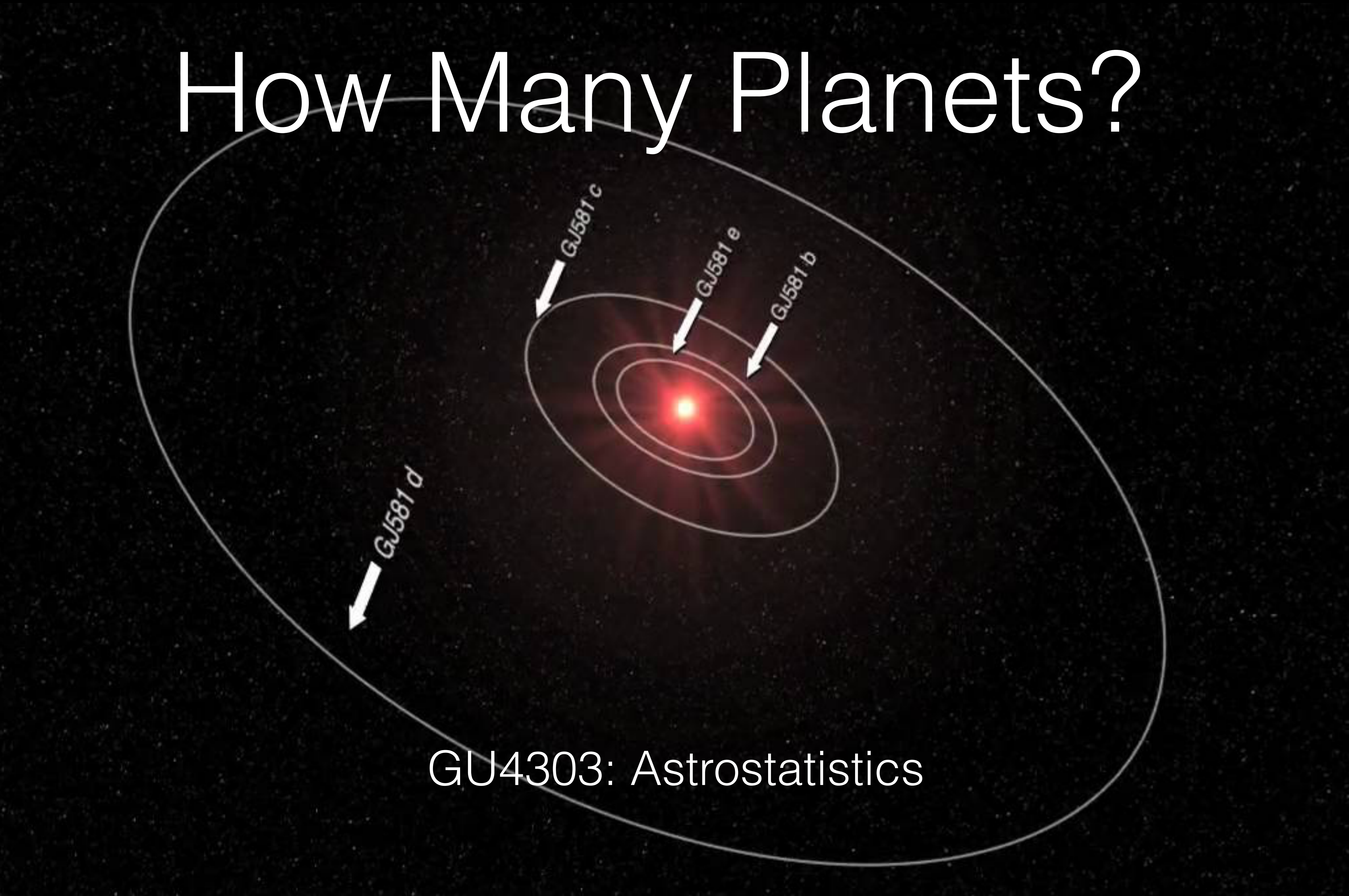
LAB 4
How Many Planets?

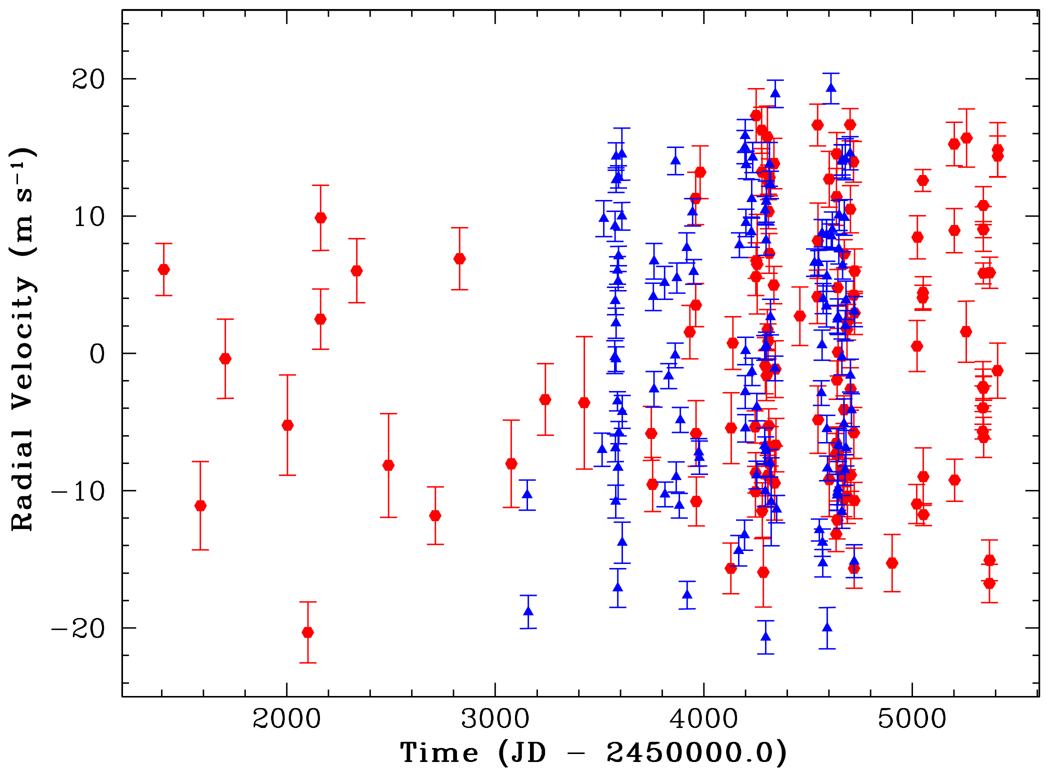


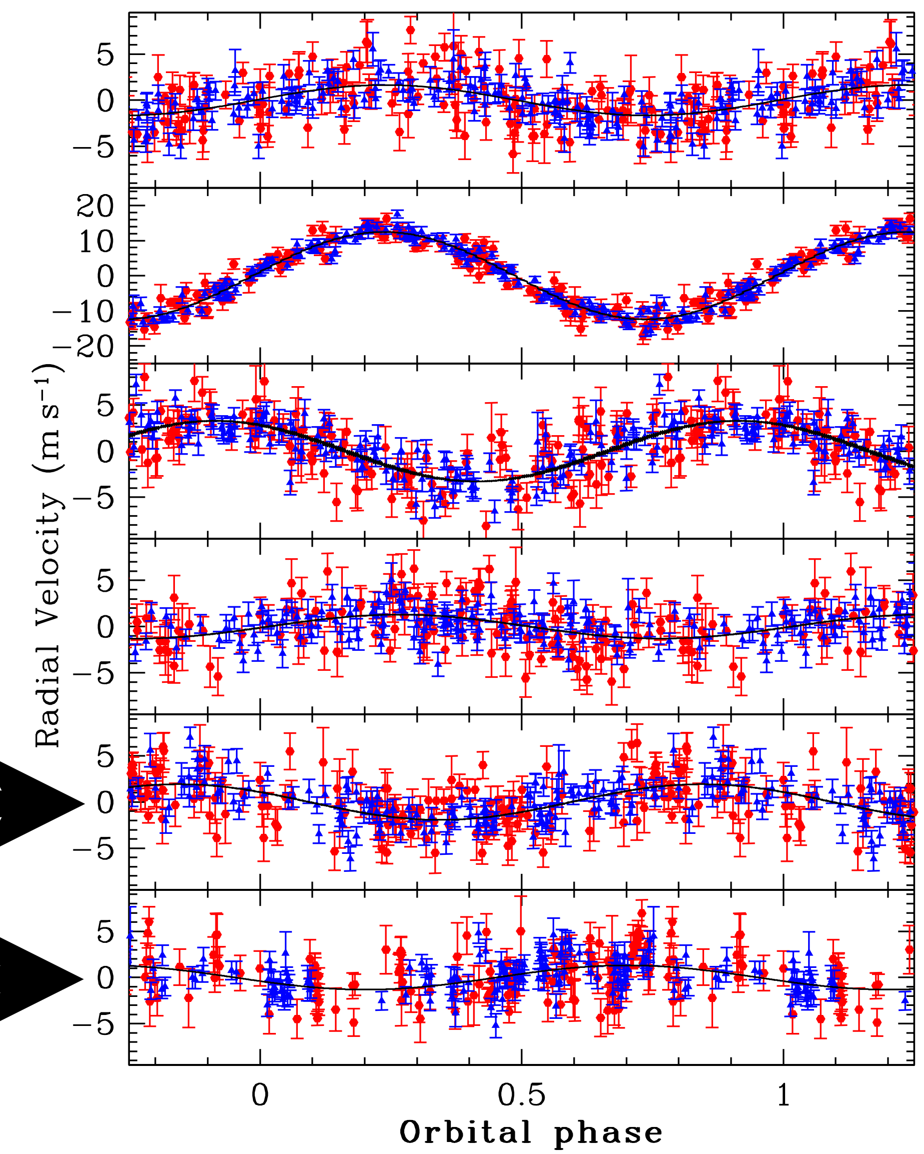
GU4303: Astrostatistics

THE ASTROPHYSICAL JOURNAL, 723:954–965, 2010 November 1 doi:10.1088/0004-637X/723/1/954

THE LICK–CARNEGIE EXOPLANET SURVEY: A 3.1 $M_\oplus$ PLANET IN THE HABITABLE ZONE OF THE NEARBY M3V STAR GLIESE 581

STEVEN S. VOGT[1], R. PAUL BUTLER[2], E. J. RIVERA[1], N. HAGHIGHIPOUR[3], GREGORY W. HENRY[4], AND MICHAEL H. WILLIAMSON[4]
[1] UCO/Lick Observatory, University of California, Santa Cruz, CA 95064, USA
[2] Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington, DC 20015-1305, USA
[3] Institute for Astronomy and NASA Astrobiology Institute, University of Hawaii-Manoa, Honolulu, HI 96822, USA
[4] Tennessee State University, Center of Excellence in Information Systems, 3500 John A. Merritt Blvd., Box 9501, Nashville, TN 37209-1561, USA
Received 2010 August 26; accepted 2010 September 15; published 2010 October 15





new

new

The sixth panel down in Figure 3 shows the periodogram of the residuals to the 5-planet fit. A lone dominant peak remains near 37 days. This peak shows the extreme narrowness expected of a truly coherent signal, that, if Keplerian and real, would have a strictly fixed period and phase for its 110 cycles spanning the past 11 years of the data set. A fit to this peak indicates a planet of minimum-mass 3.1 $M_\oplus$, on a 36.56-day orbit of size 0.146 AU. Our best 6-planet fit (again, assuming circular orbits) achieves a reduced chi-squared statistic (using 20 free parameters) of 2.506 and an rms of 2.12 m s^{-1}. The estimated FAP of the ∼37-day peak is 2.7×10^{-6}. Thus, this sixth planet also seems statistically well-justified by the present data set.

p-value

Telegraph.co.uk

Home | News | Sport | Finance | Lifestyle | Comment | Travel | Culture | Technology

UK | World | Politics | Celebrities | Obituaries | Weird | Earth | Science | Health News | Educat

Science News | Space | Roger Highfield | Dinosaurs | Evolution | Steve Jones | Science Pictu

HOME > SCIENCE > SPACE

Gliese 581g: the most Earth like planet yet discovered

A newly discovered planet may be the most Earth like yet and so most likely to be habitable, claim scientists.

By Richard Alleyne, Science Correspondent
Published: 10:00PM BST 29 Sep 2010

Comment

Email | Print

Space
News
UK News
Science

A team of planet hunters has announced the discovery of Gliese 581g, an Earth-sized planet orbiting a nearby star at a distance that places it squarely in the middle of the star's "habitable zone," where liquid water could exist on the planet's surface.

TIME

Found: An Earthlike Planet, at Last

By Michael D. Lemonick | Wednesday, Sept. 29, 2010

Like 6 | Tweet | G+1 4 | Share | Read Later

The star known as Gliese 581 is utterly unremarkable in just about every way you can imagine. It's a red dwarf, the most common type of star in the Milky Way, weighing in at about a third of the mass of the sun. At 20 light years or so away, it's relatively nearby, but not close enough to set any records (it's the 117th closest star to Earth, for what that's worth). You can't even see it without a telescope, so while it lies in the direction of Libra, it isn't one of the shining dots you'd connect to form the constellation. It's no wonder that the star's name lacks even a whiff of mystery or romance.

Lynette Cook

theguardian

New Earth-like planet discovered

Gliese 581g is in the 'Goldilocks zone' of its solar system, where liquid water could exist, and is a strong contender to be a habitable world

Artist's impression of the inner four planets of the Gliese 581 system and their host star, a red dwarf only 20 light years from Earth. Image: Lynette Cook/NSF/AP

Astronomers have discovered a potentially habitable planet of similar size to Earth in orbit around a nearby star.

...and he named the planet Zarmina's World, after his wife

news .com.au

"I called it 'Zarmina's world'," Professor Vogt said.

SPACE.com NEWS TECH SPACEFLIGHT SCIENCE & ASTRONOM

Space.com › Science & Astronomy

Odds of Life on Newfound Earth-Size Planet '100 Percent,' Astronomer Says

By Jeanna Bryner , LiveScience Managing Editor | September 29, 2010 05:03pm ET

"Personally, given the ubiquity and propensity of life to flourish wherever it can, I would say, my own personal feeling is that the chances of life on this planet are 100 percent," said Steven Vogt, a professor of astronomy and astrophysics at the University of California, Santa Cruz, during a press briefing today. "I have almost no doubt about it."

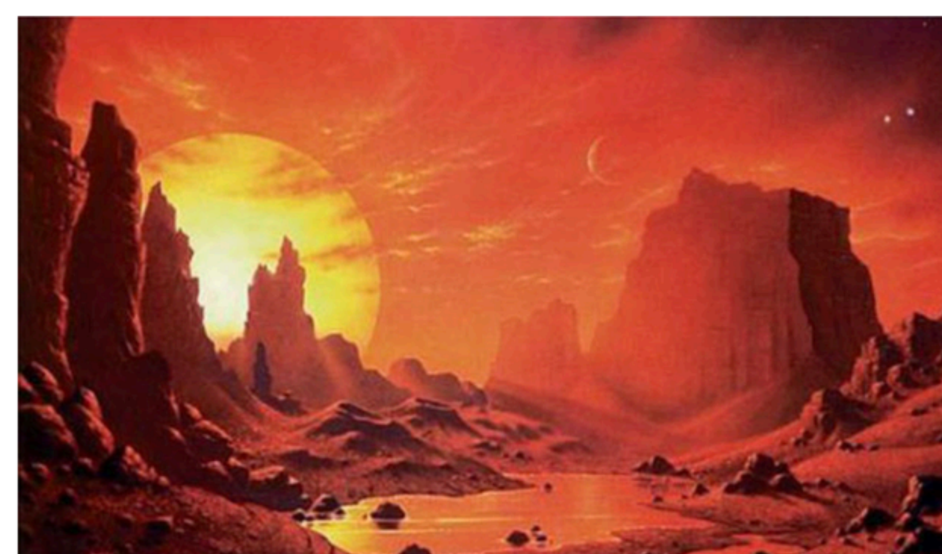
he really said that

...and started talking about the inhabitants and colonization...

The astrophysicist who discovered Zarmina describes life on "second Earth"

Annalee Newitz
10/01/10 4:36pm · Filed to: EXCLUSIVE INTERVIEW

102.3K



just two weeks later...

ORIGINS | DEEP SPACE | SOLAR SYSTEM | COMPARATIVE PLANETOLOGY | EXPLORATION | BLOGS | MULTIMEDIA

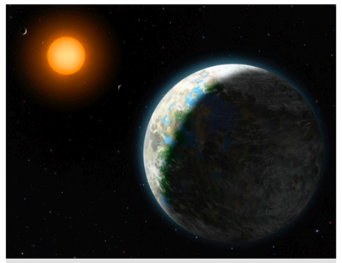
Home » Topic » Solar System » Meteorites,Comets and Asteroids » Doubt Cast on Existence of Habitable Alien World

DOUBT CAST ON EXISTENCE OF HABITABLE ALIEN WORLD

By Leslie Mullen - Oct 12, 2010

Last month, astronomers announced the discovery of the first potentially habitable extrasolar planet. But this week at an International Astronomical Union meeting, doubts were raised about the existence of this exciting new planet said to be orbiting the star Gliese 581.

Called 'Gliese 581 g,' the planet was determined to be about 3 times the mass of Earth, meaning it was a rocky world, not a gas giant like Jupiter. Rocky extrasolar planets have been found before, but the unique trait about this planet was that it orbited within the red dwarf star's habitable zone, that region of space where temperatures are sufficient for water to remain as a liquid on a planetary surface.



Gliese 581 g is thought to have three times the mass of Earth, and to orbit in the middle of its star's habitable zone, meaning liquid water could exist on the planet's surface.
Credit: *Lynette Cook*

Share this

Most Read in News

If We Had No Moon

things get worse for Gl 581g...

Bayesian Re-analysis of the Gliese 581 Exoplanet System

Philip C. Gregory[1*]
[1] *Physics and Astronomy Department, University of British Columbia, 6224 Agricultural Rd., Vancouver, BC V6T 1Z1, Canada*

Bayesian re-analysis of the radial velocities of Gliese 581

Evidence in favour of only four planetary companions

Mikko Tuomi[1,2*]

Stellar activity masquerading as planets in the habitable zone of the M dwarf Gliese 581

Paul Robertson,[1,2*] Suvrath Mahadevan,[1,2,3] Michael Endl,[4] Arpita Roy[1,2,3]

The M dwarf star Gliese 581 is believed to host four planets, including one (GJ 581d) near the habitable zone that could possibly support liquid water on its surface if it is a rocky planet. The detection of another habitable-zone planet—GJ 581g—is disputed, as its significance depends on the eccentricity assumed for d. Analyzing stellar activity using the Hα line, we measure a stellar rotation period of 130 ± 2 days and a correlation for Hα modulation with radial velocity. Correcting for activity greatly diminishes the signal of GJ 581d (to 1.5 standard deviations) while significantly boosting the signals of the other known super-Earth planets. GJ 581d does not exist, but is an artifact of stellar activity which, when incompletely corrected, causes the false detection of planet g.

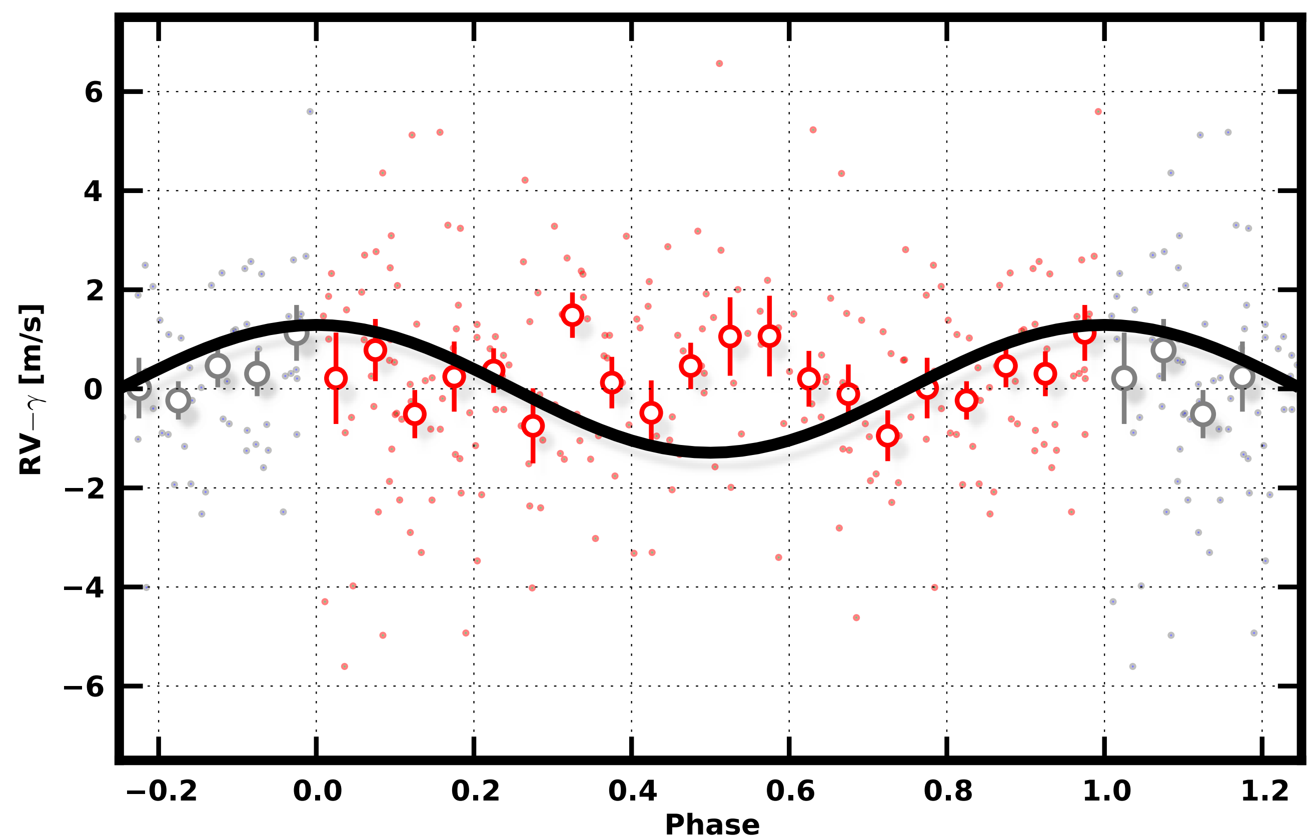
Astronomy & Astrophysics manuscript no. Gl581g
September 13, 2011

The HARPS search for southern extra-solar planets ⋆

XXXII. Only 4 planets in the Gl 581 system

T. Forveille[1,2], X. Bonfils[1], X. Delfosse[1], R. Alonso[3], S. Udry[3], F. Bouchy[4,5], M. Gillon[6], C. Lovis[3], V. Neves[1,7,8], M. Mayor[3], F. Pepe[3], D. Queloz[3], N.C. Santos[7,8], D. Ségransan[3], J.-M. Almenara[9,10,11], H.J. Deeg[10,11], and M. Rabus[10,11,12]

[1] UJF-Grenoble 1 / CNRS-INSU, Institut de Planètologie et dAstrophysique de Grenoble (IPAG) UMR 5274, Grenoble, F-38041, France
[2] Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu HI 96822 USA
[3] Observatoire de Genève, Université de Genève, 51 ch. des Maillettes, 1290 Sauverny, Switzerland
[4] Institut d'Astrophysique de Paris, CNRS, Université Pierre et Marie Curie, 98bis Bd Arago, F-75014 Paris, France
[5] Observatoire de Haute-Provence, CNRS/OAMP, F-04870 St Michel l'Observatoire, France
[6] Université de Liége, Allée du 6 Aout 17 Sart Tilman, Belgium
[7] Centro de Astrofísica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
[8] Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
[9] Laboratoire d'Astrophysique de Marseille, 38 rue Fréderic Joliot-Curie, F-13388 Marseille Cedex 13, France
[10] Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
[11] Dpto. de Astrofísica, Universidad de La Laguna, 38206 La Laguna, Tenerife, Spain
[12] Departamento de Astronomía y Astrofísica, Pontificia Universidad Católica de Chile, Casilla 306, Santiago 22, Chile



Another team use new data to show planet is disfavored

FAST COMPANY

10.20.10

Steven Vogt Stands by Claim of Planet in Habitable Zone of Gliese 581

After Steven Vogt and his team announced the discovery of a planet in the habitable zone of Gliese 581 in late September 2010, other astronomers failed to confirm the discovery. Yet, as Dr. Vogt told EarthSky, the failure to confirm does not mean the planet is not there.

SPACE.com

News Tech Spaceflight Science & Astronomy Search

TRENDING Full Moons 2019 On This Day in Space! Forums!

Home > News > Search For Lifes

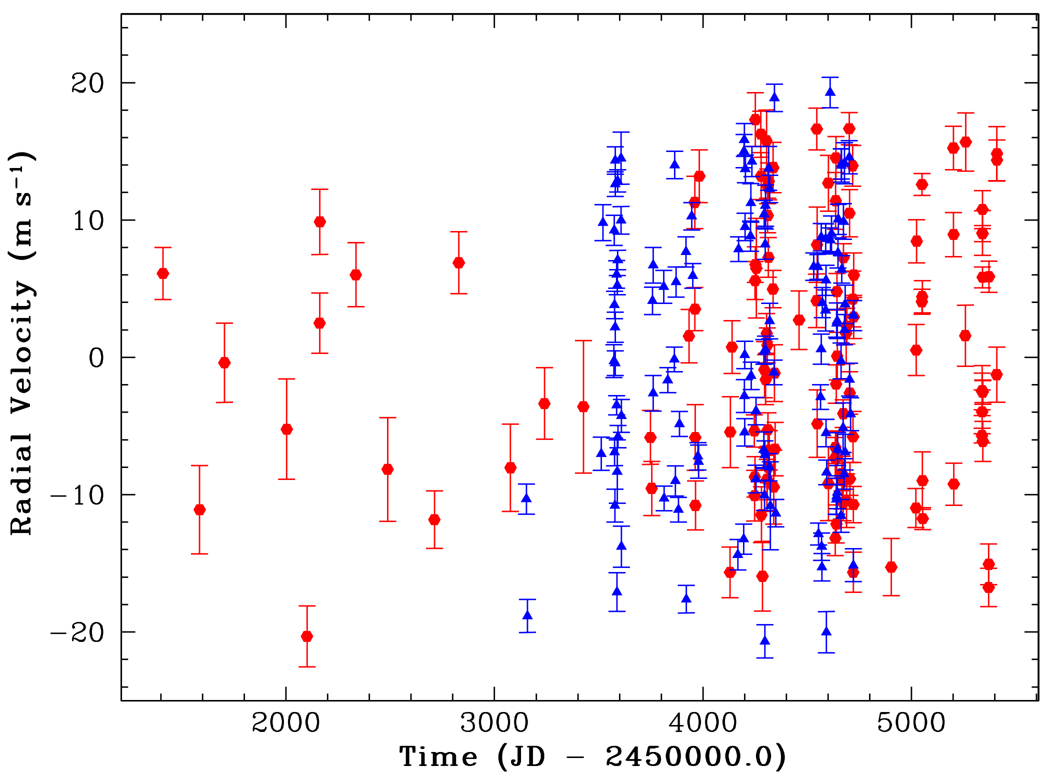
R.I.P. Possibly Habitable Planet Gliese 581g? Not So Fast, Co-Discoverer Says

By Mike Wall February 19, 2011 Search For Life

follow-up data killed Gl 581g, but was it even really necessary?

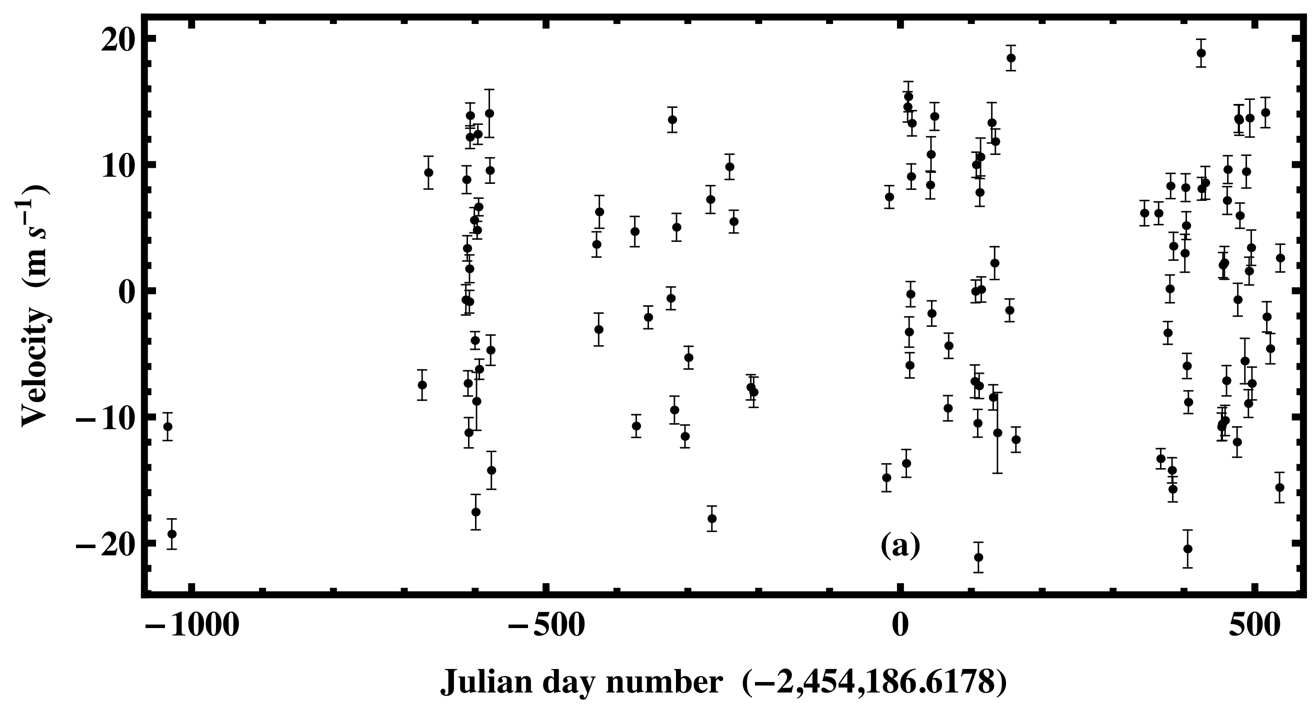
you are going to repeat the model selection on the original data!

"discovery" data



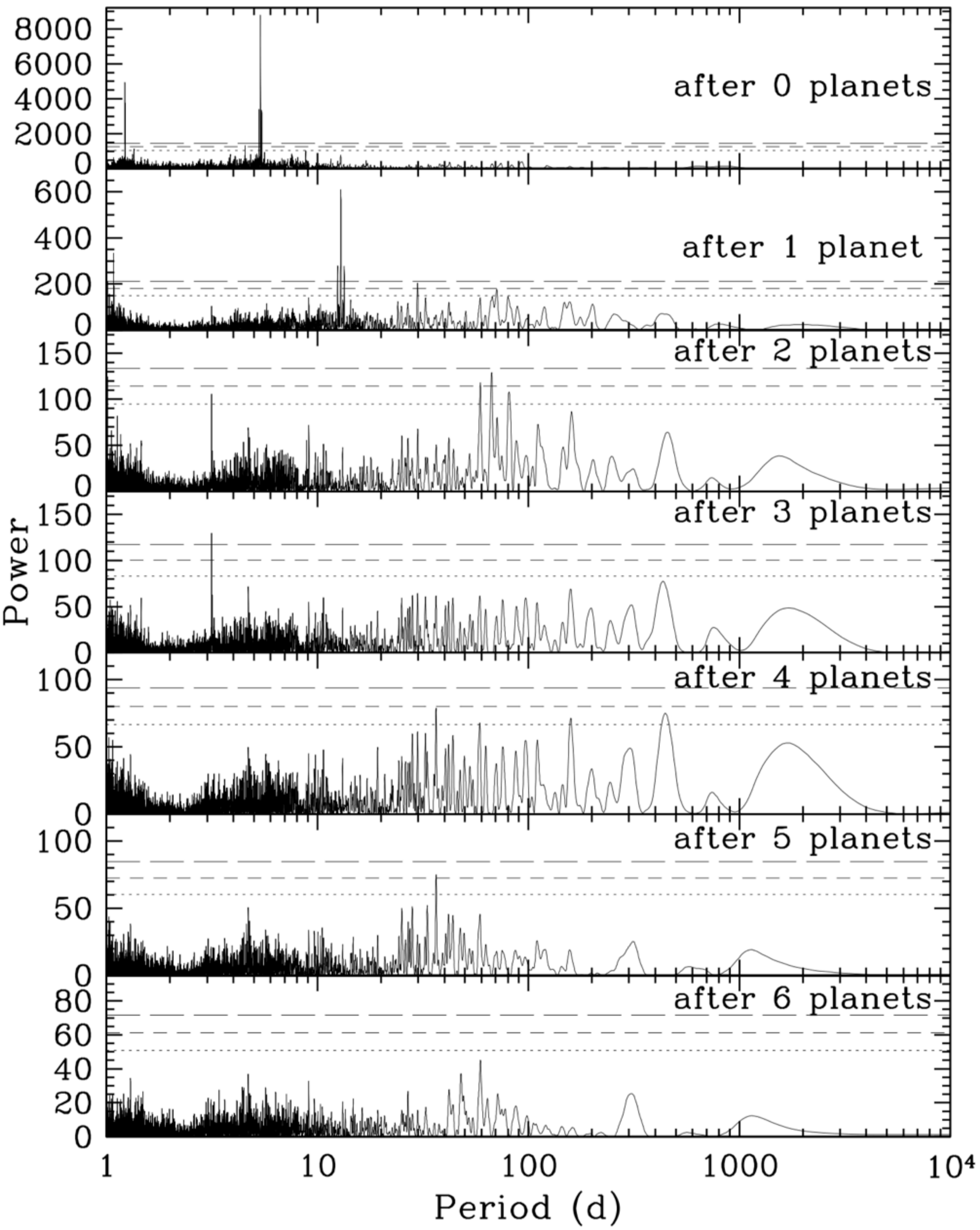
122 HIRES points
119 HARPs points
= 241 data points

refuting data



+ 121 new HARPs points
= 362 data points

Vogt et al. made several statistical errors in their analysis...



1. assumed perfect residuals

- after removing a component, the residuals were re-fitted using a periodogram which does least-squares

- least-squares assumes measurements are independent, uncorrelated and normally distributed

- since the fit to the removed component itself has uncertainty, the residuals will not be distributed so!

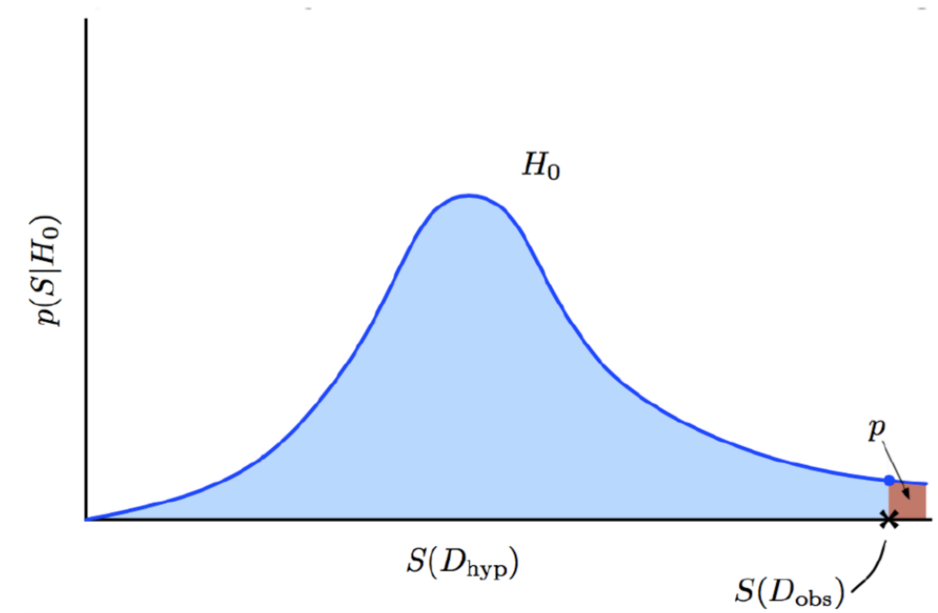
- essentially Vogt et al. assumed they could perfectly remove each component, which is not possible

Vogt et al. made several statistical errors in their analysis...

2. Detection rested upon a p-value

and an rms of 2.12 m s^{-1}. The estimated FAP of the ~37-day peak is 2.7×10^{-6}. Thus, this sixth planet also seems statistically well-justified by the present data set.

2.7e-6 => 4.7-sigma



No! ***p*** is not a property of **this** signal; rather it's the size of the ensemble of possible null-generated signals with $S > S_{obs}$

Alternatives to the null will/must sometimes act and the real FAP will depend on how often they do!

Vogt et al. made several statistical errors in their analysis...

3. reduced χ^2 ill-defined for non-linear models

$$p_0 = \frac{(N-2)}{2} \frac{\left(\chi^2_{\text{constant}} - \chi^2_{\text{circ}}\right)}{\chi^2_{\text{circ}}}, \qquad (2)$$

where χ^2_{circ} is the reduced chi-squared for a circular fit at/near the period implied by the peak and χ^2_{constant} is the reduced chi-squared for a constant RV model of the data or residuals.

reduced chi squared

only for linear model comparison & normal residuals!

$$\boxed{\chi^2 = \sum_{i=1}^{n} \left(\frac{r_i}{\sigma_i}\right)^2}$$

max likelihood

# of data points

# of parameters

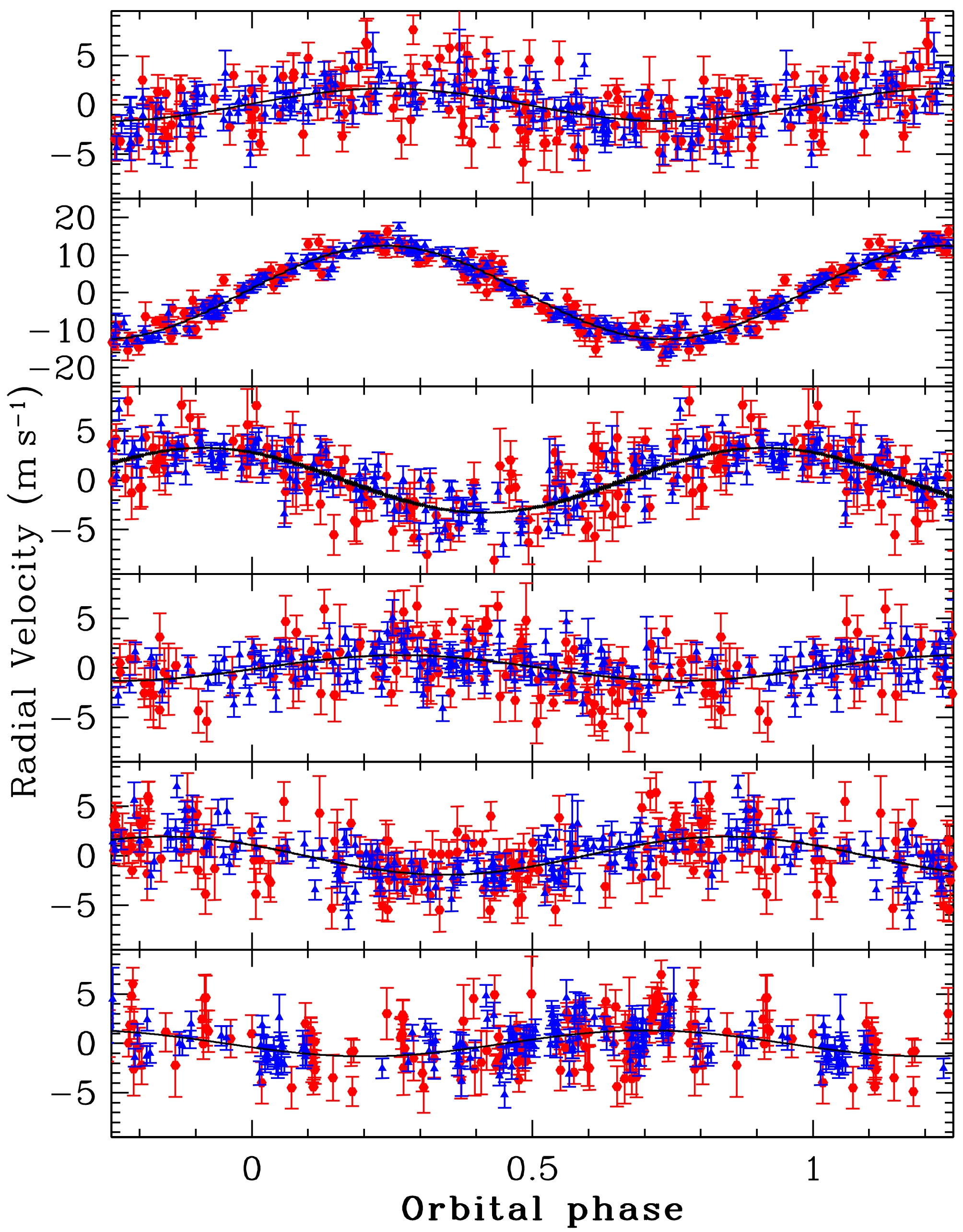
$$\chi^2_{red} = \chi^2/(n-k)$$

small χ^2_{red} is better, so prefers small k

- generally, k is unknown for non-linear models
- <1 implies overfitting
- >1 implies underfitting
- not Bayesian, doesn't consider priors

(F R O M S E M 9)

Vogt et al. made several statistical errors in their analysis...



(4. circular orbit assumed for each planet)

Figure 3 shows the power spectra of the residuals of the RV data from the best Keplerian fits for models with n planets (with n ranging from 0 to 6). The eccentricities are held fixed at 0 throughout the fitting process. The dominant spike in the top panel is at 5.368 days and is the well-known hot Neptune (GJ 581b) first reported by Bonfils05. The power implies a minimum-mass $m \sin i = 15.6\,M_{\oplus}$ companion in a 0.041 AU orbit. The reduced chi-squared statistic (using five free parameters) for this 1-planet fit is 8.426, with an rms of 3.65 m s^{-1}. The estimated FAP is 6.8×10^{-306}, in keeping with the extremely strong detection.

model selection

Nevertheless, Vogt et al. have proposed the discovery of two new planets: so four new hypotheses to consider...

M_0: Only planets {b,c,d,e} present (previously confirmed)

M_f: {b,c,d,e} + f present

M_g: {b,c,d,e} + g present

M_{fg}: {b,c,d,e} + f & g present

Planet	Period (days)	K ($\mathrm{m\,s^{-1}}$)
b	5.36841 (0.00026)	12.45 (0.21)
c	12.9191 (0.0058)	3.30 (0.19)
d	66.87 (0.13)	1.91 (0.22)
e	3.14867 (0.00039)	1.66 (0.19)
f	433 (13)	1.30 (0.22)
g	36.562 (0.052)	1.29 (0.19)

YOUR TASK: Use the original Vogt et al. data to compare these four hypotheses

1] I will provide you a notebook to fit model M_0, which returns a log-likelihood and χ^2. Test it out.

2] For model M_0 , try calculating several of the model comparison metrics of discussed in class, even if unsuitable (e.g. reduced χ^2, BIC) **and** do at least one cross-validation technique

3] Repeat for the different models (if you have time, try exploring the different models for the previously confirmed planets too and seeing if your model selection agrees i.e. 1,2,3 planet fits)

4] Summarize your results with a table or figure. Vogt thinks there is 4.7-sigma confidence in **planet g**, what do you think?

5] Write up your slides!

two weeks deadline!

jupyter fit Last Checkpoint: 08/17/2016 (autosaved)

Logout

File Edit View Insert Cell Kernel Widgets Help

Not Trusted Python 3

Run Code

In [2]:

```
import numpy as np
import matplotlib.pyplot as plt
from scipy.optimize import curve_fit

# Get the data
data1 = np.loadtxt("HARPS.dat")
data2 = np.loadtxt("HIRES.dat")
data = np.vstack((data1,data2))
print len(data1),' HARPS points; ',len(data2),' HIRES points'

# Add on jitter (additional noise term)
jitter = 1.2
for i in range(len(data)):
    data[i,2] = np.sqrt( data[i,2]**2 + jitter**2 )

# Initial information from Vogt et al. (2010)
Pb_sol = 5.36841; Pb_del = 0.00026; Kb_sol = 12.45
Pc_sol = 12.9191; Pc_del = 0.0058;  Kc_sol = 3.30
Pd_sol = 66.87;    Pd_del = 0.13;     Kd_sol = 1.91
Pe_sol = 3.14867; Pe_del = 0.00039; Ke_sol = 1.66
Pf_sol = 433.0;    Pf_del = 13.0;     Kf_sol = 1.30
Pg_sol = 36.562;  Pg_del = 0.052;   Kg_sol = 1.29
```

```
119  HARPS points;  122  HIRES points
```

In [5]:
```
# A full fit is tricky because it's not obvious where to initalize the phases (q) from
# So let's run a pre-fit first, where we only allow the phases to vary
# Trying running this a few times and make sure the same solution is coming out

# Define model M0 fix = 4-planet model using K & P parameters fixed to the Vogt+ reported values
def M0fix(t, qb, qc, qd, qe):
    return Kb_sol*np.sin(2.0*np.pi*t/Pb_sol+qb) \
           + Kc_sol*np.sin(2.0*np.pi*t/Pc_sol+qc) \
           + Kd_sol*np.sin(2.0*np.pi*t/Pd_sol+qd) \
           + Ke_sol*np.sin(2.0*np.pi*t/Pe_sol+qe)

# Define our parameters bounds
param_bounds = ( [-2.0*np.pi, \
                  -2.0*np.pi, \
                  -2.0*np.pi, \
                  -2.0*np.pi],\
                 [2.0*np.pi, \
                  2.0*np.pi, \
                  2.0*np.pi, \
                  2.0*np.pi] )

# Give an intial guess to help the fitting routine
initial_guess = [ np.random.uniform(-np.pi,np.pi),\
                  np.random.uniform(-np.pi,np.pi),\
                  np.random.uniform(-np.pi,np.pi),\
                  np.random.uniform(-np.pi,np.pi)]

# Get the best fitting parameters
M0fix_best, M0fix_cov = curve_fit(M0fix,data[:,0],data[:,1],sigma=data[:,2],p0=initial_guess,bounds=param_bounds)

# Get the chi2
chi2 = 0.0
for i in range(len(data)):
    chi2 = chi2 + ( ( data[i,1] - M0fix( data[i,0],\
                                         M0fix_best[0],\
                                         M0fix_best[1],\
                                         M0fix_best[2],\
                                         M0fix_best[3]) ) / data[i,2])**2

# Print output
print chi2,len(data)
```

```
395.796125728 241
```

In [42]:
```
# OK, I'm satisfied the above chi2 looks reasonable, so set the phase solutions as initial guesses
qb_sol = M0fix_best[0]
qc_sol = M0fix_best[1]
qd_sol = M0fix_best[2]
qe_sol = M0fix_best[3]
```

In [45]:
```
# Now we're ready to run the full 4-planet fit

# Define model M0 = 4-planet model
def M0(t, Kb, Pb, qb, Kc, Pc, qc, Kd, Pd, qd, Ke, Pe, qe):
    return Kb*np.sin(2.0*np.pi*t/Pb+qb) \
           + Kc*np.sin(2.0*np.pi*t/Pc+qc) \
           + Kd*np.sin(2.0*np.pi*t/Pd+qd) \
           + Ke*np.sin(2.0*np.pi*t/Pe+qe)

# Define our parameters bounds
param_bounds = ( [0.0,  Pb_sol-3.0*Pb_del, -2.0*np.pi, \
                  0.0,  Pc_sol-3.0*Pc_del, -2.0*np.pi, \
                  0.0,  Pd_sol-3.0*Pd_del, -2.0*np.pi, \
                  0.0,  Pe_sol-3.0*Pe_del, -2.0*np.pi],\
                 [20.0, Pb_sol+3.0*Pb_del,  2.0*np.pi, \
                  20.0, Pc_sol+3.0*Pc_del,  2.0*np.pi, \
                  20.0, Pd_sol+3.0*Pd_del,  2.0*np.pi, \
                  20.0, Pe_sol+3.0*Pe_del,  2.0*np.pi] )

# Give an intial guess to help the fitting routine
initial_guess = [ Kb_sol, Pb_sol, qb_sol,\
                  Kc_sol, Pc_sol, qc_sol,\
                  Kd_sol, Pd_sol, qd_sol,\
                  Ke_sol, Pe_sol, qe_sol]

# Get the best fitting parameters
M0_best, M0_cov = curve_fit(M0,data[:,0],data[:,1],sigma=data[:,2],p0=initial_guess,bounds=param_bounds)

# Get the chi2
chi2 = 0.0
for i in range(len(data)):
    chi2 = chi2 + ( ( data[i,1] - M0( data[i,0],\
                                      M0_best[0],M0_best[1],M0_best[2],\
                                      M0_best[3],M0_best[4],M0_best[5],\
                                      M0_best[6],M0_best[7],M0_best[8],\
                                      M0_best[9],M0_best[10],M0_best[11]) ) / data[i,2])**2
# Get the loglike
loglike = -0.5*len(data)*np.log(2.0*np.pi) - np.sum( np.log(data[:,2]) ) - 0.5*chi2

# Print output
print chi2,loglike
```

```
390.394636635 -567.779618203
```

The Astrophysical Journal, 709:168–178, 2010 January 20
doi:10.1088/0004-637X/709/1/168

HOW ECCENTRIC ORBITAL SOLUTIONS CAN HIDE PLANETARY SYSTEMS IN 2:1 RESONANT ORBITS

Guillem Anglada-Escudé, Mercedes López-Morales[1], and John E. Chambers
Carnegie Institution of Washington, Department of Terrestrial Magnetism, 5241 Broad Branch Rd. NW, Washington, DC 20015, USA;
anglada@dtm.ciw.edu, mercedes@dtm.ciw.edu, chambers@dtm.ciw.edu
Received 2008 September 8; accepted 2009 November 30; published 2009 December 29

ABSTRACT

The Doppler technique measures the reflex radial motion of a star induced by the presence of companions and is the most successful method to detect exoplanets. If several planets are present, their signals will appear combined in the radial motion of the star, leading to potential misinterpretations of the data. Specifically, two planets in 2:1 resonant orbits can mimic the signal of a single planet in an eccentric orbit. We quantify the implications of this statistical degeneracy for a representative sample of the reported single exoplanets with available data sets, finding that (1) around 35% of the published eccentric one-planet solutions are statistically indistinguishable from planetary systems in 2:1 orbital resonance, (2) another 40% cannot be statistically distinguished from a circular orbital solution, and (3) planets with masses comparable to Earth could be hidden in known orbital solutions of eccentric super-Earths and Neptune mass planets.

+10% project bonus: Try to implement eccentric solution!

In the case of a single eccentric planet, the reflex radial velocity motion of the star is

$$\begin{aligned} v_r^e = v_{r0} &+ K\cos\left[W(t-\tau_0)\right] \\ &+ Ke\cos\left[2W(t-\tau_0)-\omega\right] \\ &+ O(Ke^2)\,, \end{aligned} \tag{1}$$

unique amplitude

half-periodicity

unique phase

where v_{r0} is the linear radial velocity of the barycenter of the system, K is the semi-amplitude of the radial velocity variations induced by the planet on the star, ω is the argument of the periastron (angle between the periastron of the orbit and the ascending node), τ_0 is the time of crossing of the ascending node, and $W = 2\pi/P$ is the orbital frequency, where P is the orbital period (see Figure 1(a)). The term proportional to Ke is called the first eccentric harmonic, while the term $O(Ke^2)$ contains all the higher order contributions.