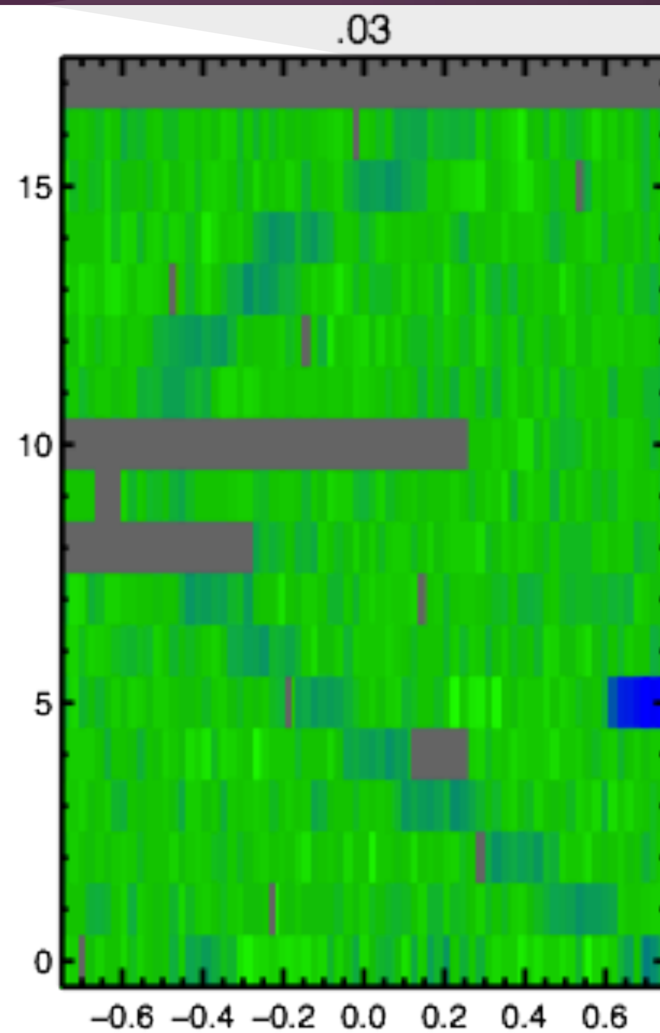
QATS Report: Spectra

- Text is about each planet candidate.
  - S/N is Signal to Noise of detection
  - P and T0 are Period and Epoch of candidate
- First three columns correspond to Kepler-30c, d, and b.
- Last column shows candidate barely above noise



Kepler-30b river plots



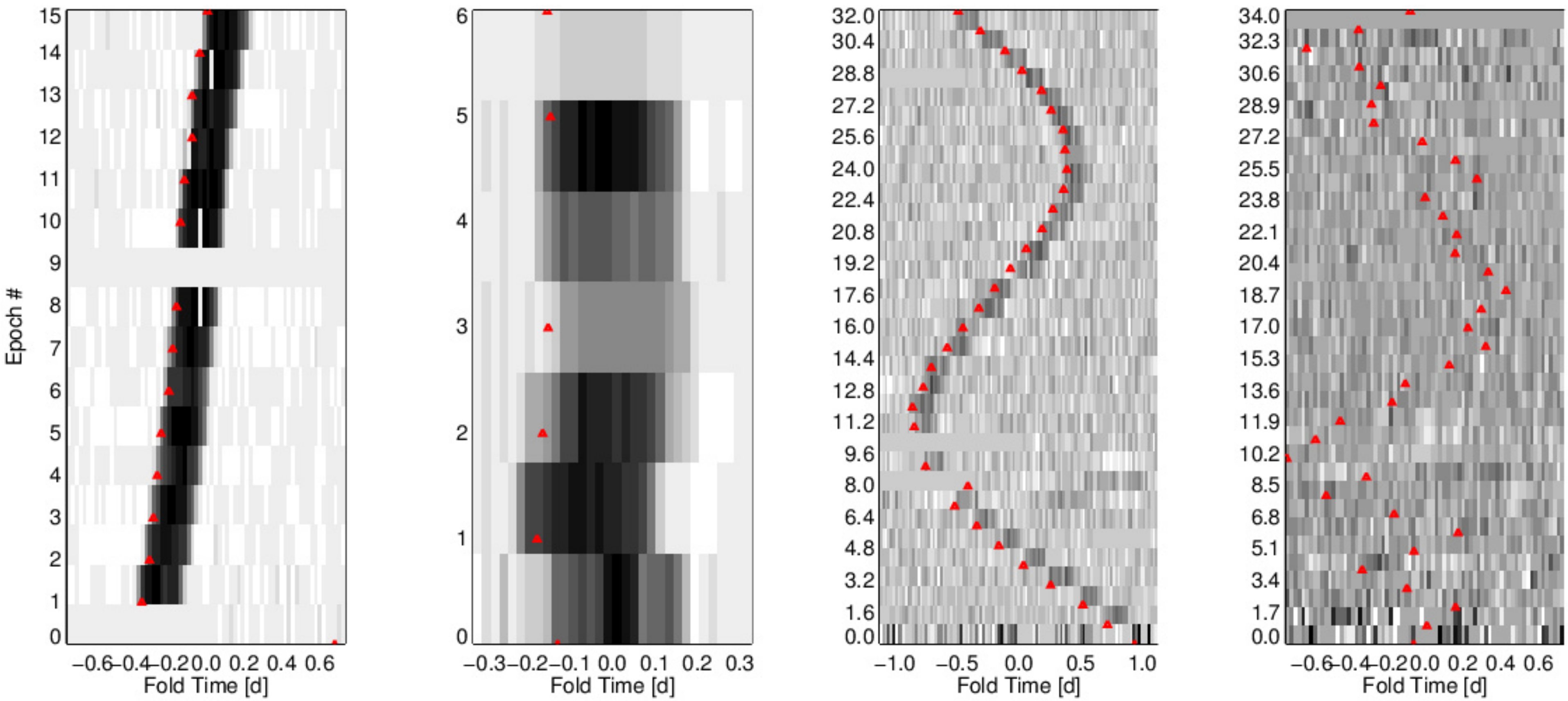


QATS Report: River Plots

- River Plot shows light curve folded on average period
- Great way to visualize TTVs, trends, anti-correlated signals, periodic transits, etc.
- Also on the river plot is a red triangle at the “transit time” detected by QATS

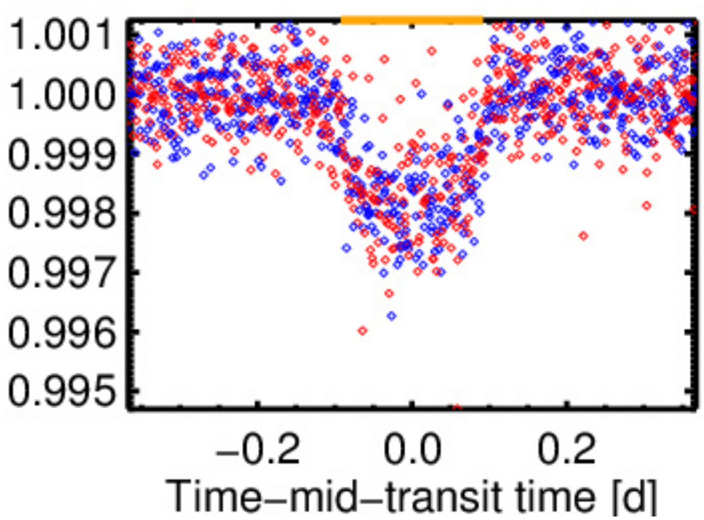
QATS Report: River Plots

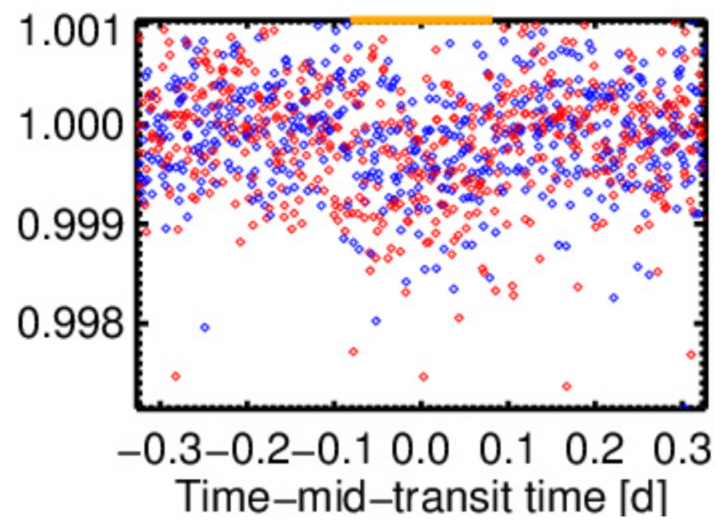
- Kepler-30 results (planets c, d, b, and a poor candidate)
- (Red triangles mark the start of the transit)



QATS Report: Co-added Signal

- Folded, de-TTVed light curves, with colors alternating between even-numbered and odd-numbered transits, y-axis is relative flux
- Below: 3rd and 4th column (30b and poor candidate).
- Yellow bar shows estimated duration





QATS: Instrumental False Positives

- QATS has a lot of freedom to choose transit times, leading to higher chances of instrumental false positives, like the fourth candidate in the report
- The “Delta BG [BackGround]” should be significant to indicate that a candidate is >~2x above the noise floor
- TTV signal doesn't need to be smooth (e.g. circumbinary planets), but random-walk river plots are not a good sign
- Although QATS has already been used to investigate various Kepler populations, there are probably many planet candidates that are clearly above the background that remain to be discovered

Conclusions

- TTVs (especially in Kepler MTSs) are powerful ways to determine planetary properties with a very ripe observational dataset currently available from Kepler
- Systemic Console is a very useful tool for fitting a variety of exoplanet data, including MTS TTVs
- Reproduced mass measurements for Kepler-18 planets
- Detected planets of Kepler-30 using QATS, an algorithm designed to find planets with non-periodic transits

Acknowledgments: Stefano Meschiari, Josh Carter, Carolyn Brinkworth, Eric Agol, Sagan Workshop Organizers

Thank You!

Table 4 of Cochran+2011

TABLE 4
ADOPTED SYSTEM PARAMETERS

Parameter	Value
$M_\star$ ($M_\odot$)[a]	0.972 ± 0.042
$R_\star$ ($R_\odot$)[a]	1.108 ± 0.051
$\log L_\star$ ($L_\odot$)[a]	-0.031 ± 0.035
Age (Gyr)[a]	10.0 ± 2.3
$\log g_\star$[b]	4.31 ± 0.12
$\rho_\star$ (g/cm^3)[c]	1.01 ± 0.12
Kepler-18b = K00137.03	
T_0[c]	2454966.5068 ± 0.0021
P (days)[c]	3.504725 ± 0.000028
Transit depth (ppm)[c]	254.0 ± 7.8
b (Impact Parameter)[c]	0.771 ± 0.025
$R_p/R_\star$[c]	0.01656 ± 0.00032
M_p ($M_\oplus$)[d]	6.9 ± 3.4
R_p ($R_\oplus$)[c]	2.00 ± 0.10
i (deg)[e]	84.92 ± 0.26
$a/R_\star$[e]	8.58 ± 0.37
$\bar{\rho}_p$ (g/cm^3)[3,4]	4.9 ± 2.4
a (AU)[e]	0.0447 ± 0.0006
K (m/s)[c]	5.2 ± 2.4
T_{14} (h)[e]	2.076 ± 0.036
T_{12} (h)[e]	0.0818 ± 0.0082
Kepler-18c = K00137.01	
T_0[d]	2455167.0883 ± 0.0023
P (days)[d]	7.64159 ± 0.00003
Transit depth (ppm)[c]	2286.6 ± 8.6
b (Impact Parameter)[c]	0.593 ± 0.050
$R_p/R_\star$[c]	0.04549 ± 0.00055
M_p ($M_\oplus$)[d]	17.3 ± 1.9
R_p ($R_\oplus$)[c]	5.49 ± 0.26
i (deg)[e]	87.68 ± 0.22
$a/R_\star$[e]	14.43 ± 0.61
$\bar{\rho}_p$ (g/cm^3)[3,4]	0.59 ± 0.07
a (AU)[e]	0.0752 ± 0.0011
K (m/s)[c]	5.1 ± 1.9
T_{14} (h)[e]	3.488 ± 0.020
T_{12} (h)[e]	0.229 ± 0.022
Kepler-18d = K00137.02	
T_0[d]	2455169.1776 ± 0.0013
P (days)[d]	14.85888 ± 0.00004
Transit depth (ppm)[c]	$3265. \pm 12.$
b (Impact Parameter)[c]	0.767 ± 0.024
$R_p/R_\star$[c]	0.05782 ± 0.00069
M_p ($M_\oplus$)[d]	16.4 ± 1.4
R_p ($R_\oplus$)[c]	6.98 ± 0.33
i (deg)[e]	88.07 ± 0.10
$a/R_\star$[e]	22.48 ± 0.96
$\bar{\rho}_p$ (g/cm^3)[3,4]	0.27 ± 0.03
a (AU)[e]	0.1172 ± 0.0017
K (m/s)[c]	7.3 ± 2.1
T_{14} (h)[e]	3.679 ± 0.036
T_{12} (h)[e]	0.459 ± 0.045

Tables 7 & 8

TABLE 7
OSCULATING JACOBIAN ELEMENTS, AT EPOCH 2455168.0 [BJD], FOR THE 3-PLANET TTV DYNAMICAL SOLUTION.

	Period (days)	T_0 (days)	$e\cos\omega$	$e\sin\omega$
b	3.504674 ± 0.000054	266.276996 ± 0.005453	0	0
c	7.641039 ± 0.000087	267.092502 ± 0.000262	0.000291 ± 0.000079	0.000173 ± 0.000233
d	14.860509 ± 0.000148	269.174850 ± 0.000253	-0.000076 ± 0.000019	0.000516 ± 0.000450

TABLE 8
MASSES AND DENSITIES OF THE PLANETS IN THE KEPLER-18 SYSTEM

Method		Kepler-18b (K00137.03)	Kepler-18c (K00137.01)	Kepler-18d (K00137.02)
MCMC (lightcurve + RV) Solution	($M_\oplus$)	13.4 ± 5.8	16.9 ± 6.1	29.9 ± 8.8
RV + transit time P and T_0	($M_\oplus$)	12 ± 5	15 ± 5	28 ± 7
TTV dynamical model	($M_\oplus$)	18 ± 9	17.3 ± 1.7	15.8 ± 1.3
TTV + RV dynamical model (adopted values)	($M_\oplus$)	6.9 ± 3.4	17.3 ± 1.9	16.4 ± 1.4
density from adopted mass	(g cm^{-3})	4.9 ± 2.4	0.59 ± 0.07	0.27 ± 0.03