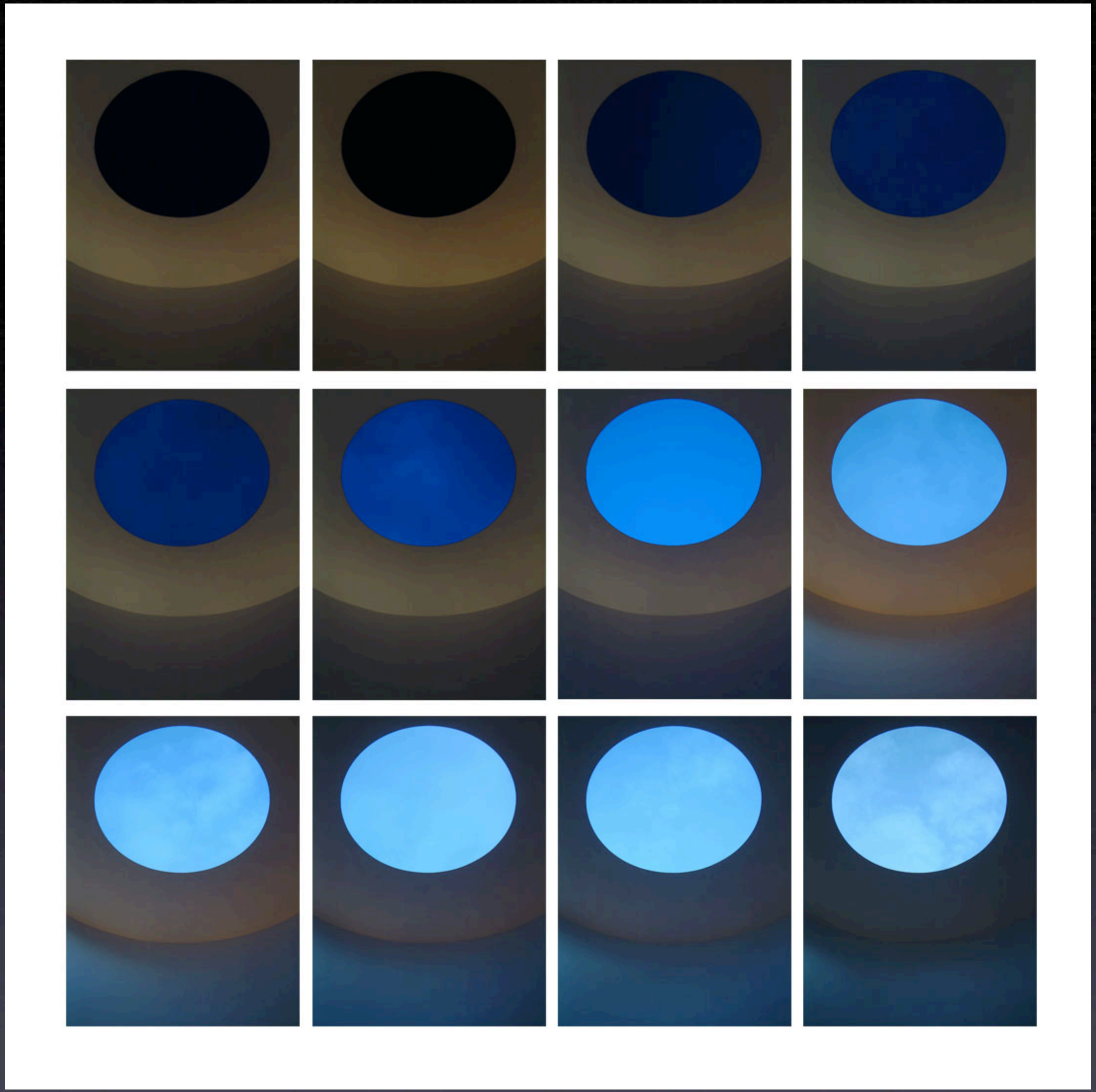


The Detection and Characterization of Extrasolar Planets

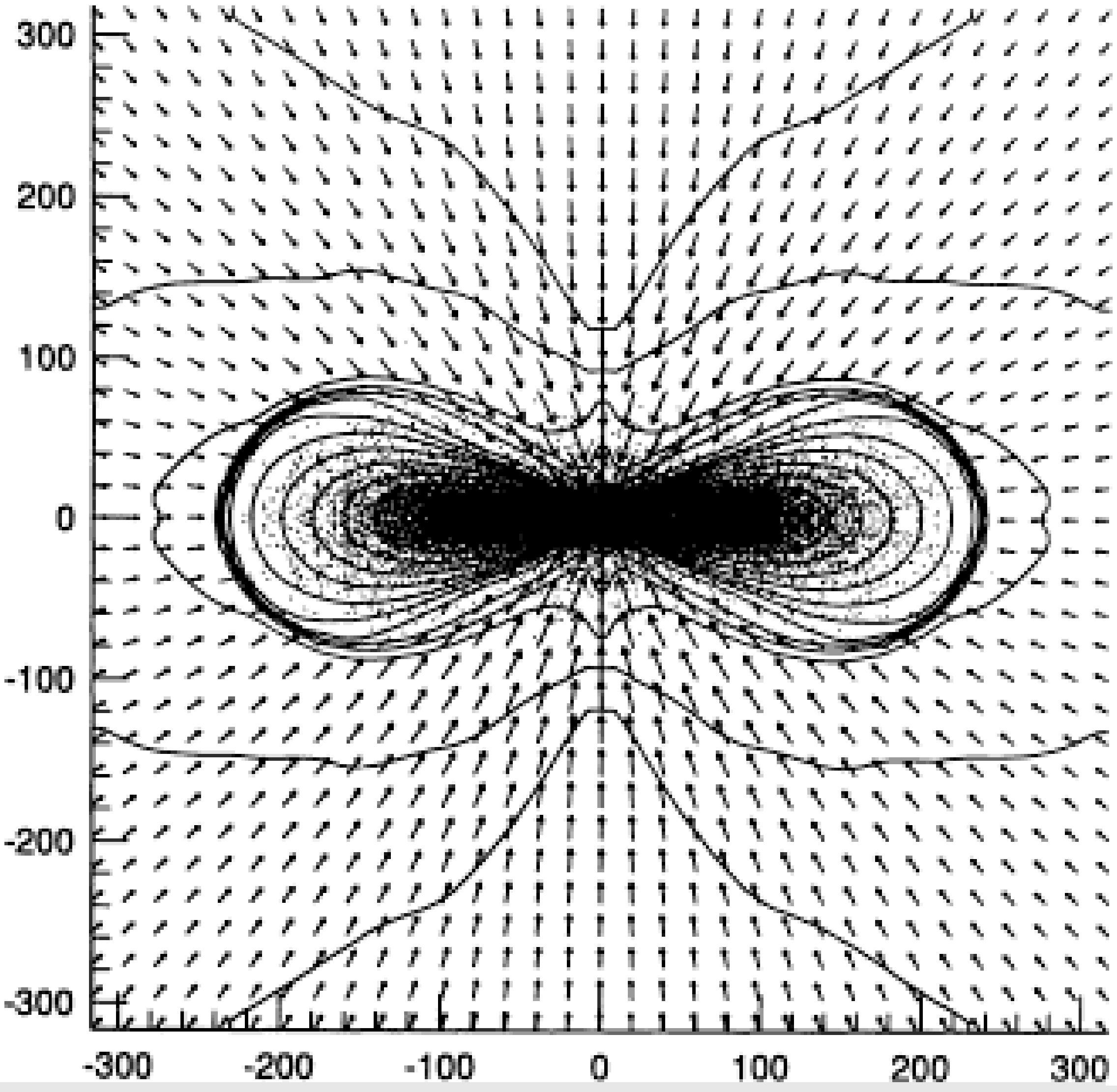
gregory laughlin - uco/lick observatory

Collaborators

- Fred Adams, Mark Ammons, Peter Bodenheimer, Paul Butler, Debra Fischer, Greg Henry Shigeru Ida, Geoff Marcy, Sally Robinson, Jay Strader, Bunei Sato, Steve Vogt, Aaron Wolf

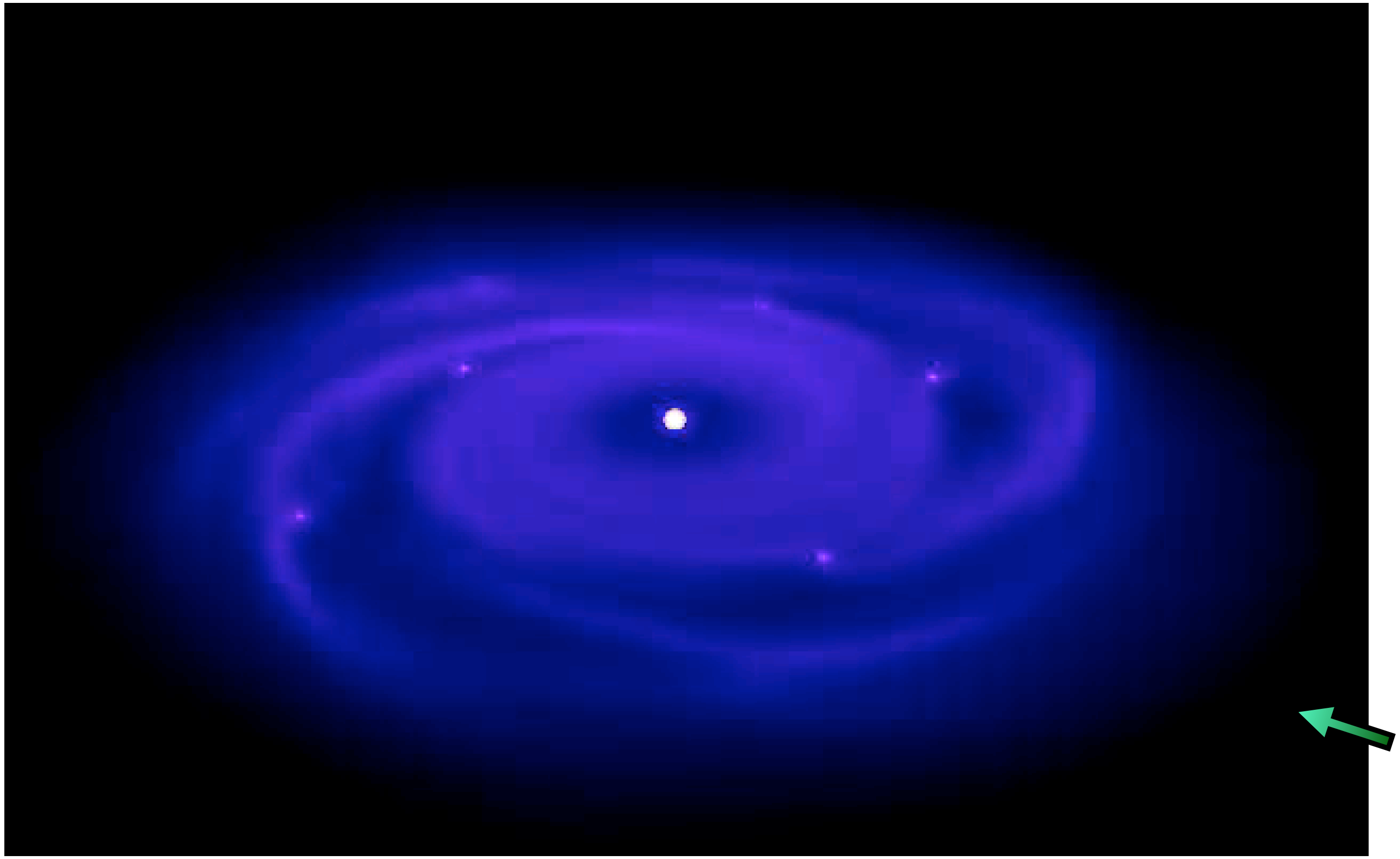
- Funding from the NASA TPF Program and the NSF CAREER Program

Simulation showing infall onto a massive protostellar disk



AU

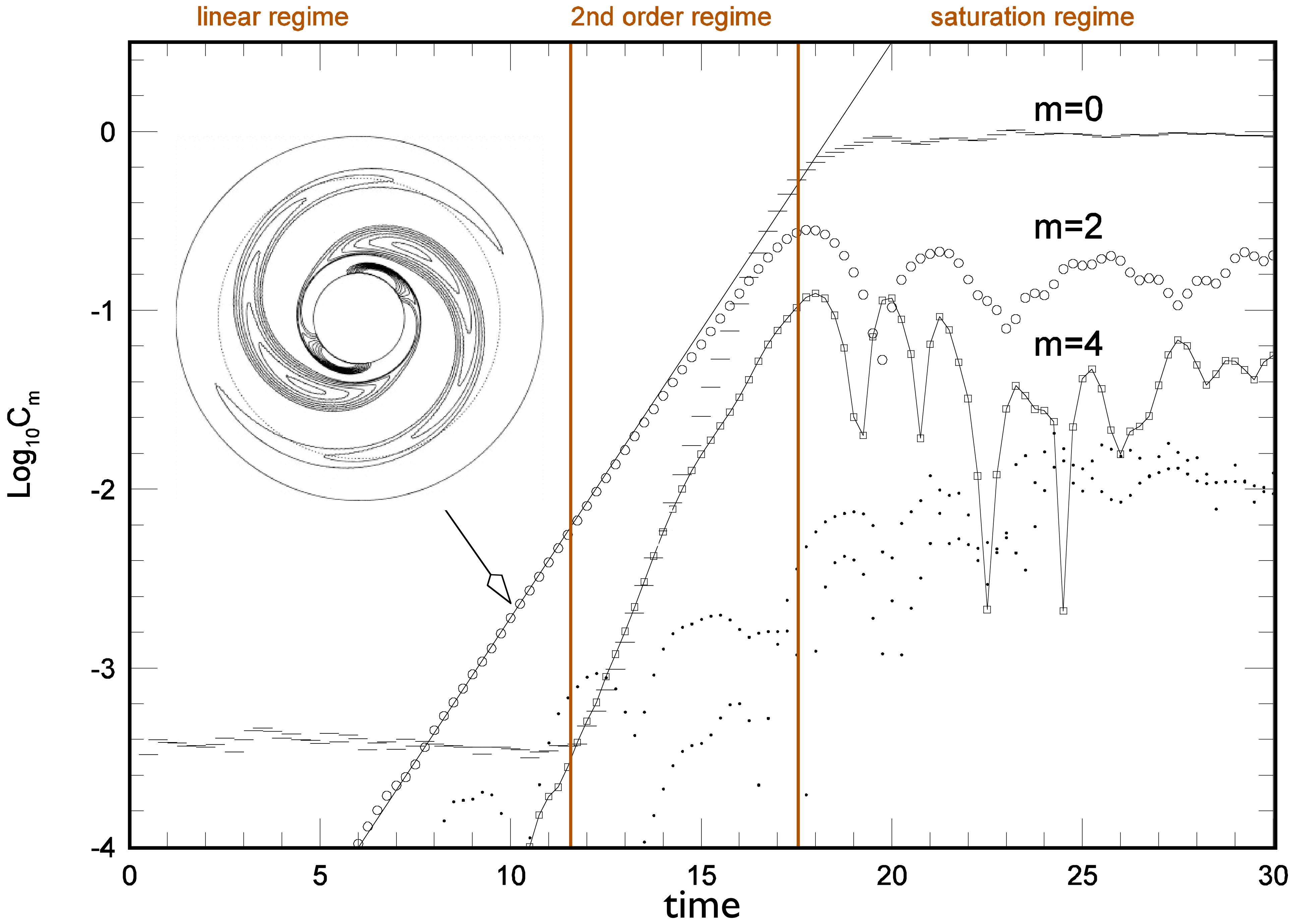
The Gravitational Instability Paradigm



Kuiper 1951
Cameron 1978
DeCampli & Cameron 1979
Boss 1998
Boss 2000
Mayer et al. 2002
Pickett et al. 2003
Rice et al 2003a
Rice et al 2003b
Boss 2003
Cai et al 2004
Boss 2004
Mayer et al 2004
Mejia et al 2005

Two basic requirements for gravitational disk instability to work:

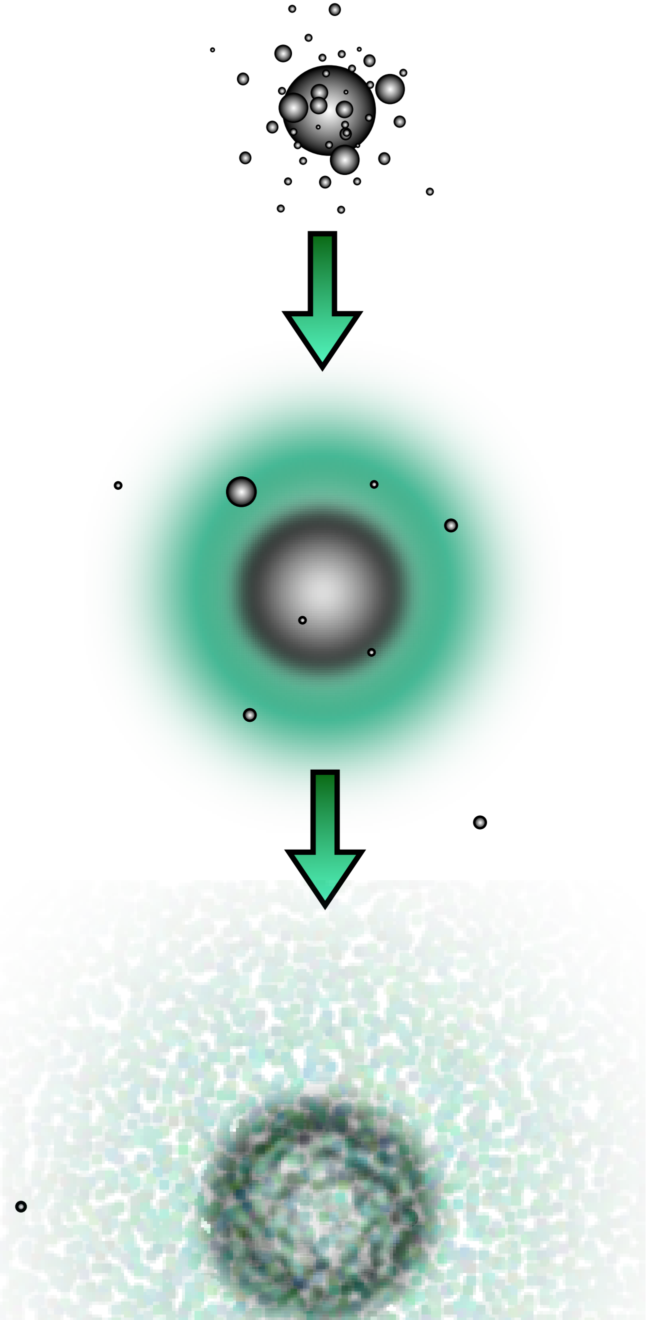
1. $Q = \dfrac{c_s \kappa}{\pi G \sigma} \sim 1$ somewhere in the disk
2. The cooling time for fragments must be less than half an orbital period (Gammie (2001).



Another unresolved issue for G.I. is the feasibility of having a highly gravitationally unstable axisymmetric disk.

The Core Accretion Paradigm

Perri & Cameron 1974, Mizuno et al 1978, Mizuno 1980, Bodenheimer & Pollack 1986, Pollack et al 1996



During Phase 1, the growing planet consists mostly of solid material. The planet experiences runaway accretion until the feeding zone is depleted. Solid accretion occurs much faster than gas accretion during this phase.

During Phase 2, both solid and gas accretion rates are small and are nearly independent of time. This phase dictates the overall evolutionary time-scale.

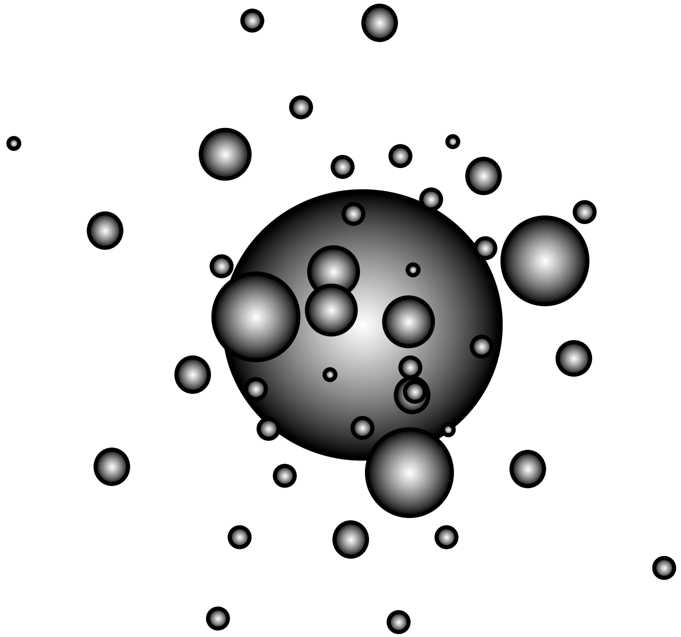
During Phase 3, runaway gas accretion occurs. Runaway gas accretion starts when the solid and gas masses are roughly equal.

The Core Accretion Paradigm

(Pollack et al 1996)

During Phase 1, the mass increase of the planet depends on the planetary radius, and the ratio of the gravitational to geometric cross section:

$$\frac{dM_p}{dt} = \pi R_c^2 \sigma \Omega F_g$$

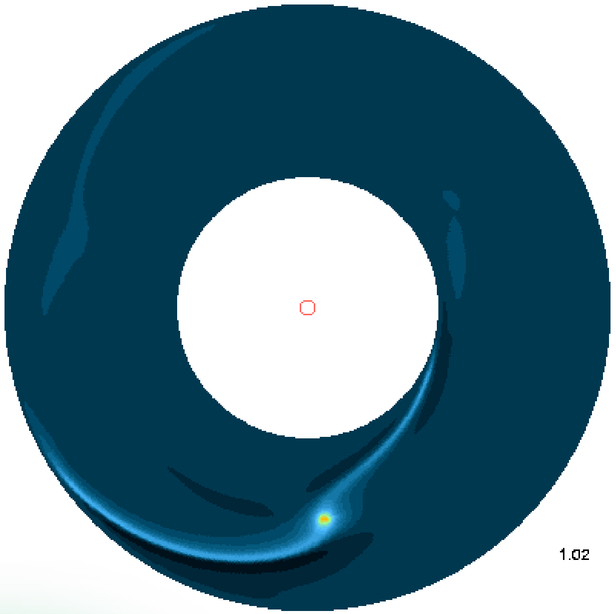


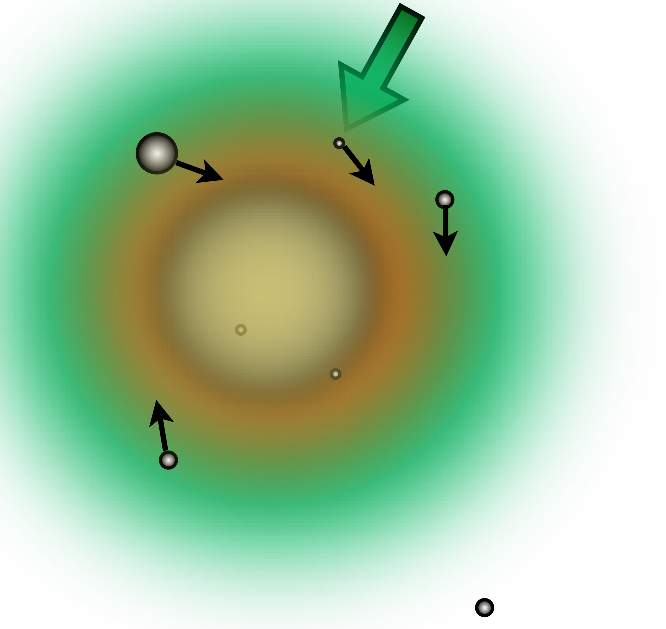
Because the escape velocity from the planetary surface is much faster than the relative velocity of planetesimals, this phase is characterized by a runaway growth of the solid core which ends when the core depletes its feeding zone, defined by:

$$a_f = (\sqrt{12 + e_h^2}) R_H$$

Hill Radius → $R_H = a(\frac{M_P}{3M_\odot})^{1/3}$

As runaway solid accretion proceeds through several Earth masses, the gas envelope becomes increasingly significant. Modeling of this stage requires computation of the hydrodynamic structure and effect of the gas envelope.





1. Stellar Evolution code for the quasi-equilibrium envelope:

$$\frac{dP}{dR} = -g\rho$$

$$\frac{dM}{dR} = 4\pi R^2 \rho$$

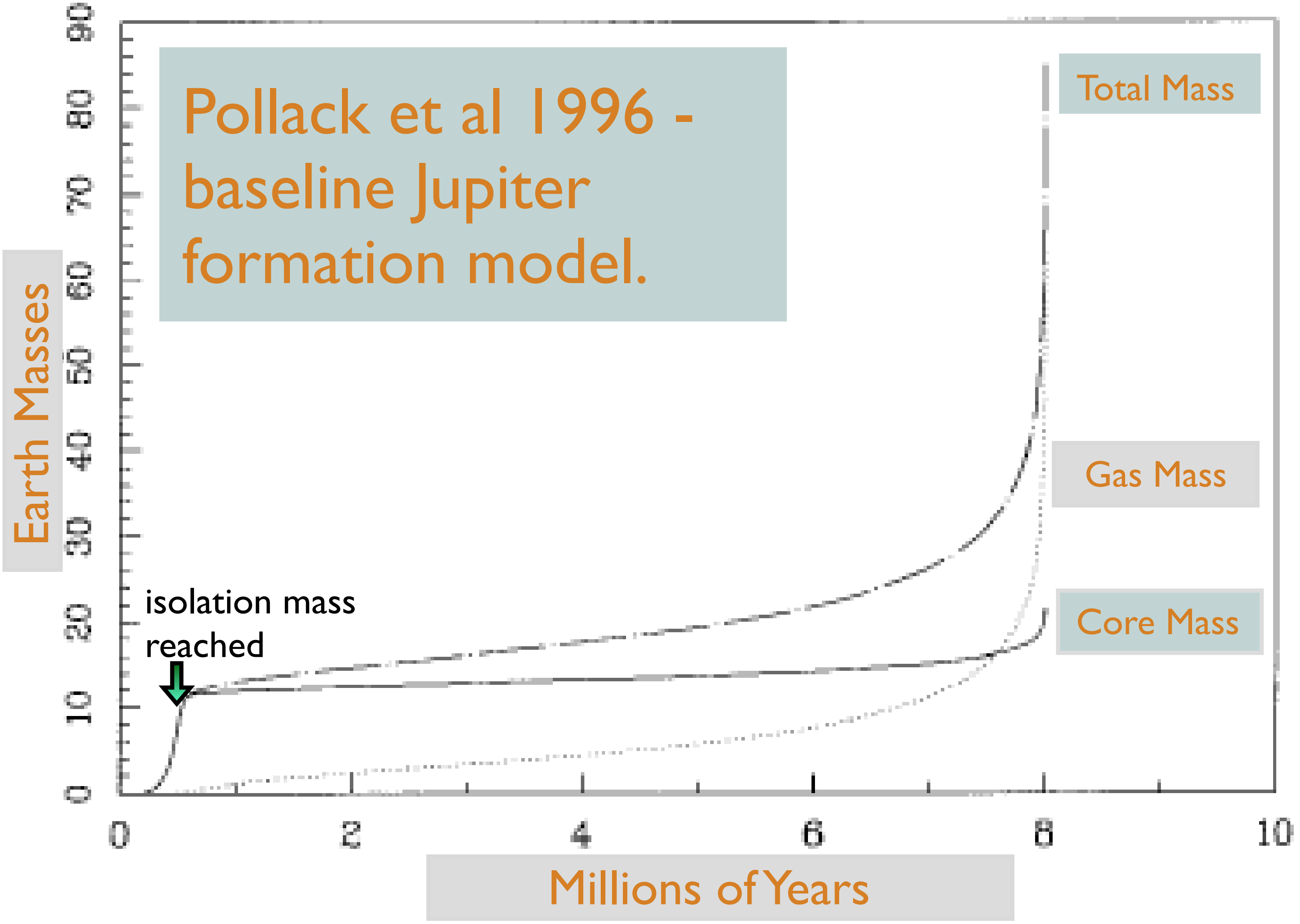
$$\frac{dT}{dR} = \frac{-3\kappa\rho}{16\sigma T^3}\frac{L}{4\pi R^2}$$

$$L_{core} = \frac{G M_{core} \dot{M}_{core}}{R_{core}}$$

2. Planetesimal dissolution routine:

$$v_{encounter} = (\sqrt{\frac{5e^2}{8} + i^2}) v_{kepler}$$

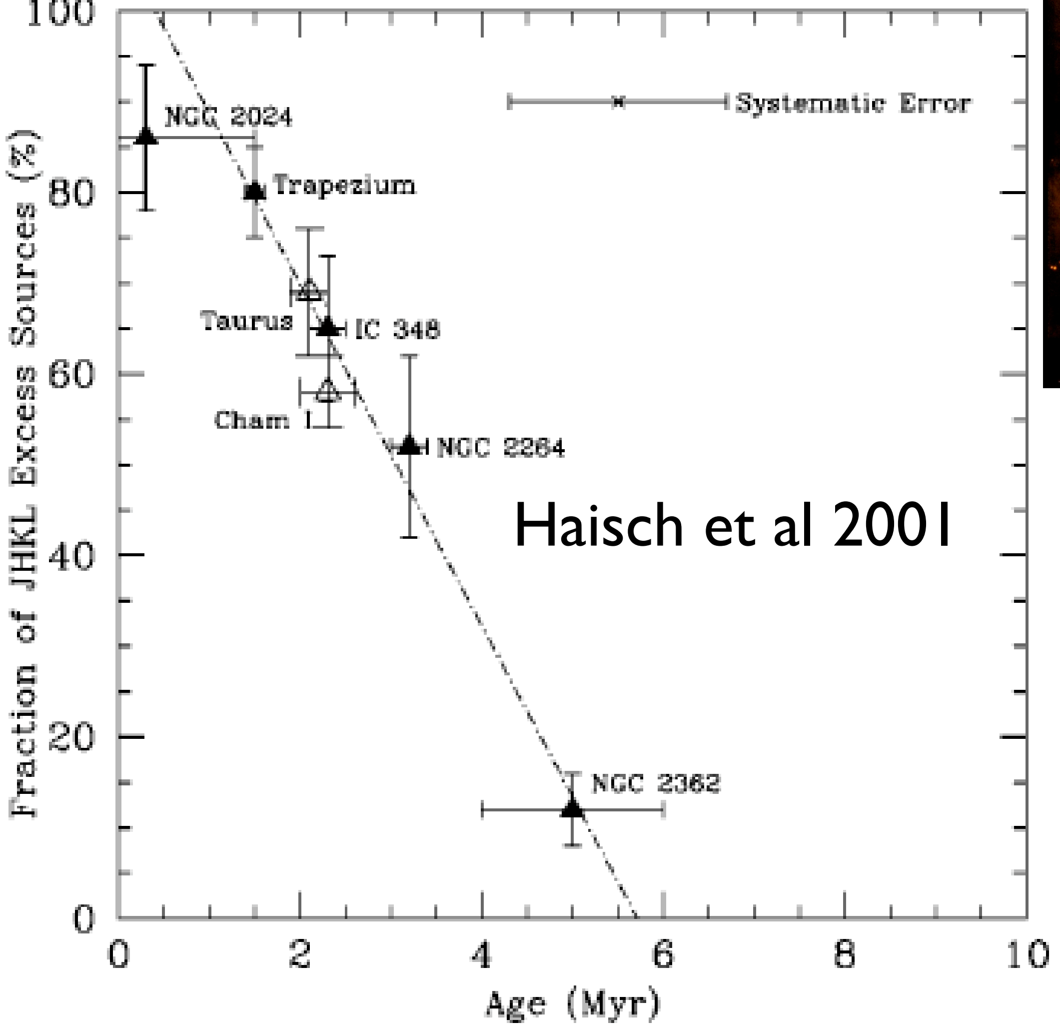
- numerical integration in envelope
- energy deposition into envelope



Pollack et al 1996 - baseline Jupiter formation model.

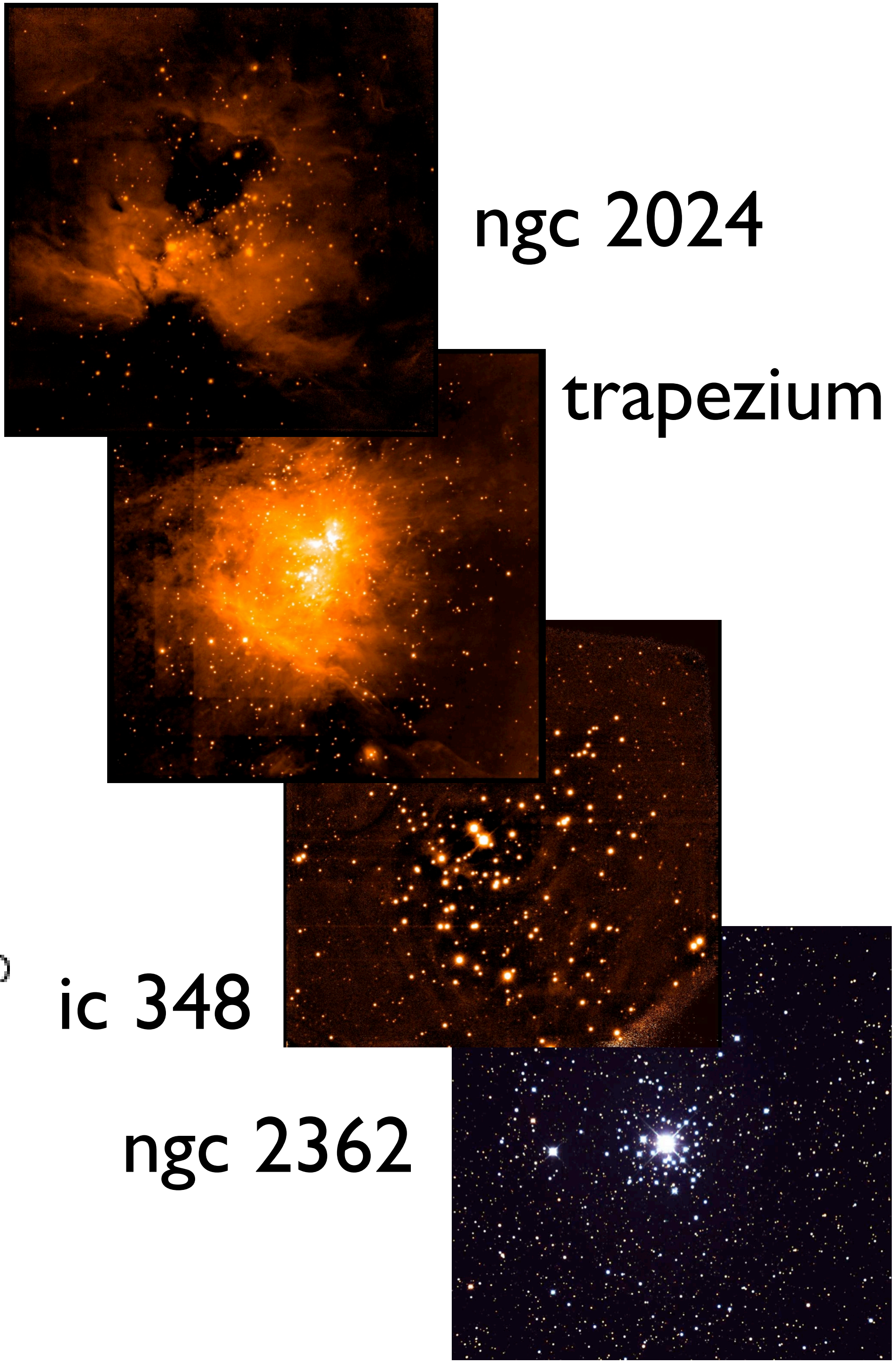
$$d = 5.2\,\mathrm{AU} \qquad \sigma_{solids} = 10\,\mathrm{g\,cm}^{-2}$$

$$T_{neb} = 150\,\mathrm{K} \qquad \rho_{neb} = 5 \times 10^{-11}\,\mathrm{gcm}^{-3}$$



Haisch et al 2001

Observed disk lifetimes tend to be shorter than the ~8 Myr required in the Pollack et al. (1996) standard case model



ngc 2024

trapezium

ic 348

ngc 2362

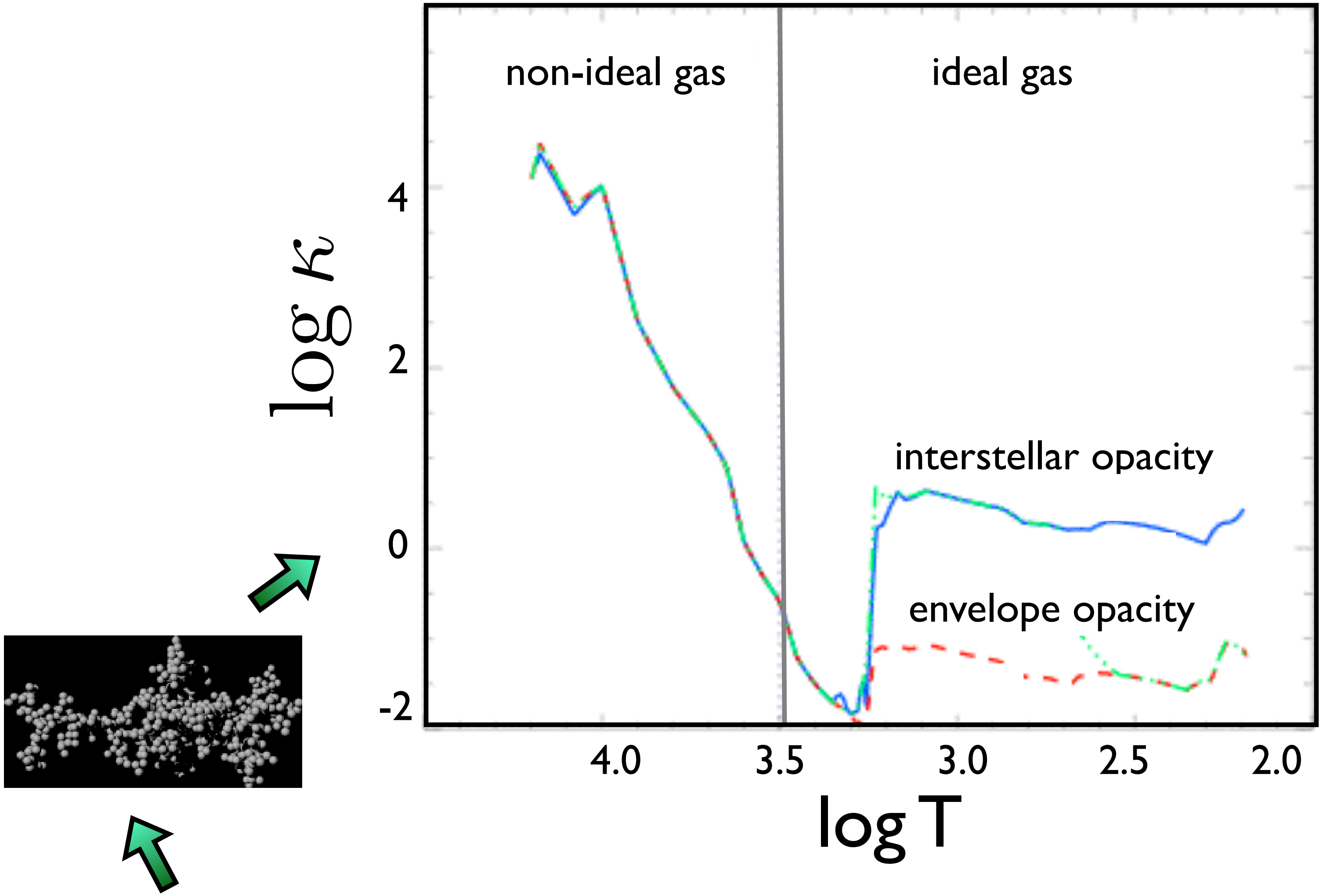
The “standard model” of Pollack et al 1996 predicts:

1. A planet with a core mass that seems too high.
2. A timescale to reach runaway gas accretion that seems too long.

A great deal of work has been done from 1996-2006 to refine core accretion. Examples include:

1. Improved physics:
   - equation of state (reviewed by Saumon & Guillot 2004)
   - envelope opacity (Ikoma et al 2000, Podolak 2003)

2. Additional physics:
   - migration of the cores (Papaloizou & Terquem 1999, Alibert et al 2004, Ida & Lin 2004)
   - turbulence in the disk (Rice and Armitage 2003)
   - competition between embryos (Hubickyj, Bodenheimer & Lissauer 2005)
   - time evolution of the disk (Alibert et al 2004, Ida & Lin 2004, Laughlin, Bodenheimer & Adams)

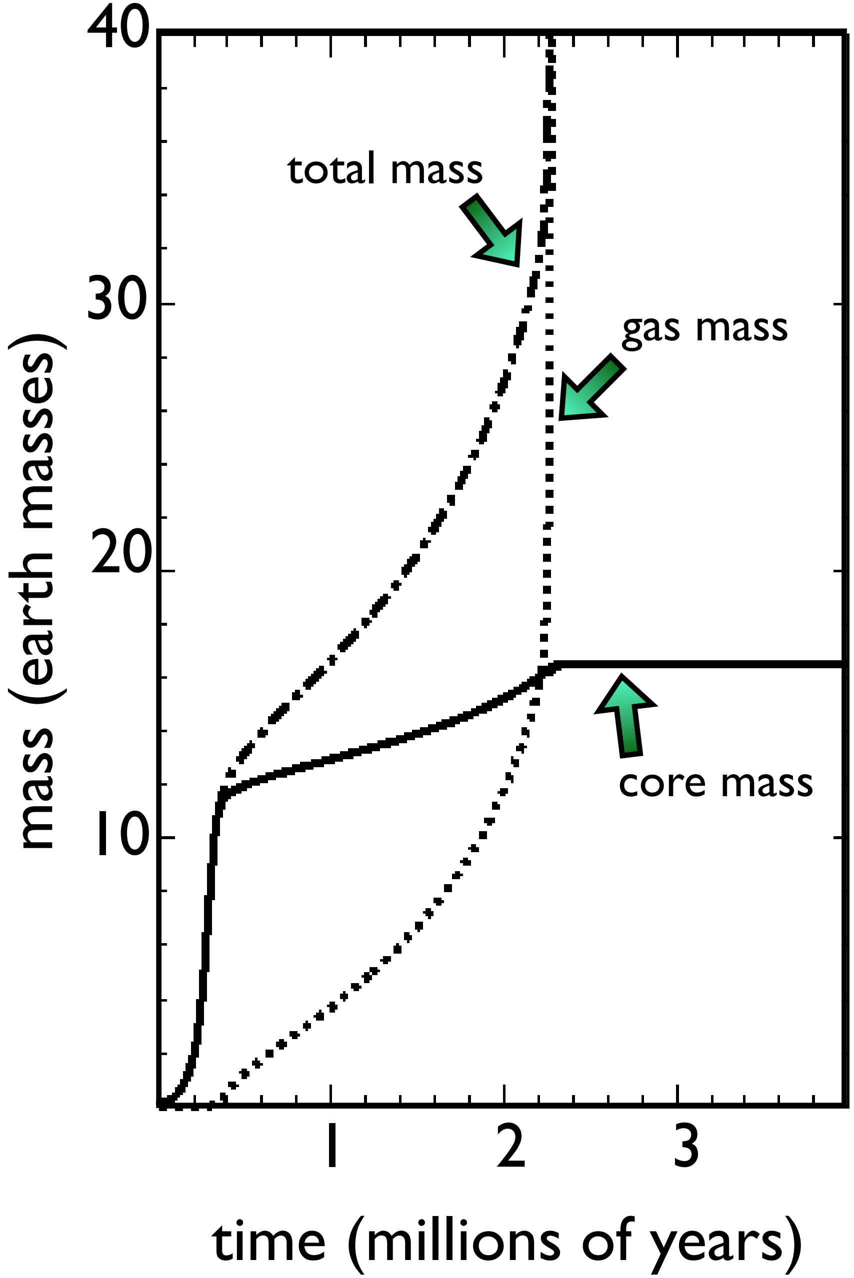


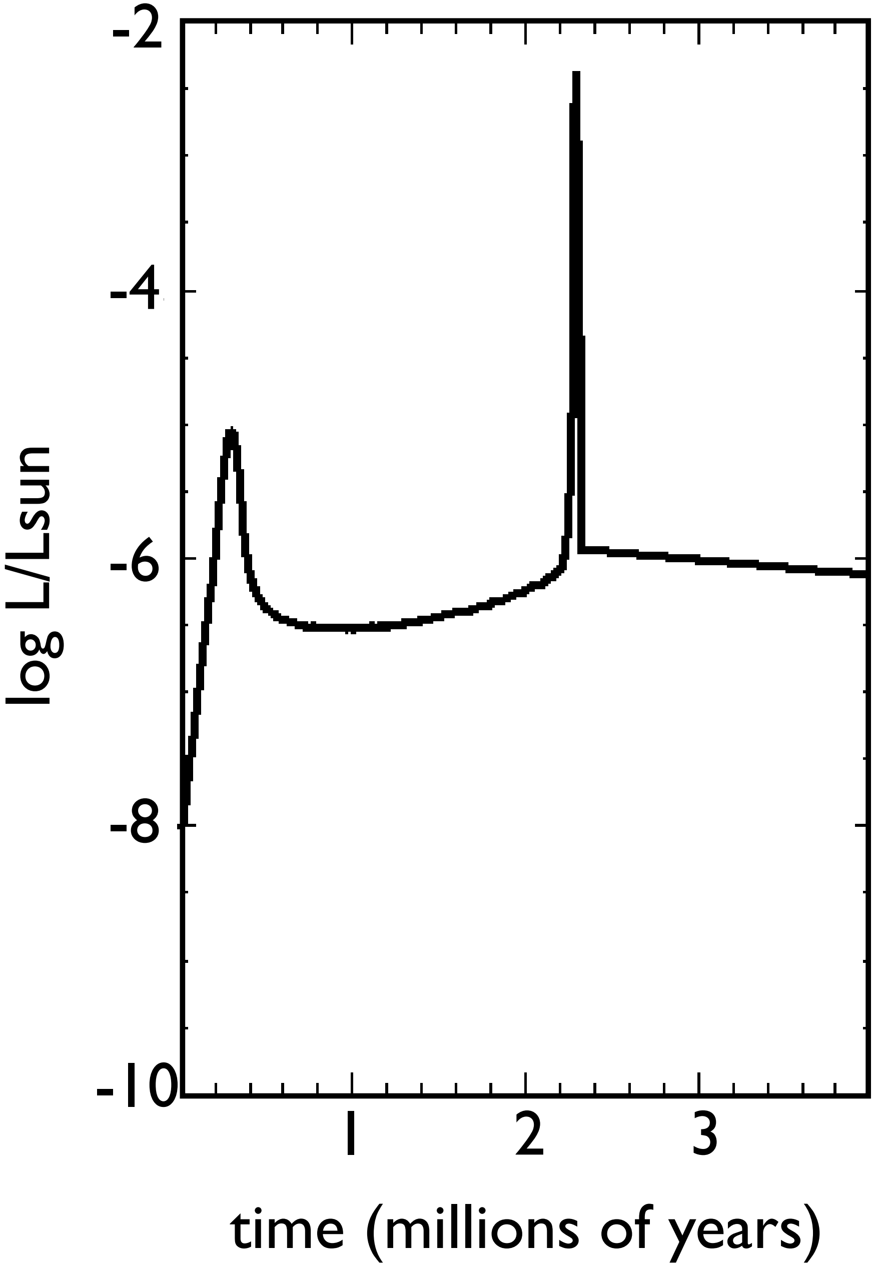
- Grain opacities are a key issue. Original studies (e.g Pollack et al 1996) used envelope opacities with an interstellar size distribution.

- But material that enters a giant planet envelope has been modified from the original interstellar grains by coagulation and fragmentation.

- Calculations by Podolak (2003) indicate that once grains enter the protoplanetary envelope, they coagulate and settle out quickly into warmer regions where they are destroyed. Podolak argues that true opacities are ~50x smaller than interstellar.

Reduced grain opacity greatly speeds up the gas accretion timescale.

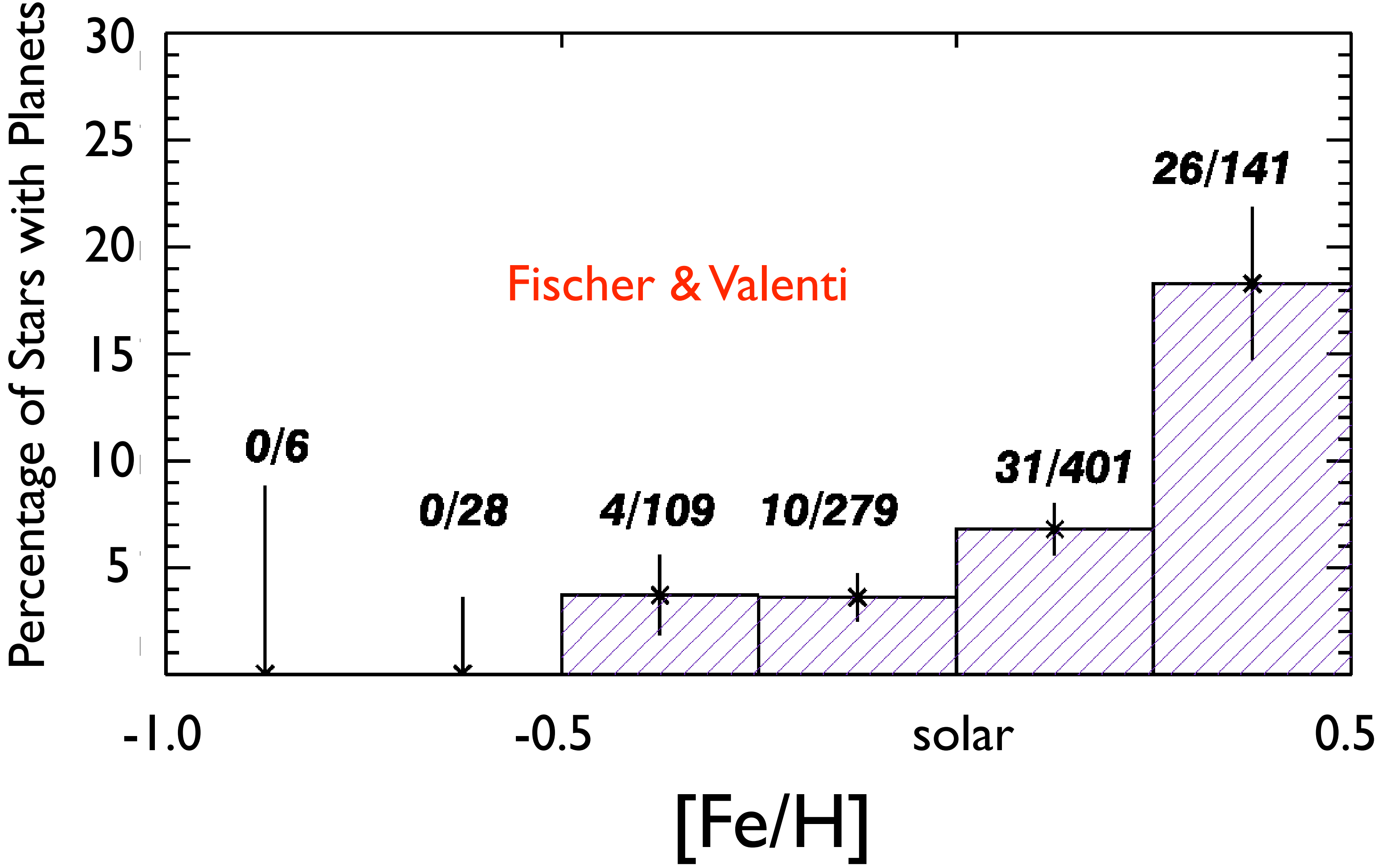




(Hubickyj et al. 2005)

A key (and well established) result of standard core accretion theory is the extraordinary sensitivity of the time of onset of rapid gas accretion to the surface density of solids in the disk.

Recent calculations by Hubickyj et al (2005), illustrate that decreasing the solid surface density from 10 to 6 gm/cm^2 causes a 12 Myr delay in the onset of rapid gas accretion.

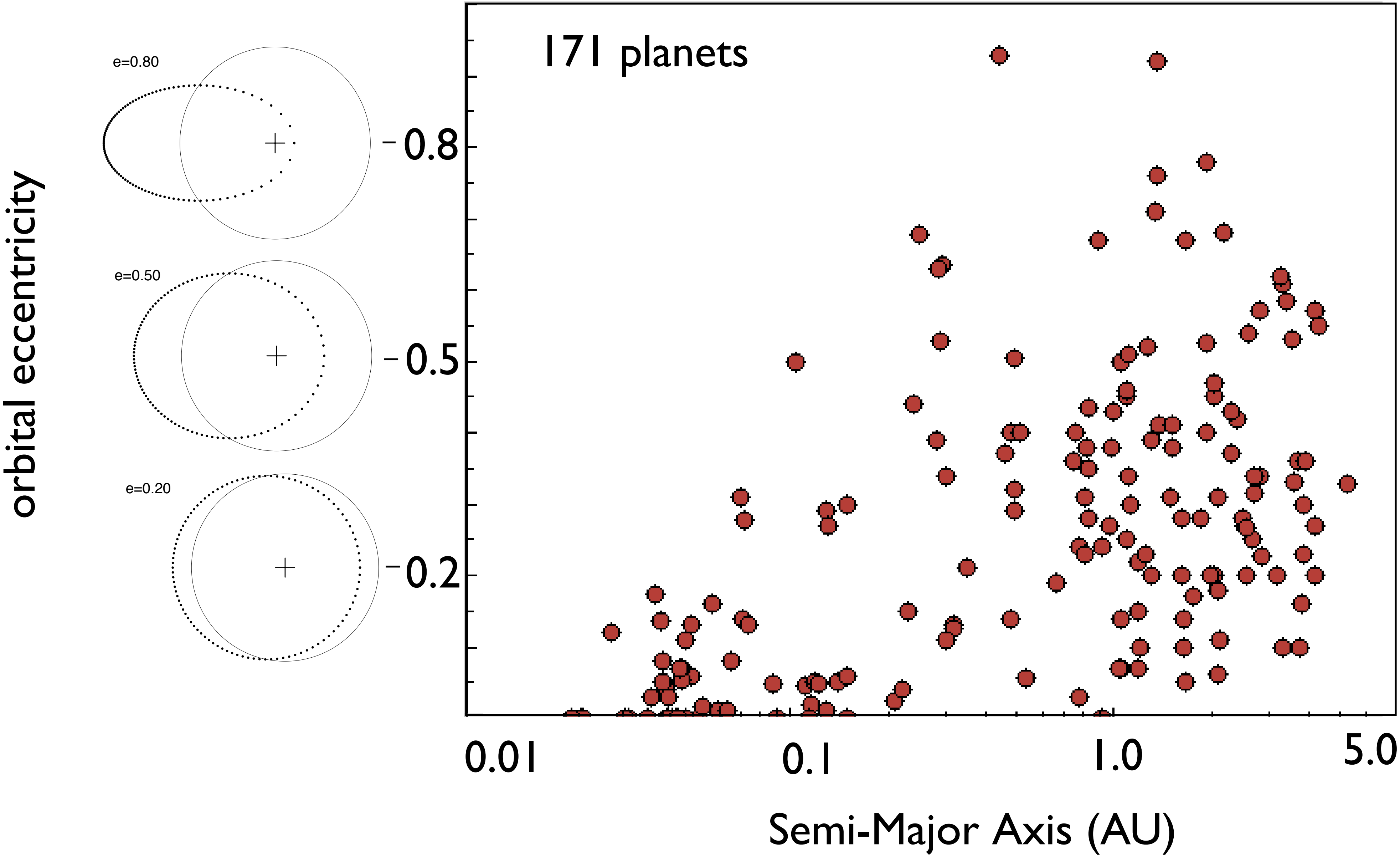


The extrasolar planet - host star metallicity connection is one of the most remarkable results to have emerged from the radial velocity surveys. This correlation certainly provides an important clue to the planet formation process.

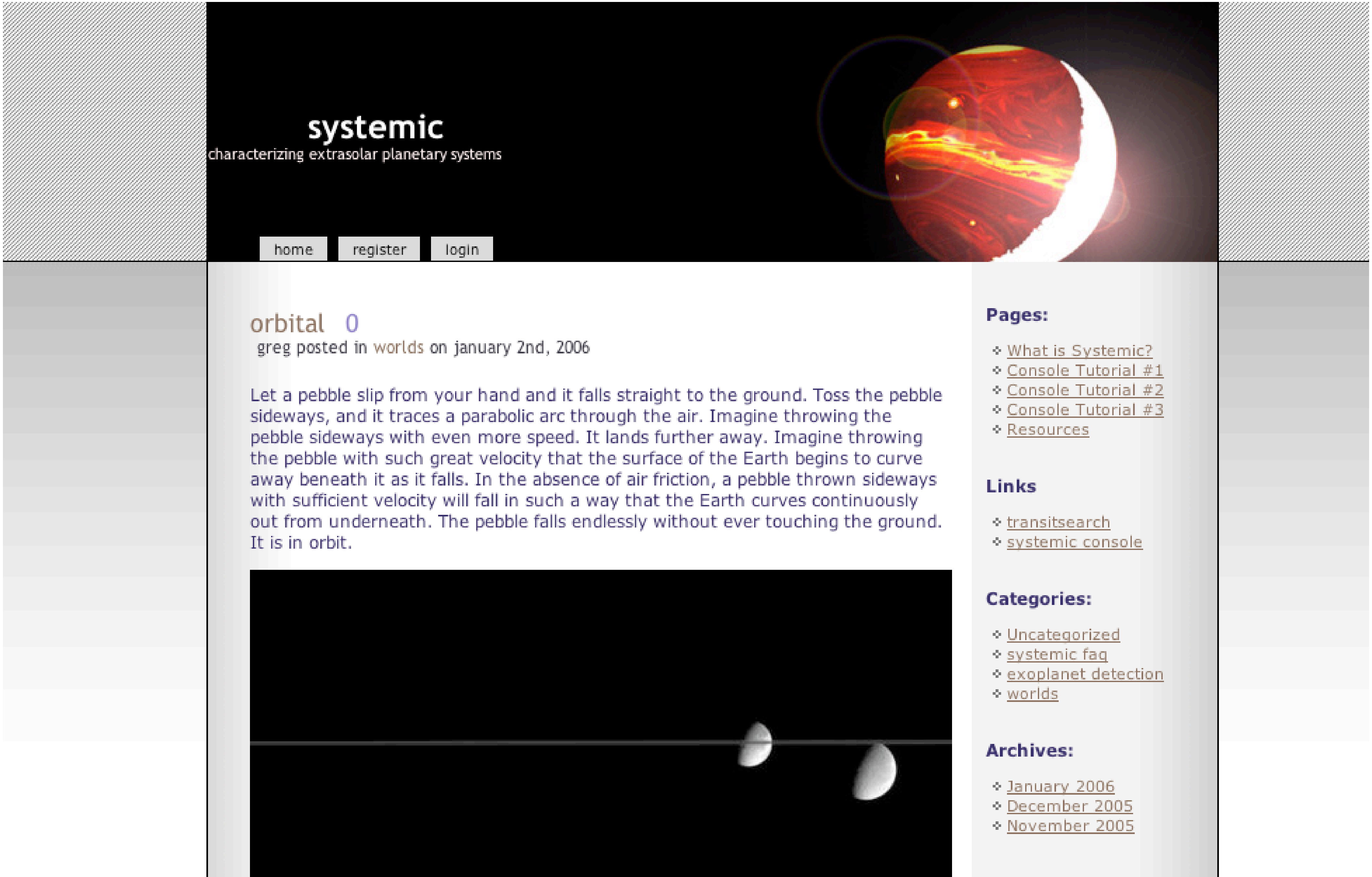
The metallicity -- planet connection suggests that giant planet formation is a threshold phenomenon that depends sensitively on the surface density of solids (planetesimals) in the disk.

This is a characteristic and generic property of core-accretion.

The metallicity connection is very hard to understand within the gravitational instability paradigm (e.g. Boss 2002).


171 planets
e=0.80
e=0.50
e=0.20
orbital eccentricity
0.8
0.5
0.2
0.01
0.1
1.0
5.0
Semi-Major Axis (AU)

www.oklo.org



systemic

characterizing extrasolar planetary systems

orbital 0

greg posted in worlds on january 2nd, 2006

Let a pebble slip from your hand and it falls straight to the ground. Toss the pebble sideways, and it traces a parabolic arc through the air. Imagine throwing the pebble sideways with even more speed. It lands further away. Imagine throwing the pebble with such great velocity that the surface of the Earth begins to curve away beneath it as it falls. In the absence of air friction, a pebble thrown sideways with sufficient velocity will fall in such a way that the Earth curves continuously out from underneath. The pebble falls endlessly without ever touching the ground. It is in orbit.

Pages:

- What is Systemic?
- Console Tutorial #1
- Console Tutorial #2
- Console Tutorial #3
- Resources

Links

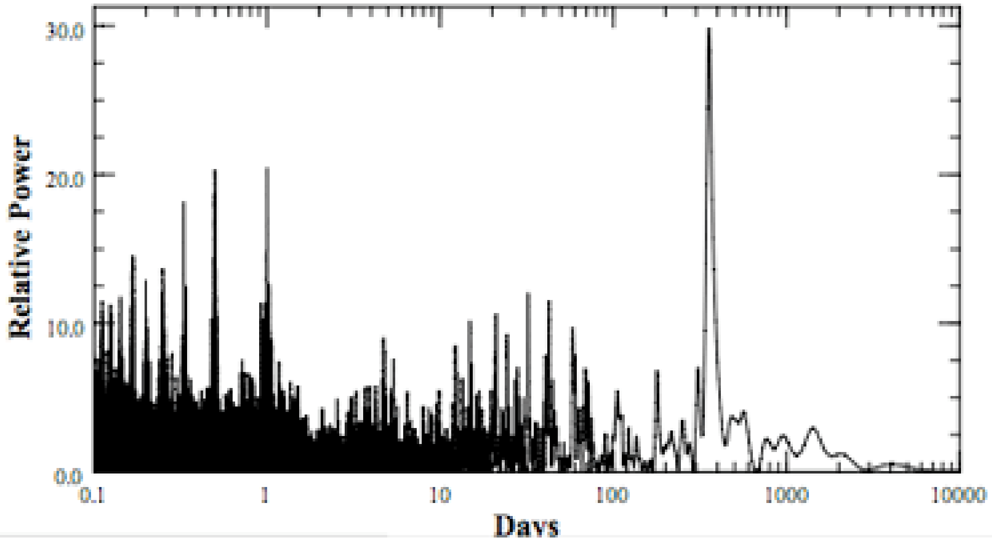
- transitsearch
- systemic console

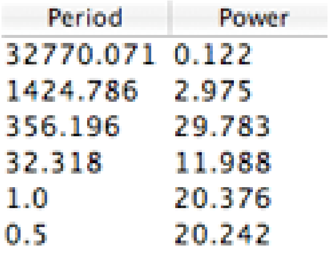
Categories:

- Uncategorized
- systemic faq
- exoplanet detection
- worlds

Archives:

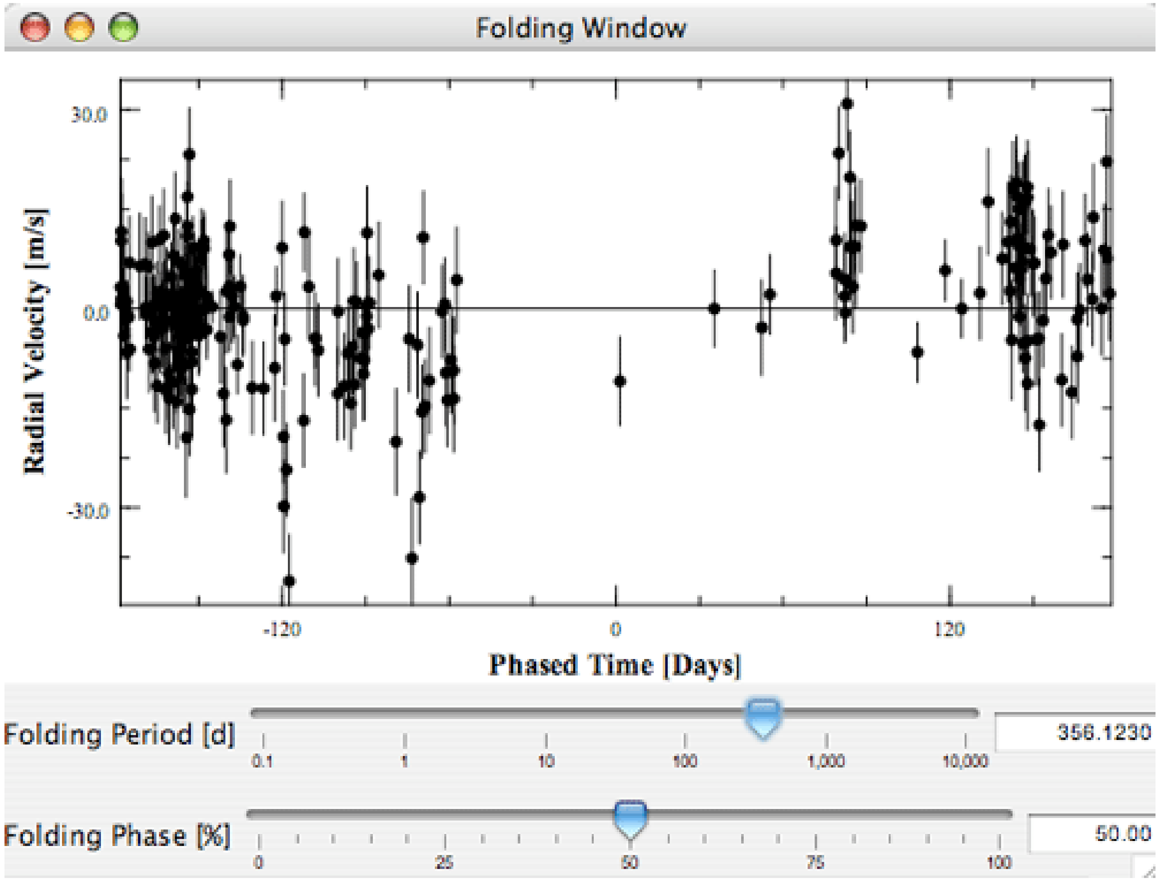
- January 2006
- December 2005
- November 2005





Period	Power
32770.071	0.122
1424.786	2.975
356.196	29.783
32.318	11.988
1.0	20.376
0.5	20.242

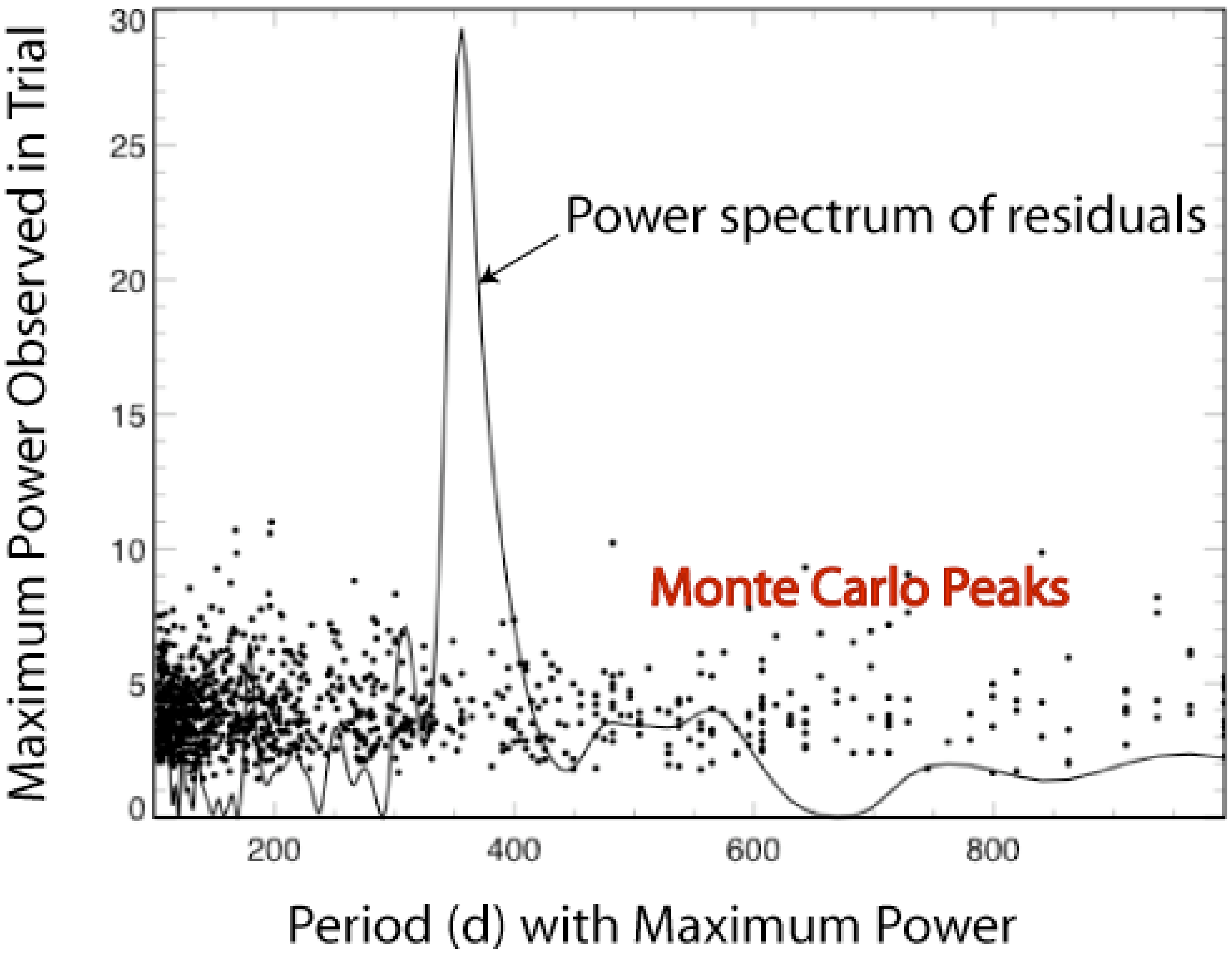
51 Peg shows a strong residual peak at 356 days.
Is this peak an alias?



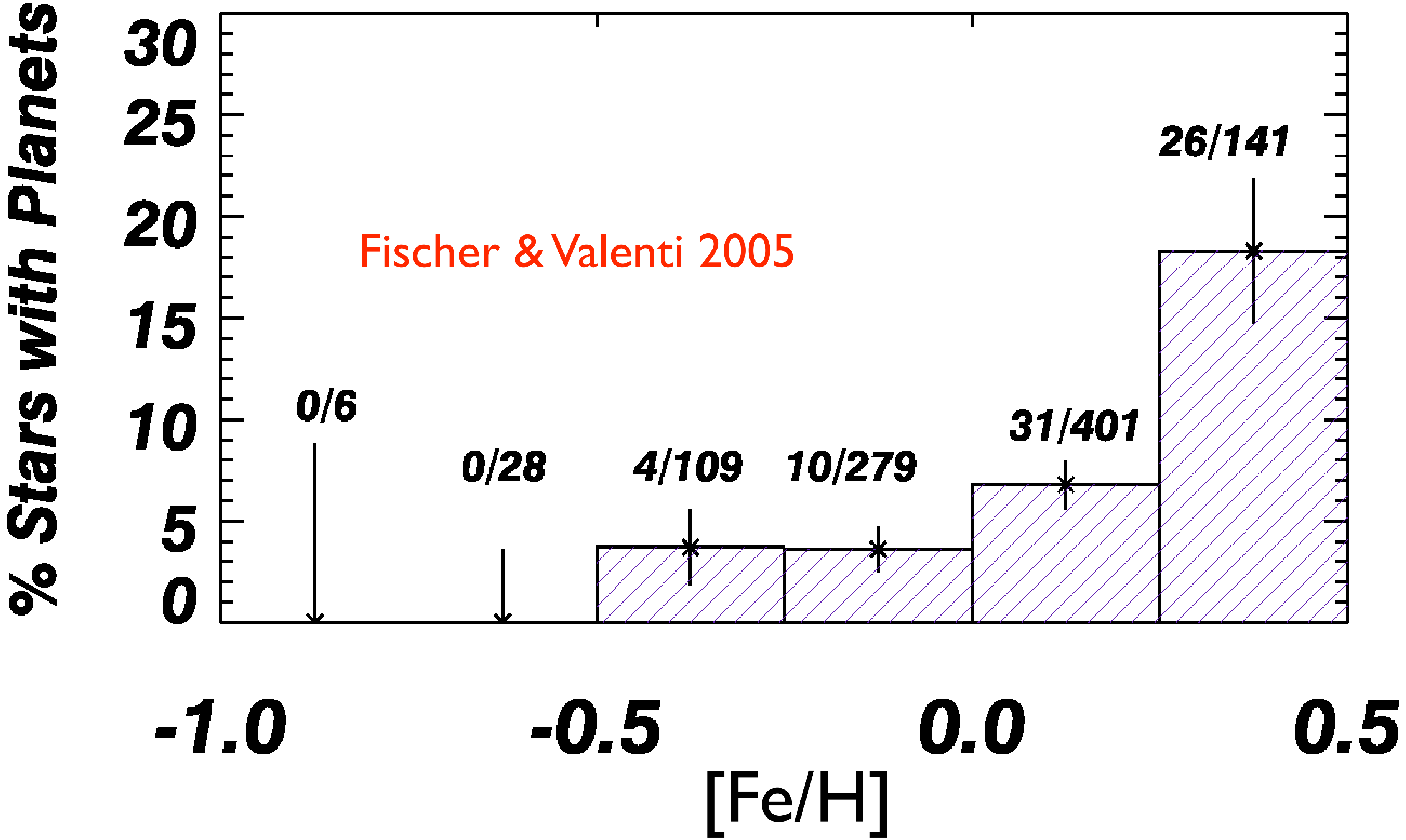
Folding Period [d]: 356.1230

Folding Phase [%]: 50.00

51 Peg Residuals folded at 356.123 days



The 51 Peg 356.1 day peak is not an alias peak.

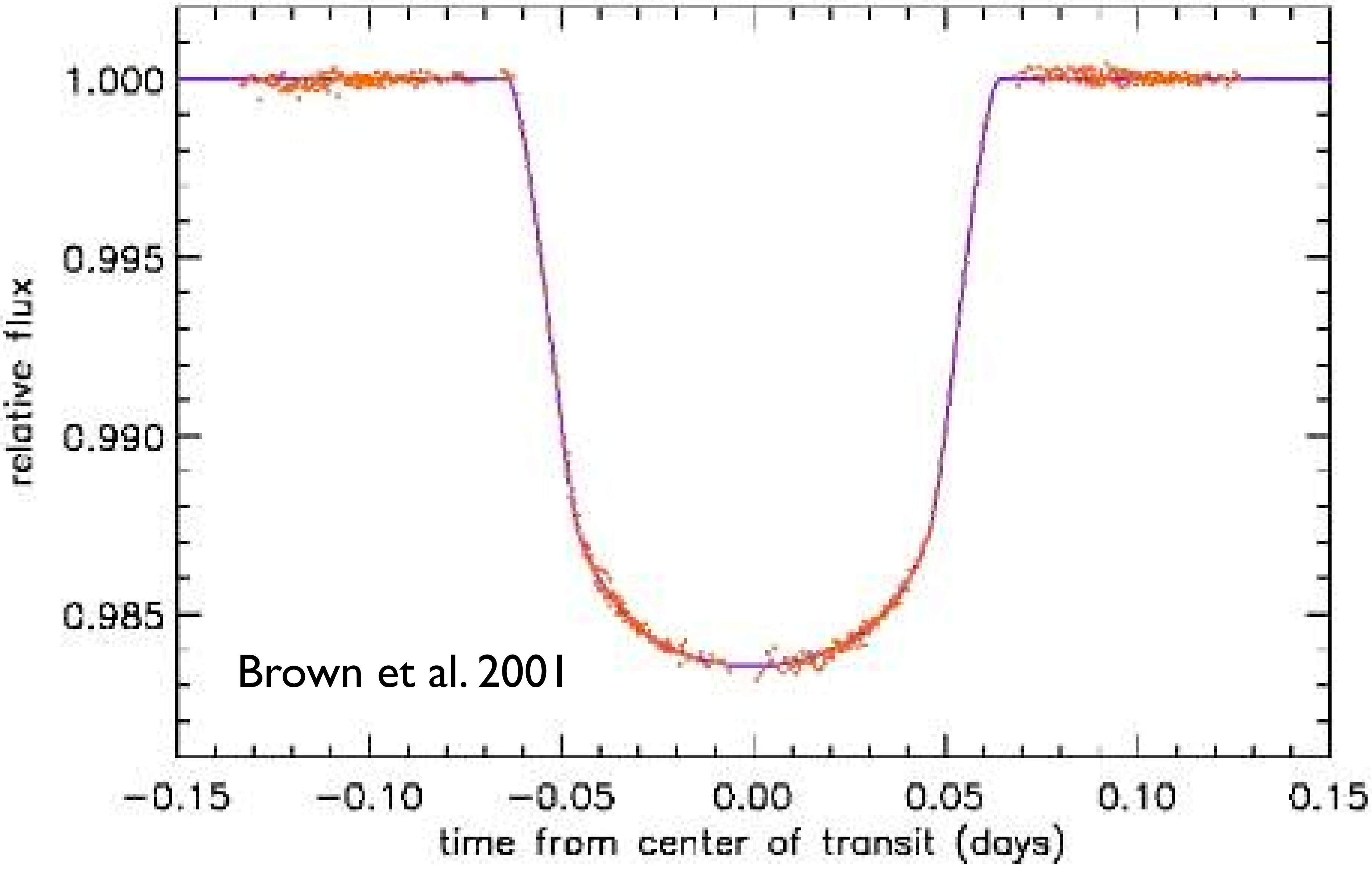


Fischer & Valenti 2005

The extrasolar planet - host star metallicity connection is one of the most remarkable results to have emerged from the radial velocity surveys. This correlation is saying something important about planet formation. *It also shows how to efficiently find planets.*

candy for breakfast

- A quick-look Doppler velocity survey that searches metal-rich stars for planets will certainly skew the overall statistical census of extrasolar planets. Why is it important to
- quickly find more hot-Jupiter type planets?



Brown et al. 2001

Short-period planets have a high probability of transiting. When a planet transits a bright star, a tremendous amount can be learned.

Statistical Anomalies

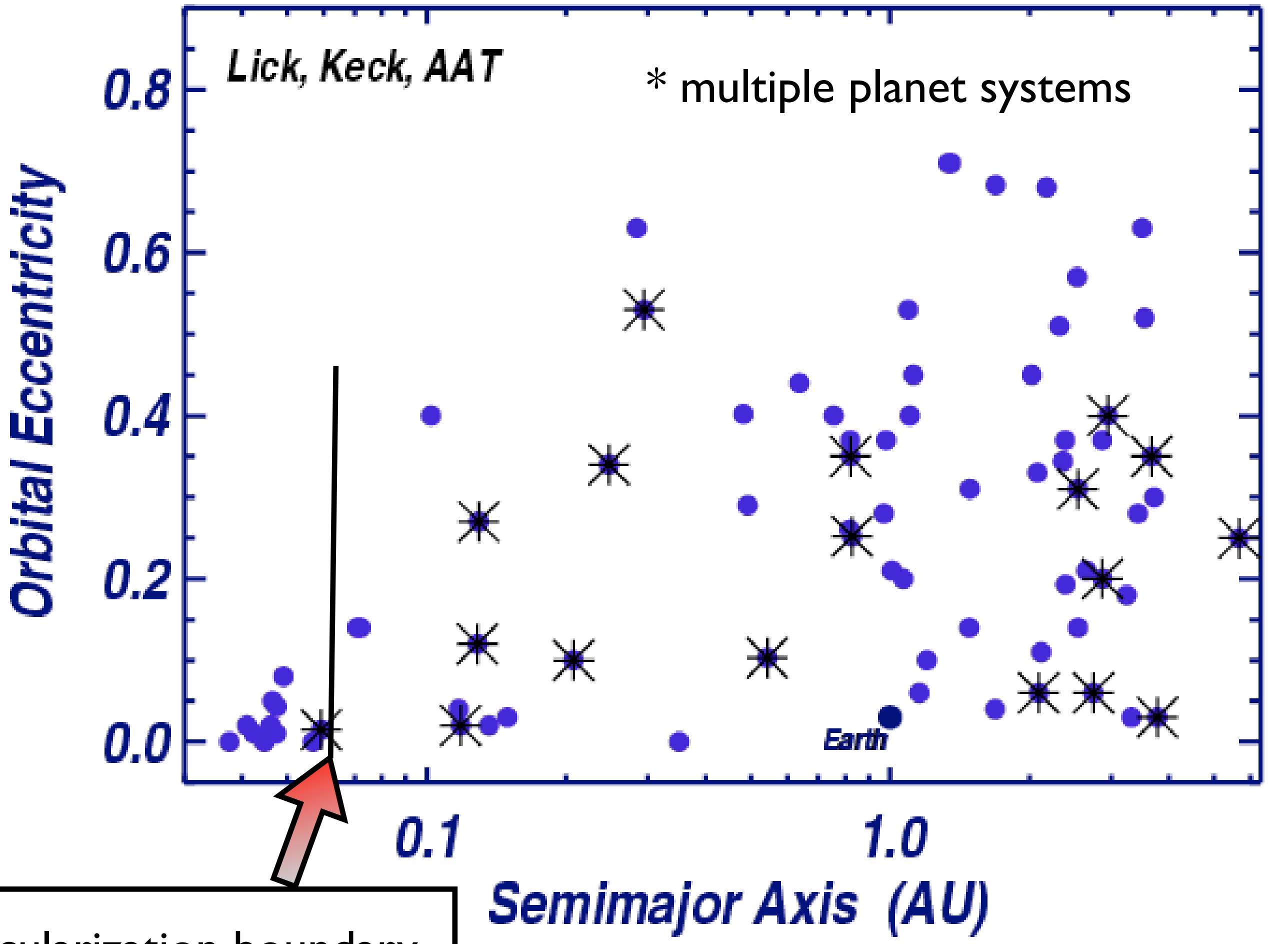
- A curious concentration (11 out of 26) planets with periods $0<P<10$ days have periods between 3 and 4 days.

- All of the short-period planets are solar or higher metallicity.

- A possible relation (of negative slope) exists between the mass of transiting planets and their periods.

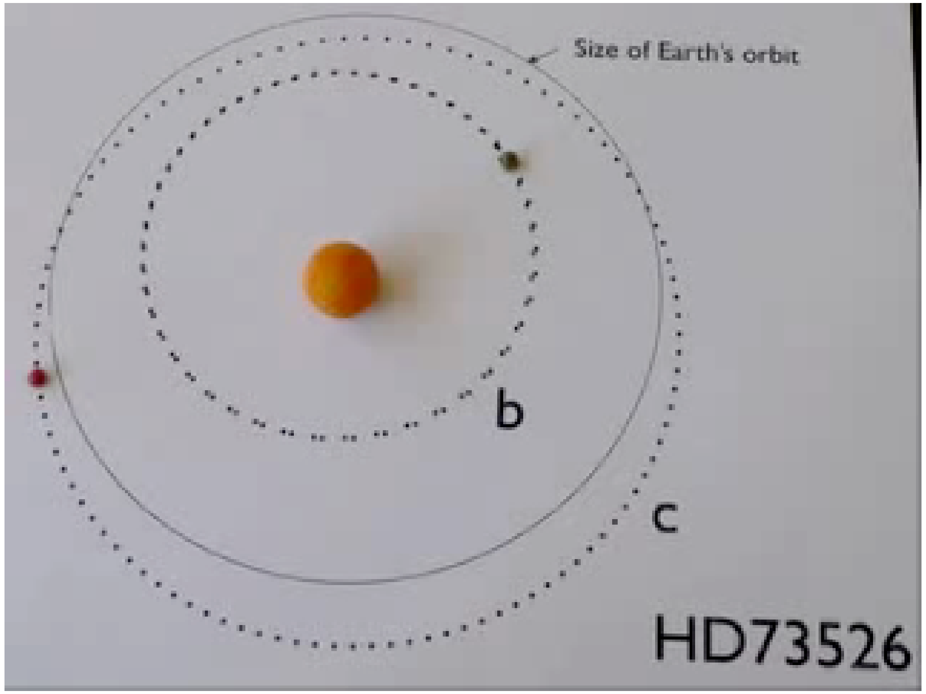
- Planets with periods $P<10$ days have an average mass $M<1M_{Jup}$. Planets with periods $10<P<200$ days have an average mass $M\sim5M_{jup}$ (this is not due to an observational bias). Furthermore, the mass-period relation for planets appears to be different for the cases of single parent stars and binary parent stars.

As more planets with periods of approximately one week are discovered, the tidal quality factor, *Q*, which in general should depend on Mass, Teff, and composition will become better constrained. Right now, the circularization boundary suggests <Q>~10^6

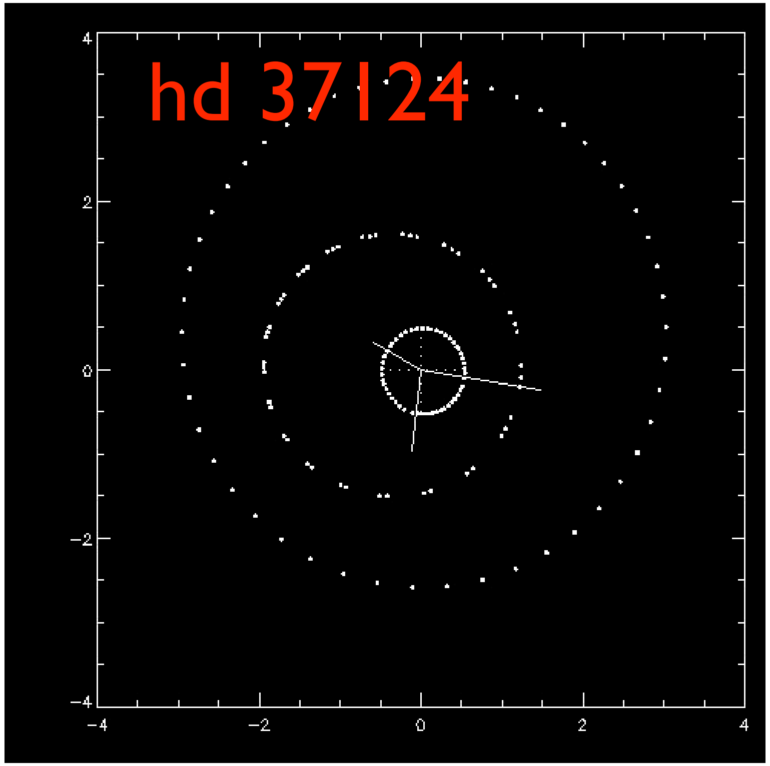


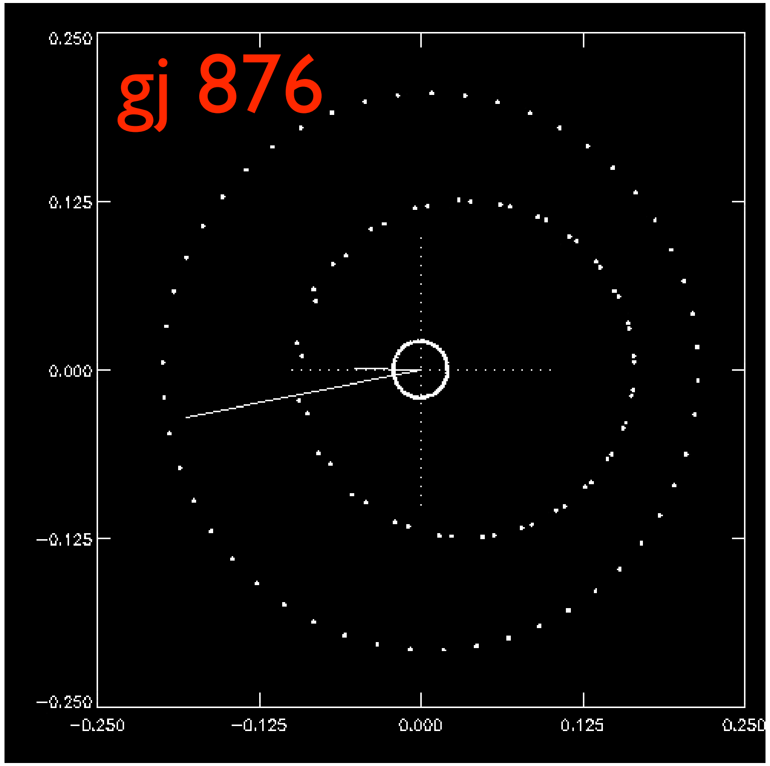
circularization boundary occurs at a period of about one week.

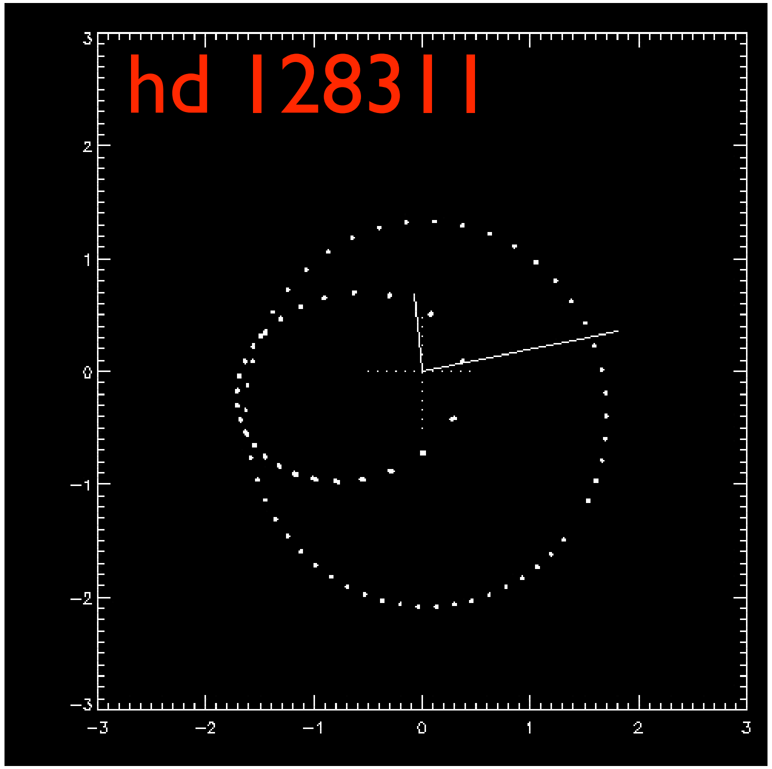
$$\tau_{\rm circ} = \frac{\mathbf{e}}{\dot{\mathbf{e}}} = \left(\frac{\mathbf{4Q_P}}{\mathbf{63n}}\right)\left(\frac{\mathbf{M_P}}{\mathbf{M_\star}}\right)\left(\frac{\mathbf{a}}{\mathbf{R_p}}\right)^{\mathbf{5}}$$


Size of Earth's orbit
b
c
HD73526

Over half of the short-period planets that have been discovered show evidence for detectable additional companions. Multiple-planet systems can tell us much more about the formation and evolutionary processes that are sculpting the galactic planetary census.







The N2K Survey

- An international Consortium to survey the "next" two thousand metal rich stars (identified via broadband photometric calibrations).

- Our strategy is to obtain 3+1 Doppler velocities for each star. Stars with scatter characteristic of a Hot Jupiter sent to Keck for follow-up.

- 1000 stars have been surveyed so far.

- Fischer, Laughlin, Butler, Marcy, Henry (US: NASA / NOAO Keck); Ida, Sato (Japan: Subaru); Minniti (Chile: Magellan)

Table 1. Derived Parameters for Stars with Planets

Star ID	$T_{\rm eff}$ [K]	log g [cm s^{-2}]	[Fe/H]	[Si/H]	[Ti/H]	[Na/H]	[Ni/H]	$v \sin i$ [km/s]
HD-178911	5667	4.55	0.28	0.26	0.26	0.34	0.30	1.9
BD-103166	5393	4.69						0.9
HD142	6248	4.19						10.3
HD1237	5580	4.56						5.0
HD2039	5940	4.38						3.2
HD3651	5220	4.45						1.1
HD4203	5701	4.36						1.2
HD4208	5600	4.52						0.0
HD8574	6049	4.20						4.5
HD9826	6212	4.25						9.6
HD10647	6104	4.34						5.6
HD10697	5680	4.12						2.4
HD11964	5349	4.03						2.7
HD12661	5742	4.42						1.3
HD13445	5150	4.59						2.3
HD16141	5793	4.22						1.9
HD17051	6097	4.34						6.4
HD20367	5971	4.31	0.08	0.20	0.05	-0.08	-0.02	3.5

Broadband calibrations:

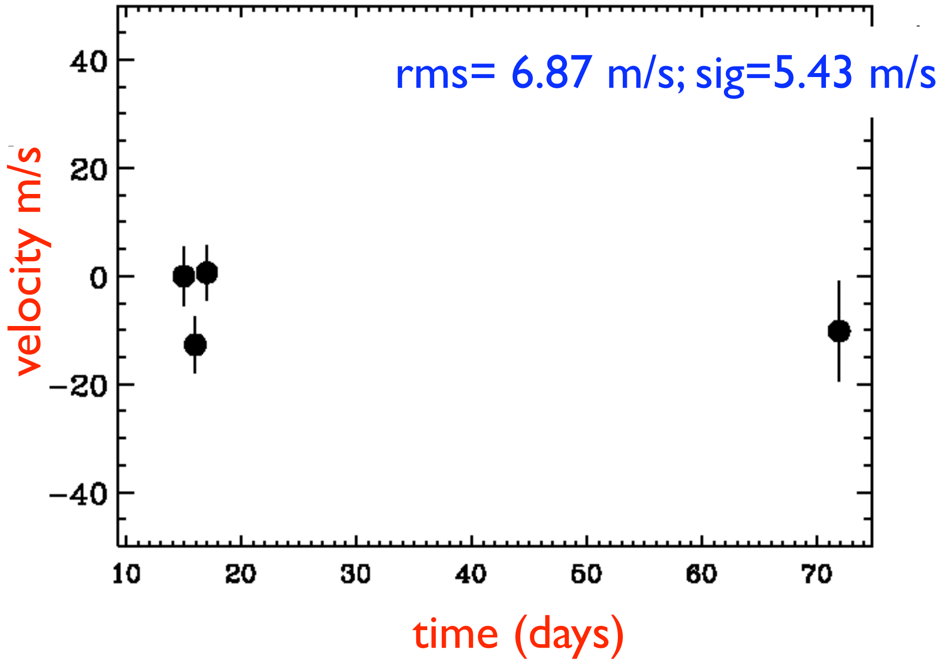
Fischer & Valenti (2005) have derived accurate physical properties (Fe/H, log g, Teff) from uniformly obtained high-resolution spectra of 1330 stars in the Keck, Lick, and AAT surveys.

All of these stars have Tycho B and V photometry, and 2-Mass J, H, and K photometry.

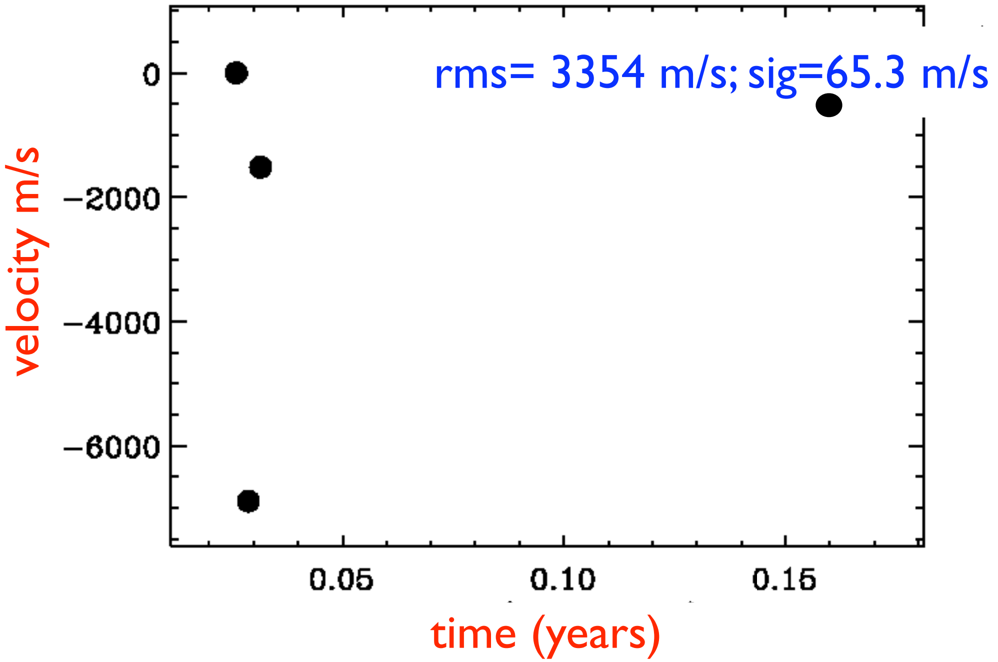
Use the Levenberg-Marquardt method to derive empirical calibrations (by varying the coefficients of polynomials constructed from the broadband colors) to calibrate Fe/H, etc.

Ammons et al. (2006)

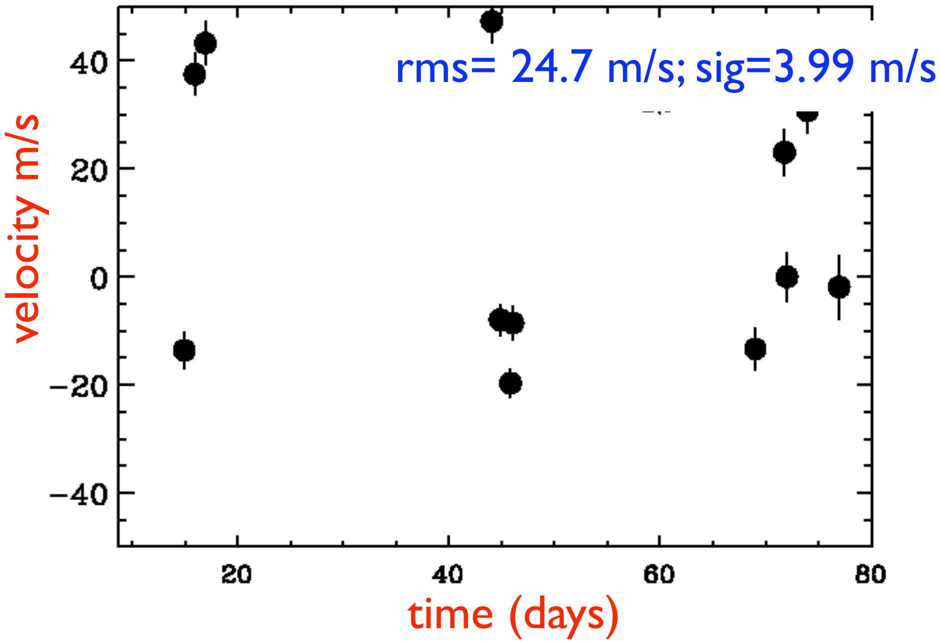
no hot jupiter



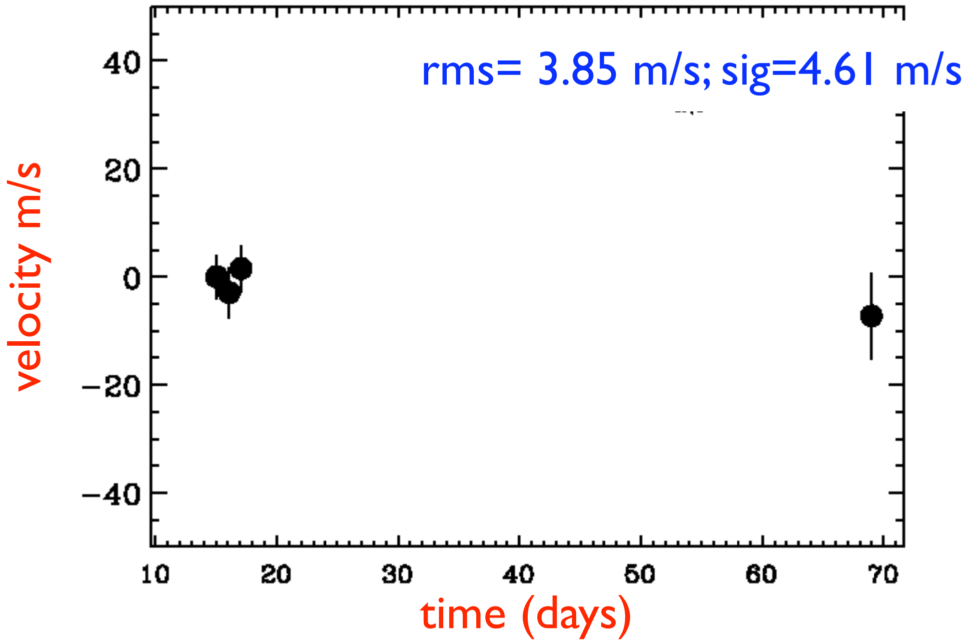
spectroscopic binary



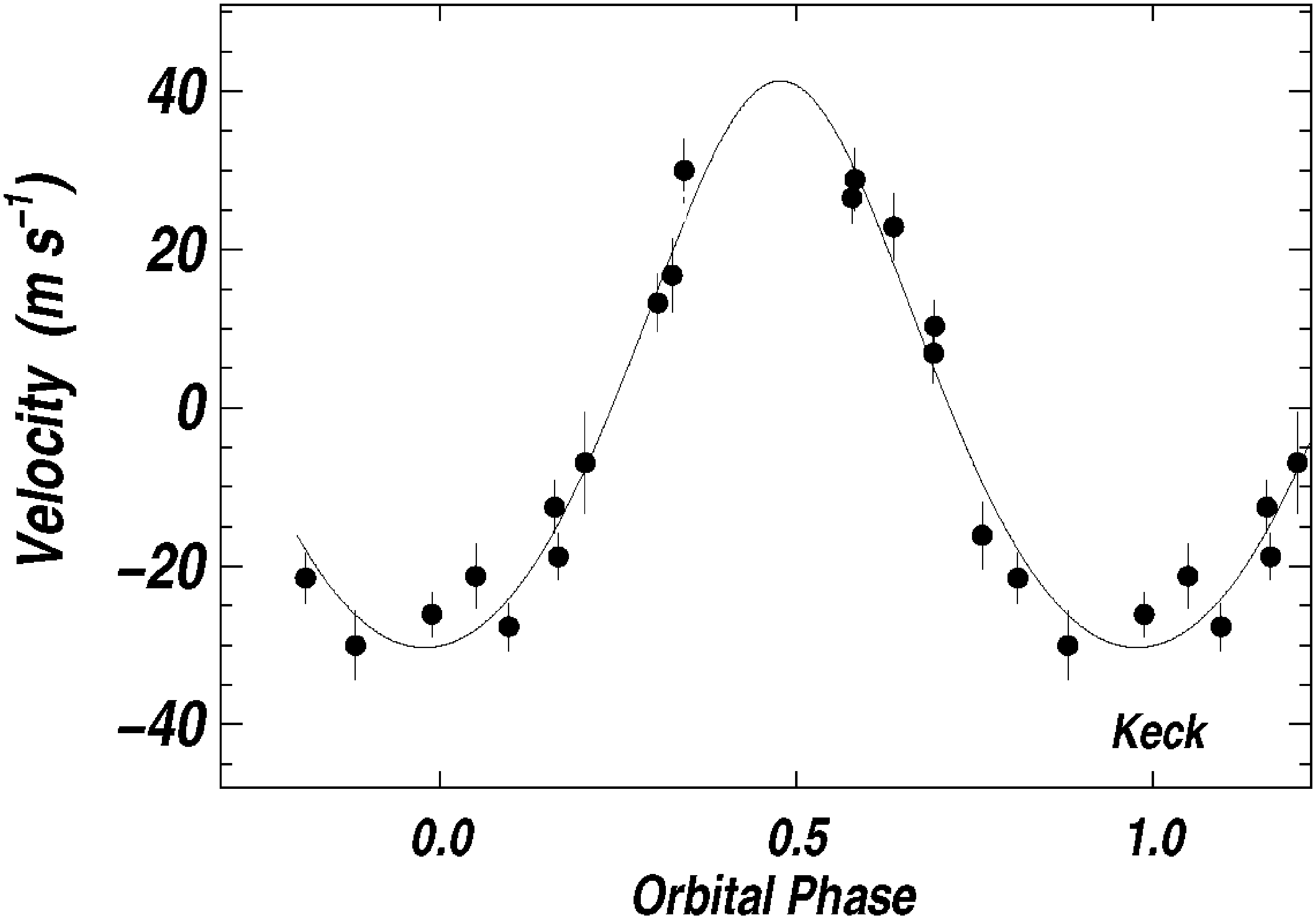
hot jupiter candidate



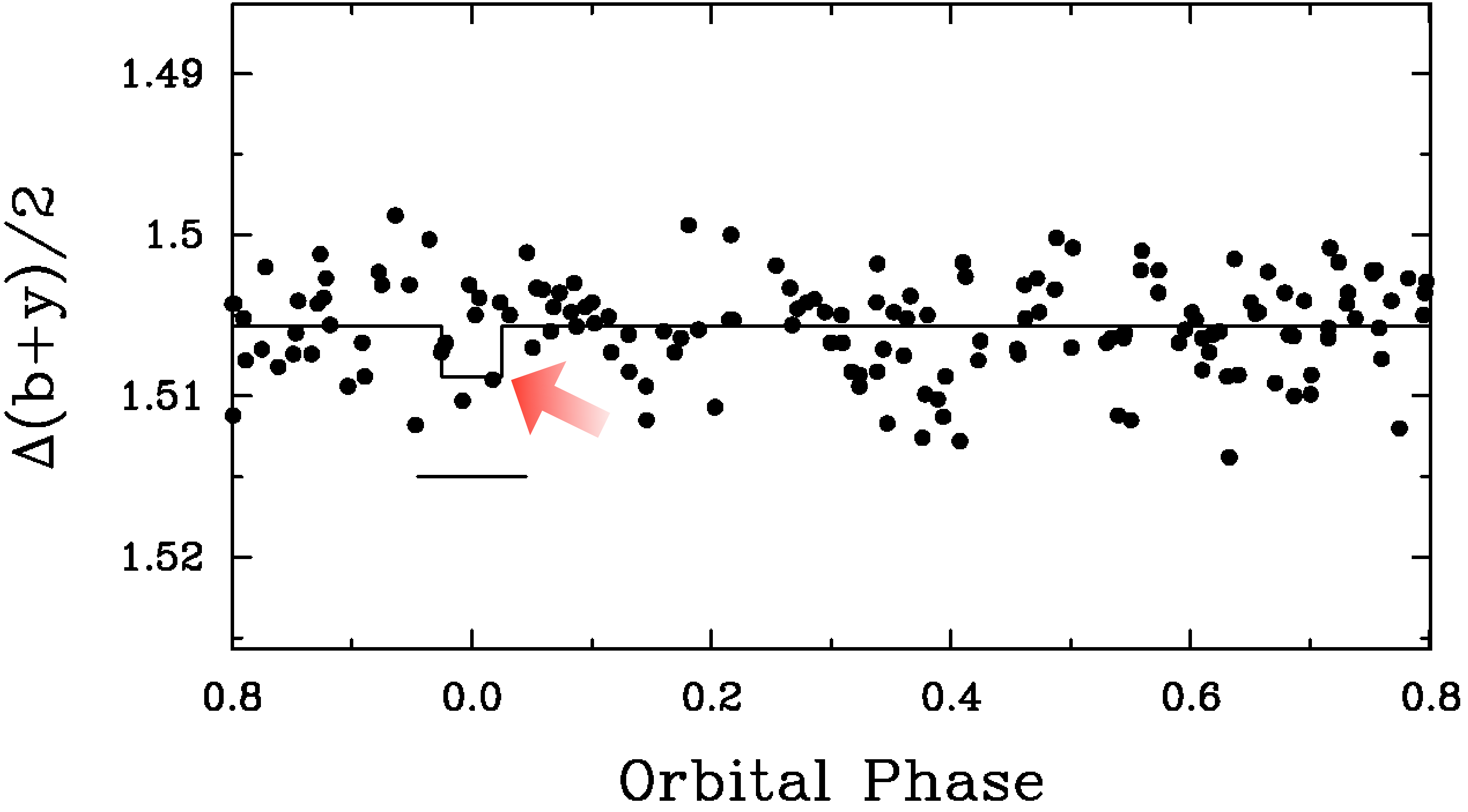
no hot jupiter



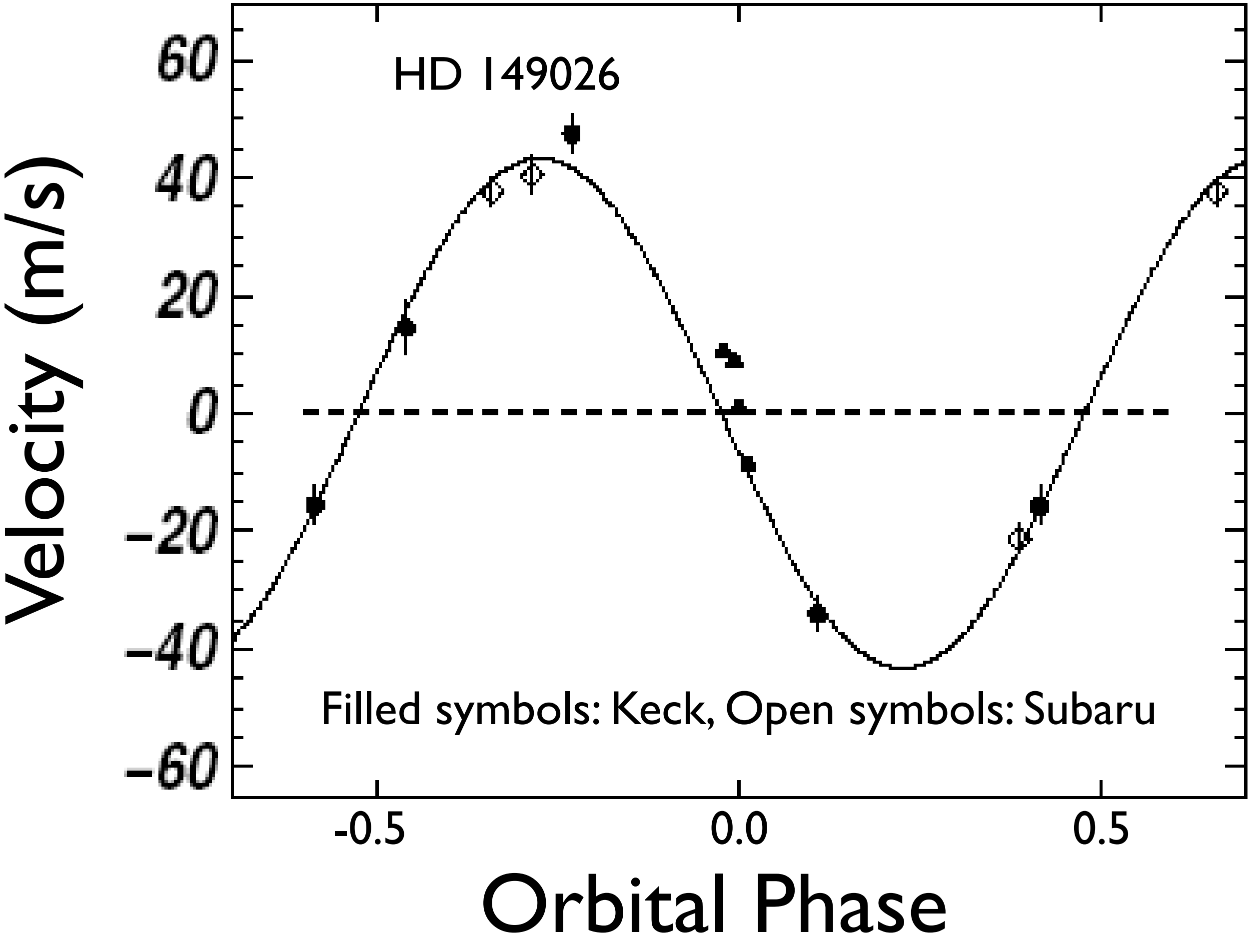
A Hot-Saturn Orbiting HD 88133



P=3.41 d, e=0, $M\sin i$= 0.29 M_{Jup}

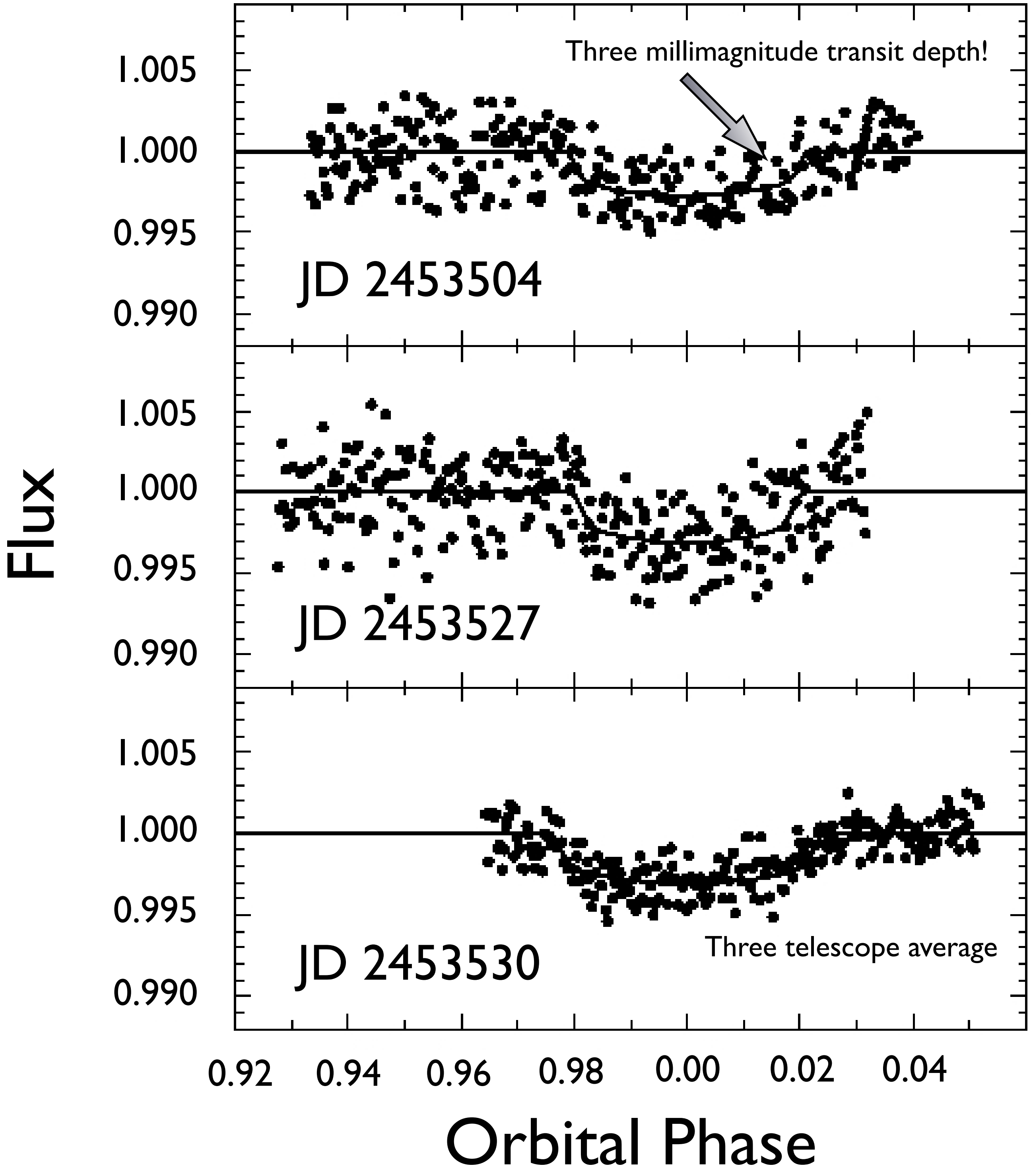


Photometry from Greg Henry, using a 0.8 m automated telescope, shows no evidence of transit for HD88133b.

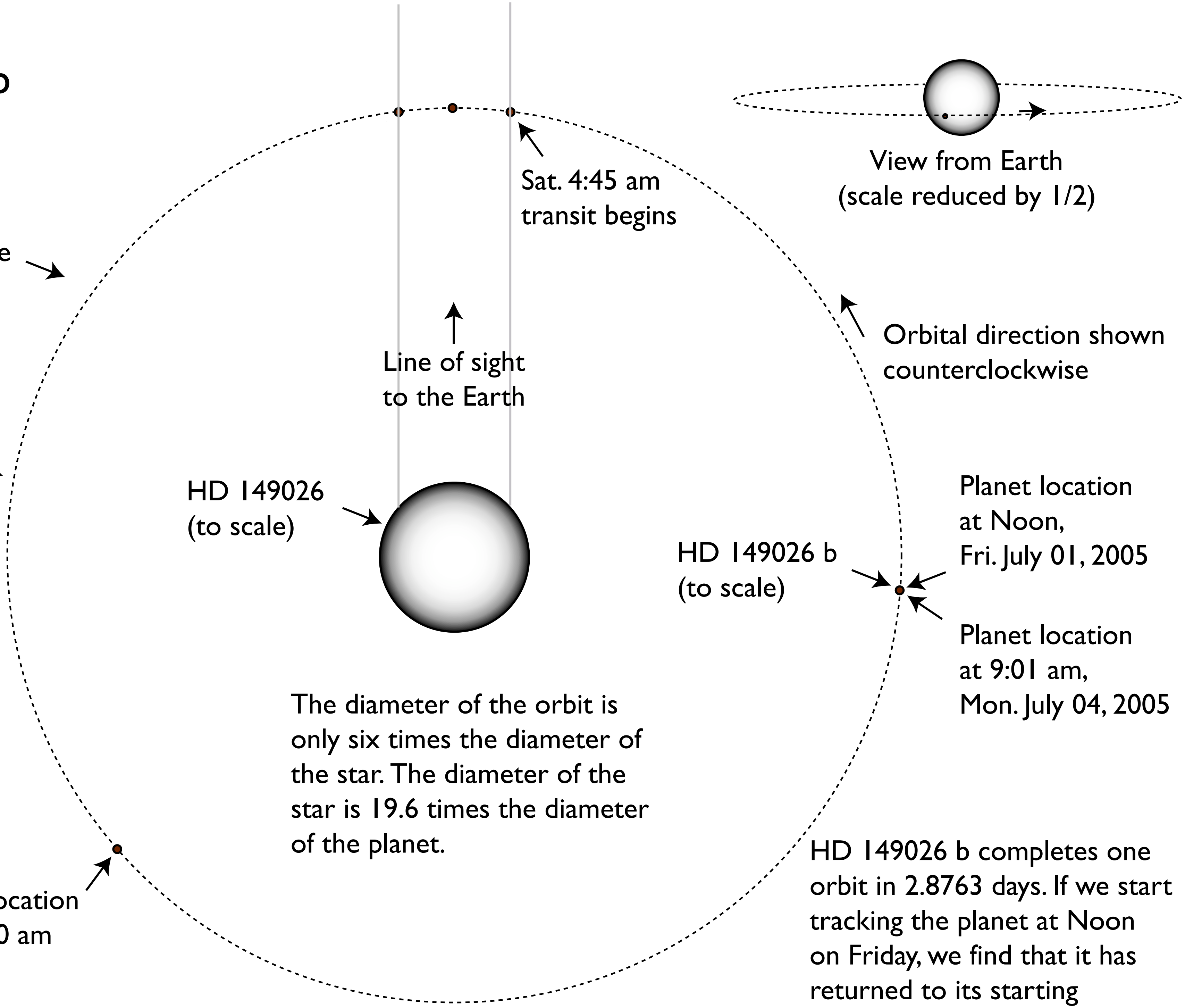


HD149026	
R	1.45 (0.1) Rsun
M	1.3 (0.1) Msun
L	2.7 (0.5) Lsun
d	79 (7) pc
Teff	6147 (50) K
Age	2.0 (0.8) Gyr
Type	G0 IV
V	8.15
vsini	6.0 (0.5) km/s
[Fe/H]	0.36 (0.05) dex
dec	+30

HD149026 b	
P	2.8766 (0.001) d
e	0.00 (fixed)
K	43.3 (1.2) m/s
Msini	0.36 (0.03) Mjup


Three millimagnitude transit depth!
JD 2453504
JD 2453527
JD 2453530
Three telescope average
Flux
1.005
1.000
0.995
0.990
Orbital Phase
0.92
0.94
0.96
0.98
0.00
0.02
0.04

HD 149026b



Sat. 4:45 am
transit begins

View from Earth
(scale reduced by 1/2)

Viewed from above

Line of sight
to the Earth

Orbital direction shown
counterclockwise

Orbital path
(to scale)

HD 149026
(to scale)

HD 149026 b
(to scale)

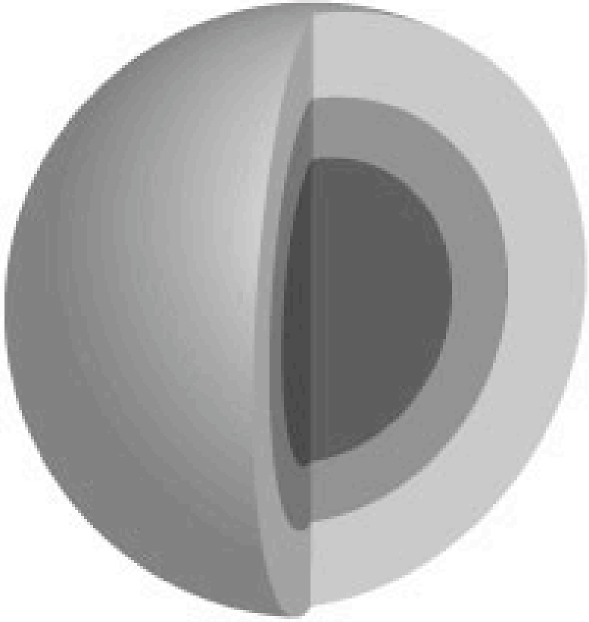
Planet location
at Noon,
Fri. July 01, 2005

Planet location
at 9:01 am,
Mon. July 04, 2005

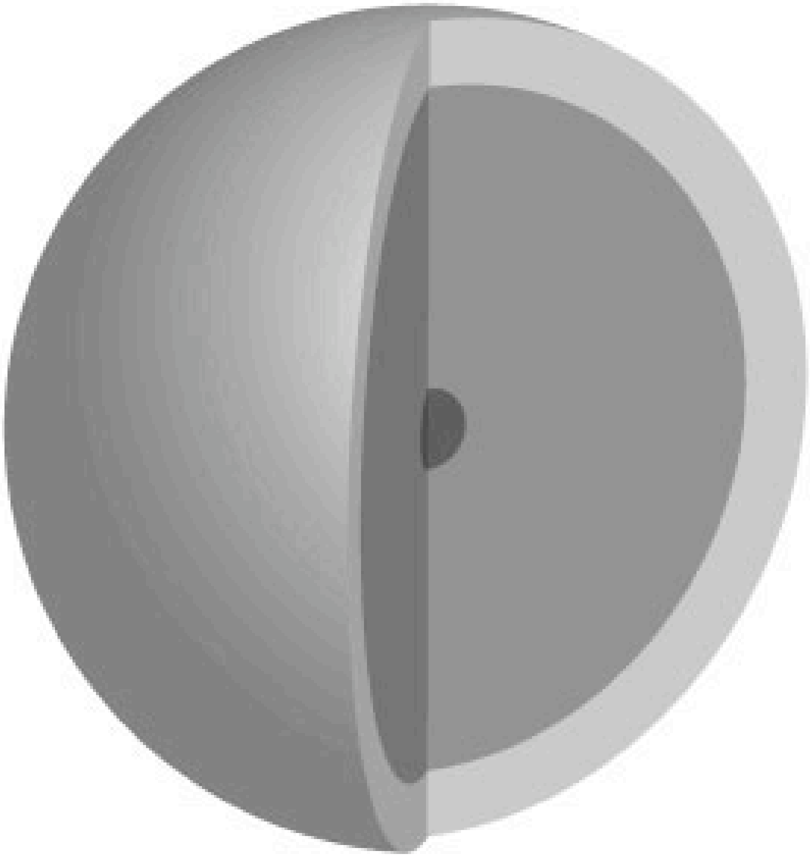
The diameter of the orbit is only six times the diameter of the star. The diameter of the star is 19.6 times the diameter of the planet.

Planet location
Sun. 5:00 am

HD 149026 b completes one orbit in 2.8763 days. If we start tracking the planet at Noon on Friday, we find that it has returned to its starting position by 9:01 am on Monday morning.



HD 149026 b



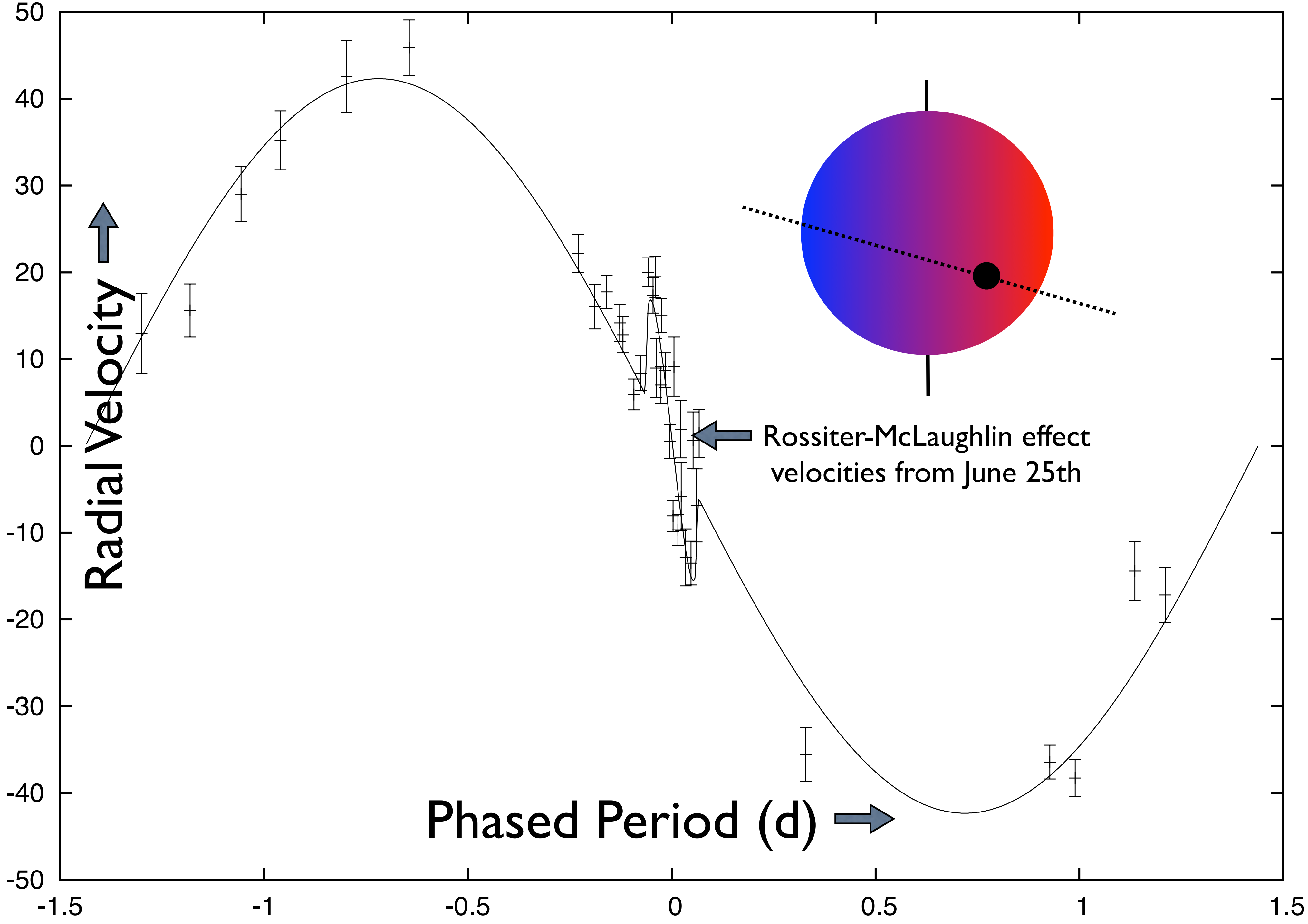
Jupiter

R/Rjup 10.5 gm/cc	R/Rjup 5.5 gm/cc	Mcore
0.594	0.662	89.3
0.681	0.745	74.5
0.769	0.818	60.0
0.866	0.905	43.6

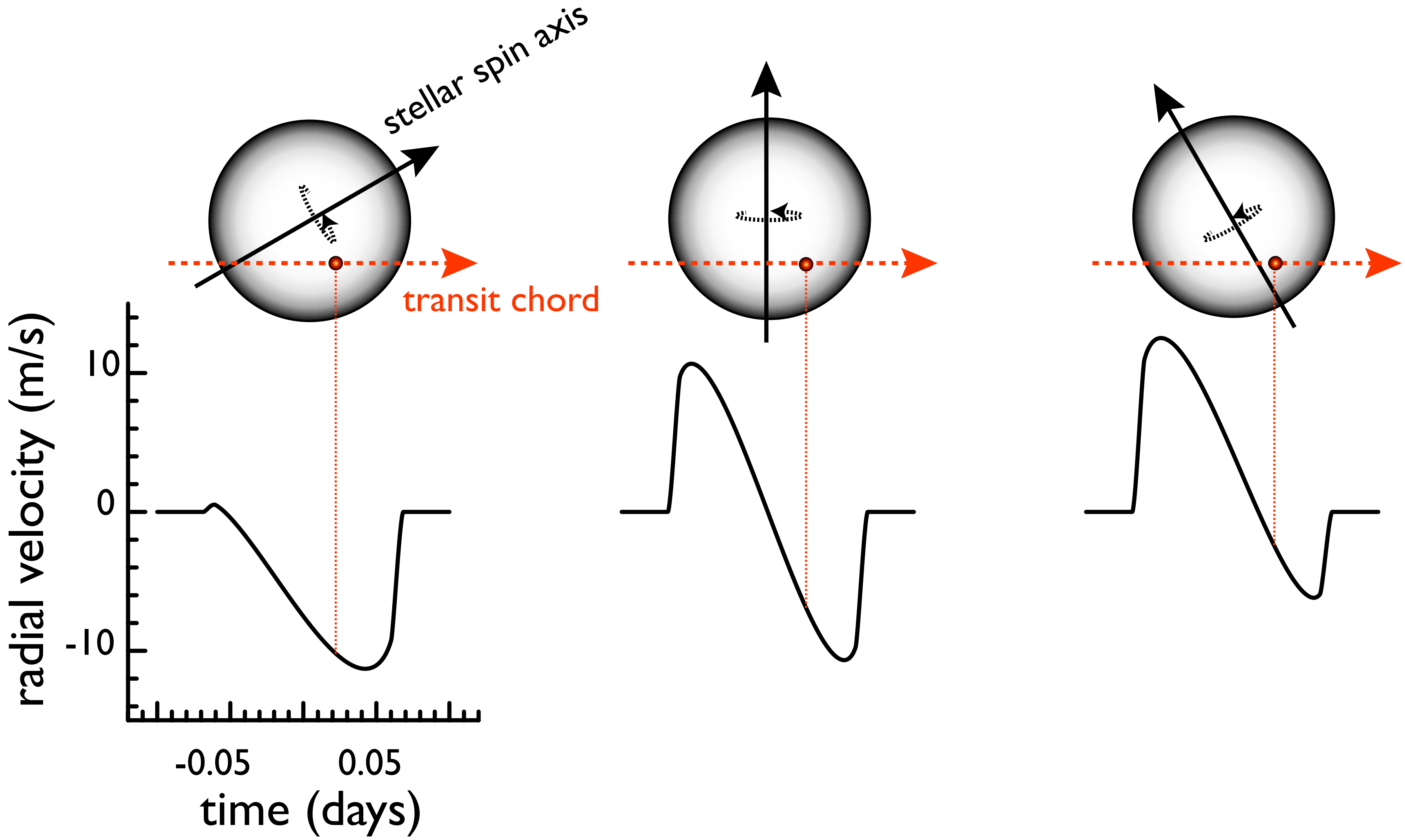
░ molecular hydrogen and helium

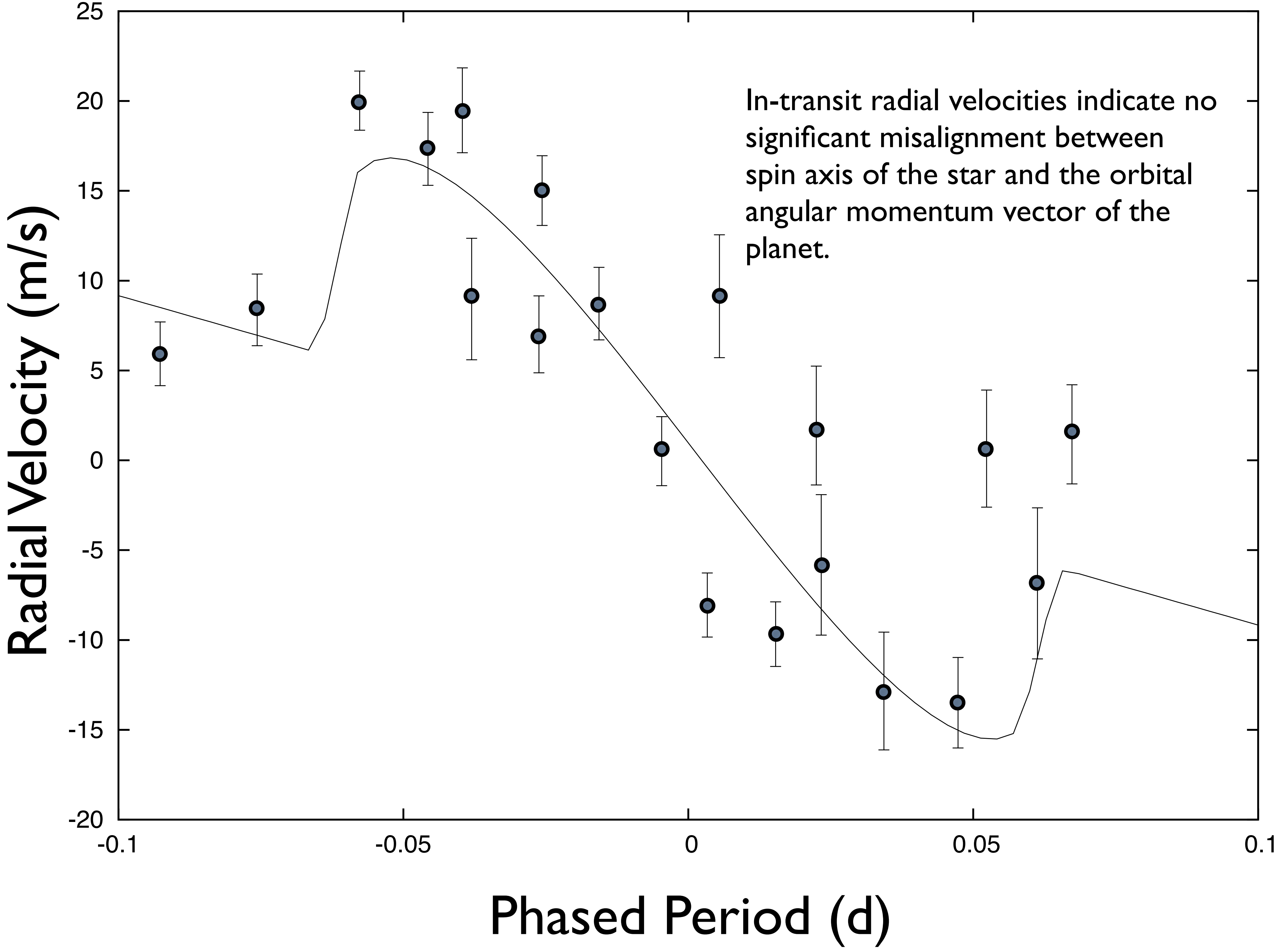
▒ liquid metallic hydrogen

▓ heavy element core

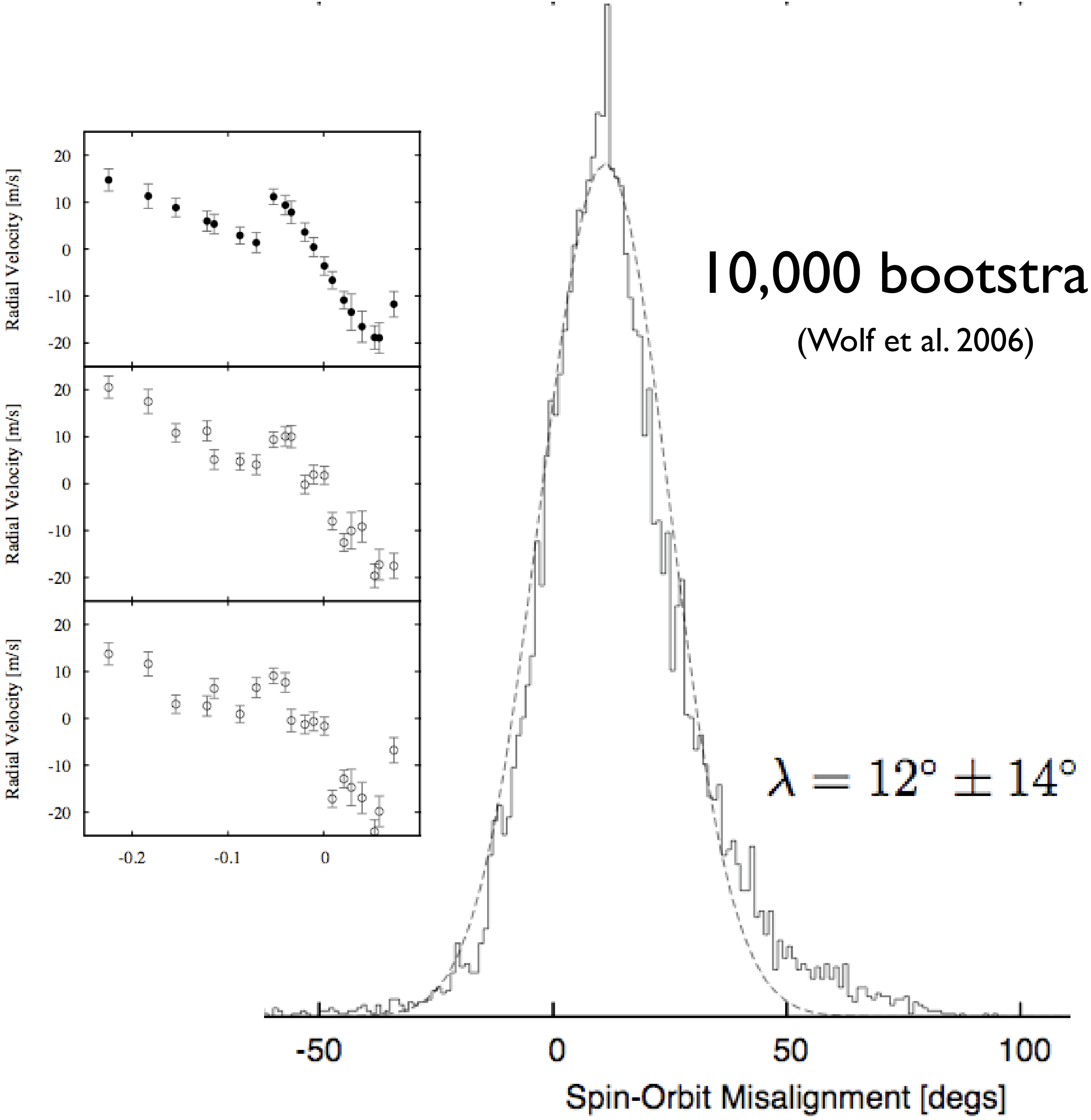


Rossiter-McLaughlin effect velocities from June 25th


stellar spin axis
transit chord
radial velocity (m/s)
10
0
-10
-0.05
0.05
time (days)



In-transit radial velocities indicate no significant misalignment between spin axis of the star and the orbital angular momentum vector of the planet.

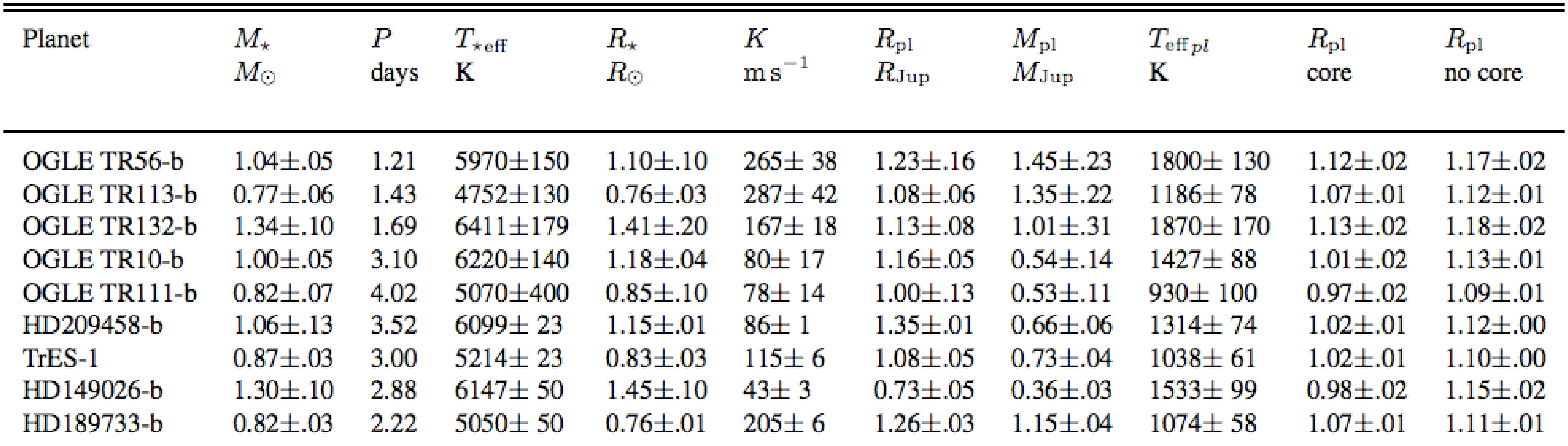


10,000 bootstrap trials

(Wolf et al. 2006)

$\lambda = 12^\circ \pm 14^\circ$

The Known Transiting Planets

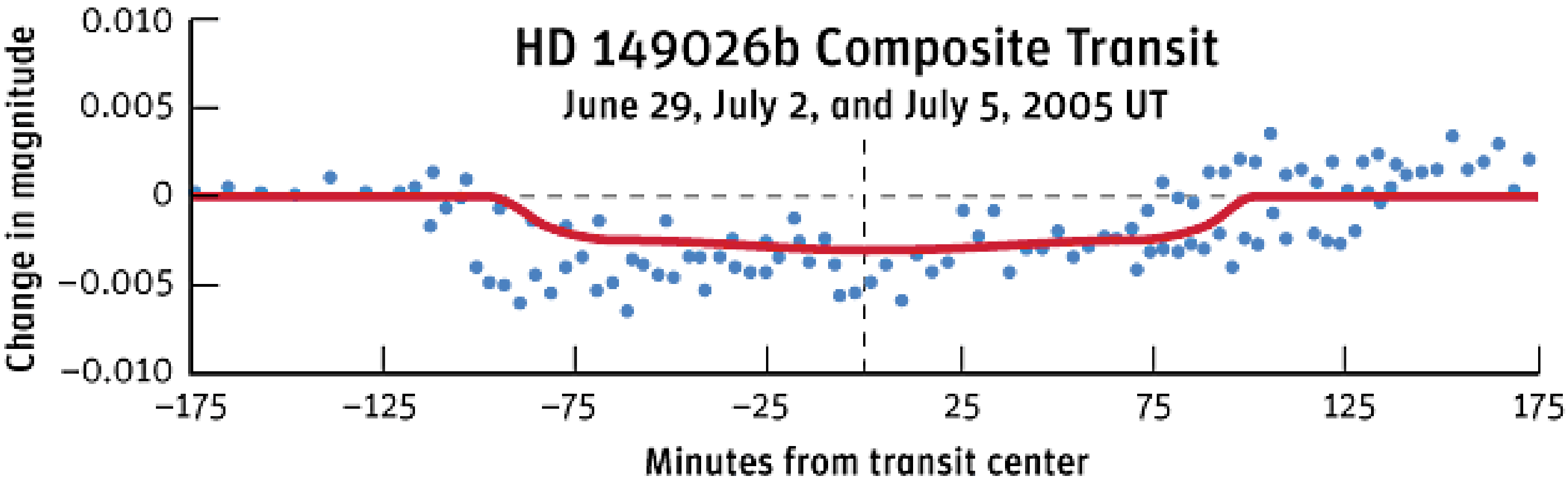


Planet	$M_\star$ $M_\odot$	P days	$T_{\star\,\rm eff}$ K	$R_\star$ $R_\odot$	K $\rm m\,s^{-1}$	$R_{\rm pl}$ $R_{\rm Jup}$	$M_{\rm pl}$ $M_{\rm Jup}$	$T_{{\rm eff}\,pl}$ K	$R_{\rm pl}$ core	$R_{\rm pl}$ no core
OGLE TR56-b	1.04±.05	1.21	5970±150	1.10±.10	265± 38	1.23±.16	1.45±.23	1800± 130	1.12±.02	1.17±.02
OGLE TR113-b	0.77±.06	1.43	4752±130	0.76±.03	287± 42	1.08±.06	1.35±.22	1186± 78	1.07±.01	1.12±.01
OGLE TR132-b	1.34±.10	1.69	6411±179	1.41±.20	167± 18	1.13±.08	1.01±.31	1870± 170	1.13±.02	1.18±.02
OGLE TR10-b	1.00±.05	3.10	6220±140	1.18±.04	80± 17	1.16±.05	0.54±.14	1427± 88	1.01±.02	1.13±.01
OGLE TR111-b	0.82±.07	4.02	5070±400	0.85±.10	78± 14	1.00±.13	0.53±.11	930± 100	0.97±.02	1.09±.01
HD209458-b	1.06±.13	3.52	6099± 23	1.15±.01	86± 1	1.35±.01	0.66±.06	1314± 74	1.02±.01	1.12±.00
TrES-1	0.87±.03	3.00	5214± 23	0.83±.03	115± 6	1.08±.05	0.73±.04	1038± 61	1.02±.01	1.10±.00
HD149026-b	1.30±.10	2.88	6147± 50	1.45±.10	43± 3	0.73±.05	0.36±.03	1533± 99	0.98±.02	1.15±.02
HD189733-b	0.82±.03	2.22	5050± 50	0.76±.01	205± 6	1.26±.03	1.15±.04	1074± 58	1.07±.01	1.11±.01

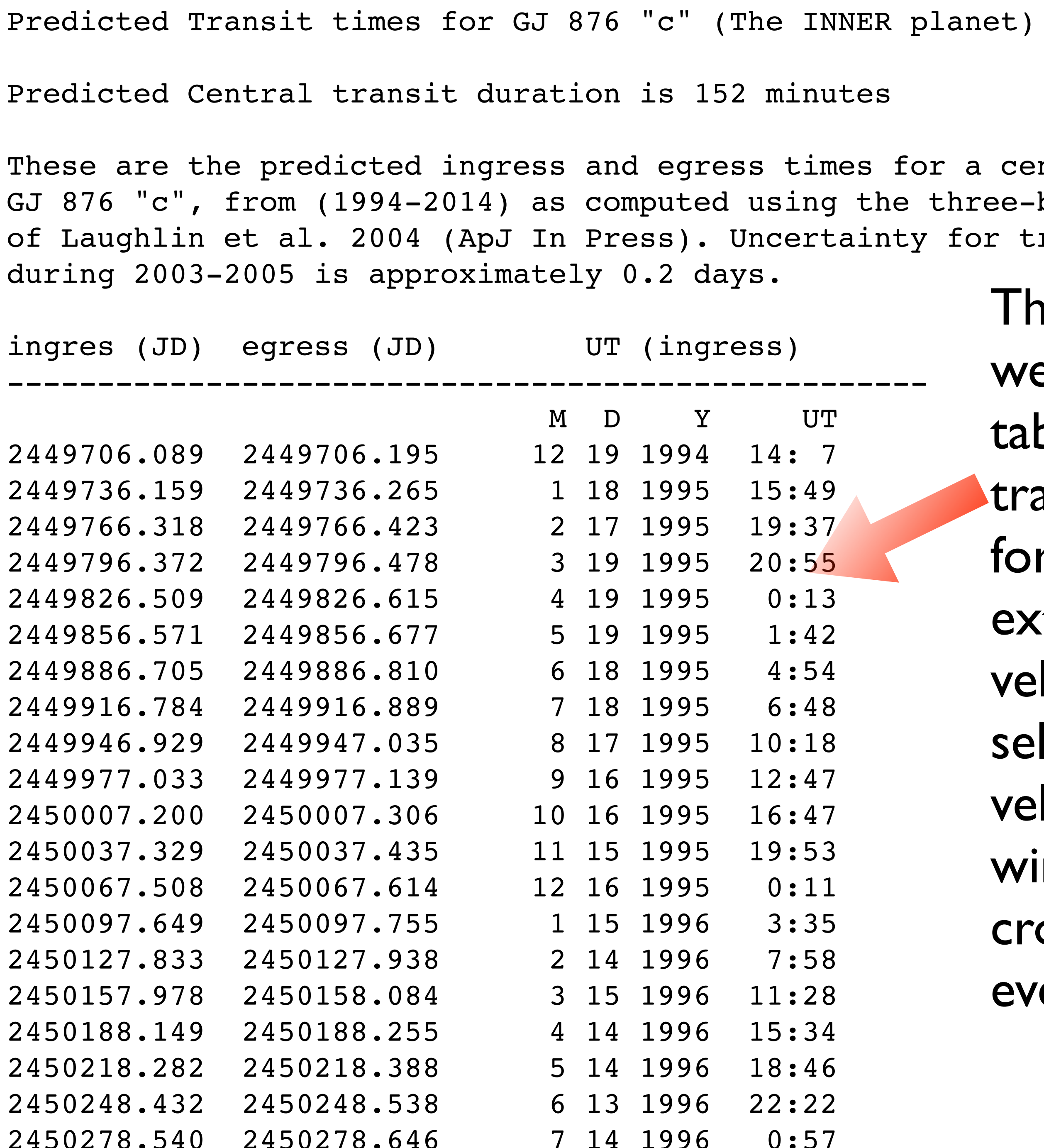
Model Predictions

HD 209458b and HD 189733b "too large"
HD 149026b "too small"

Amateur astronomer Ron Bissinger observed the transit from his backyard in Pleasanton as soon as the transit was announced



http://www.ucolick.org/%7elaugh/GJ876____c.transits.txt



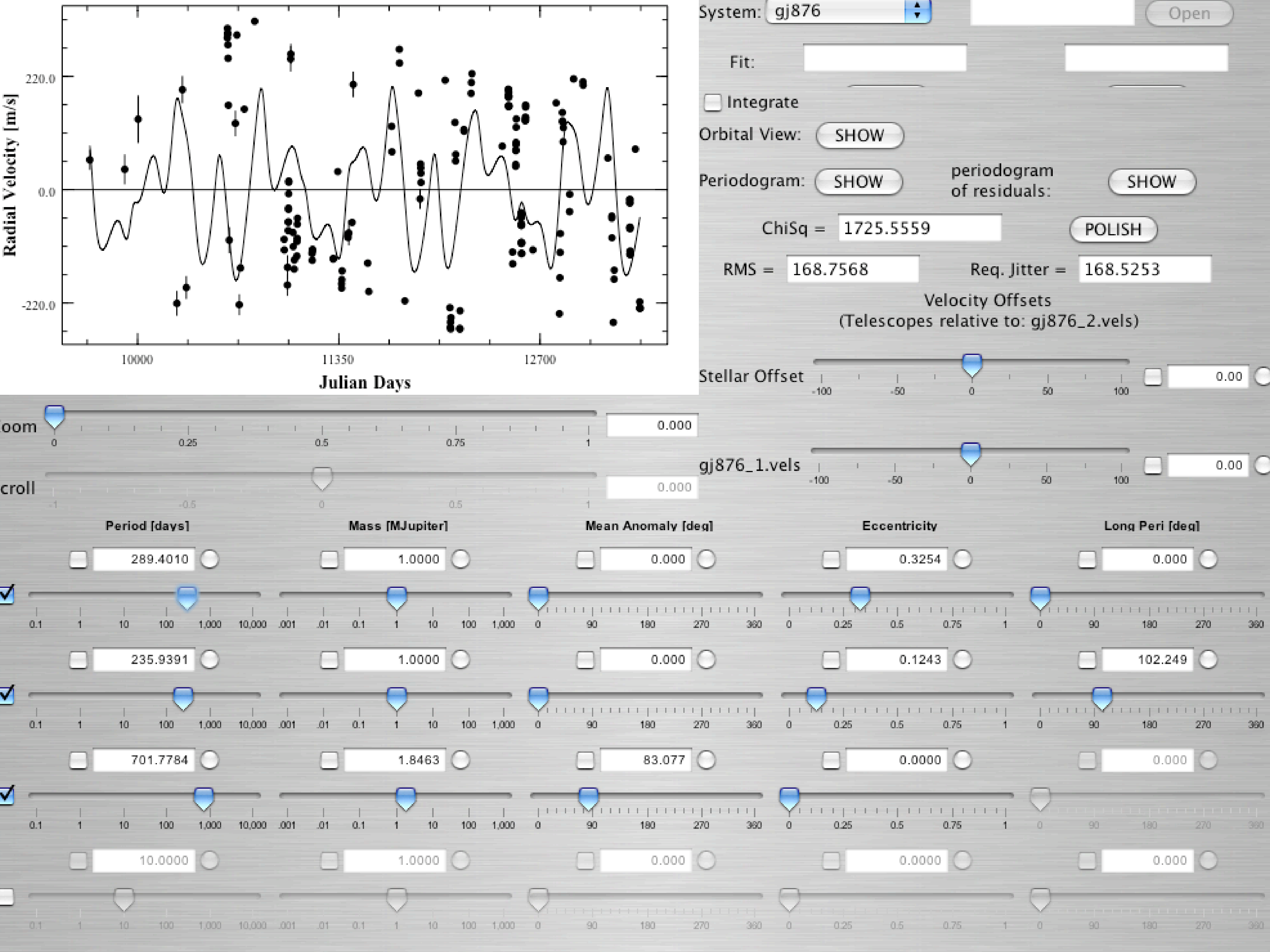
```
Predicted Transit times for GJ 876 "c" (The INNER planet)

Predicted Central transit duration is 152 minutes

These are the predicted ingress and egress times for a central transit of
GJ 876 "c", from (1994-2014) as computed using the three-body dynamical model
of Laughlin et al. 2004 (ApJ In Press). Uncertainty for transit opportunities
during 2003-2005 is approximately 0.2 days.

ingres (JD)  egress (JD)        UT (ingress)
---------------------------------------------------
                              M  D    Y      UT
2449706.089  2449706.195     12 19 1994   14: 7
2449736.159  2449736.265      1 18 1995   15:49
2449766.318  2449766.423      2 17 1995   19:37
2449796.372  2449796.478      3 19 1995   20:55
2449826.509  2449826.615      4 19 1995    0:13
2449856.571  2449856.677      5 19 1995    1:42
2449886.705  2449886.810      6 18 1995    4:54
2449916.784  2449916.889      7 18 1995    6:48
2449946.929  2449947.035      8 17 1995   10:18
2449977.033  2449977.139      9 16 1995   12:47
2450007.200  2450007.306     10 16 1995   16:47
2450037.329  2450037.435     11 15 1995   19:53
2450067.508  2450067.614     12 16 1995    0:11
2450097.649  2450097.755      1 15 1996    3:35
2450127.833  2450127.938      2 14 1996    7:58
2450157.978  2450158.084      3 15 1996   11:28
2450188.149  2450188.255      4 14 1996   15:34
2450218.282  2450218.388      5 14 1996   18:46
2450248.432  2450248.538      6 13 1996   22:22
2450278.540  2450278.646      7 14 1996    0:57
```

The www.transitsearch.org website provides ephemeris tables for the predicted transit times and uncertainties for all of the known extrasolar planets. As new velocities are published, new self-consistent (n-body) radial velocity fits and transit windows are computed. A cron job updates the table every night.



System: gj876

Fit:

☐ Integrate

Orbital View: SHOW

Periodogram: SHOW

periodogram of residuals: SHOW

ChiSq = 1725.5559

RMS = 168.7568

Req. Jitter = 168.5253

Velocity Offsets
(Telescopes relative to: gj876_2.vels)

Stellar Offset ☐ 0.00

gj876_1.vels ☐ 0.00

oom 0.000

croll 0.000

	Period [days]	Mass [MJupiter]	Mean Anomaly [deg]	Eccentricity	Long Peri [deg]
☑	☐ 289.4010	☐ 1.0000	☐ 0.000	☐ 0.3254	☐ 0.000
☑	☐ 235.9391	☐ 1.0000	☐ 0.000	☐ 0.1243	☐ 102.249
☑	☐ 701.7784	☐ 1.8463	☐ 83.077	☐ 0.0000	☐ 0.000
☐	☐ 10.0000	☐ 1.0000	☐ 0.000	☐ 0.0000	☐ 0.000

www.oklo.org