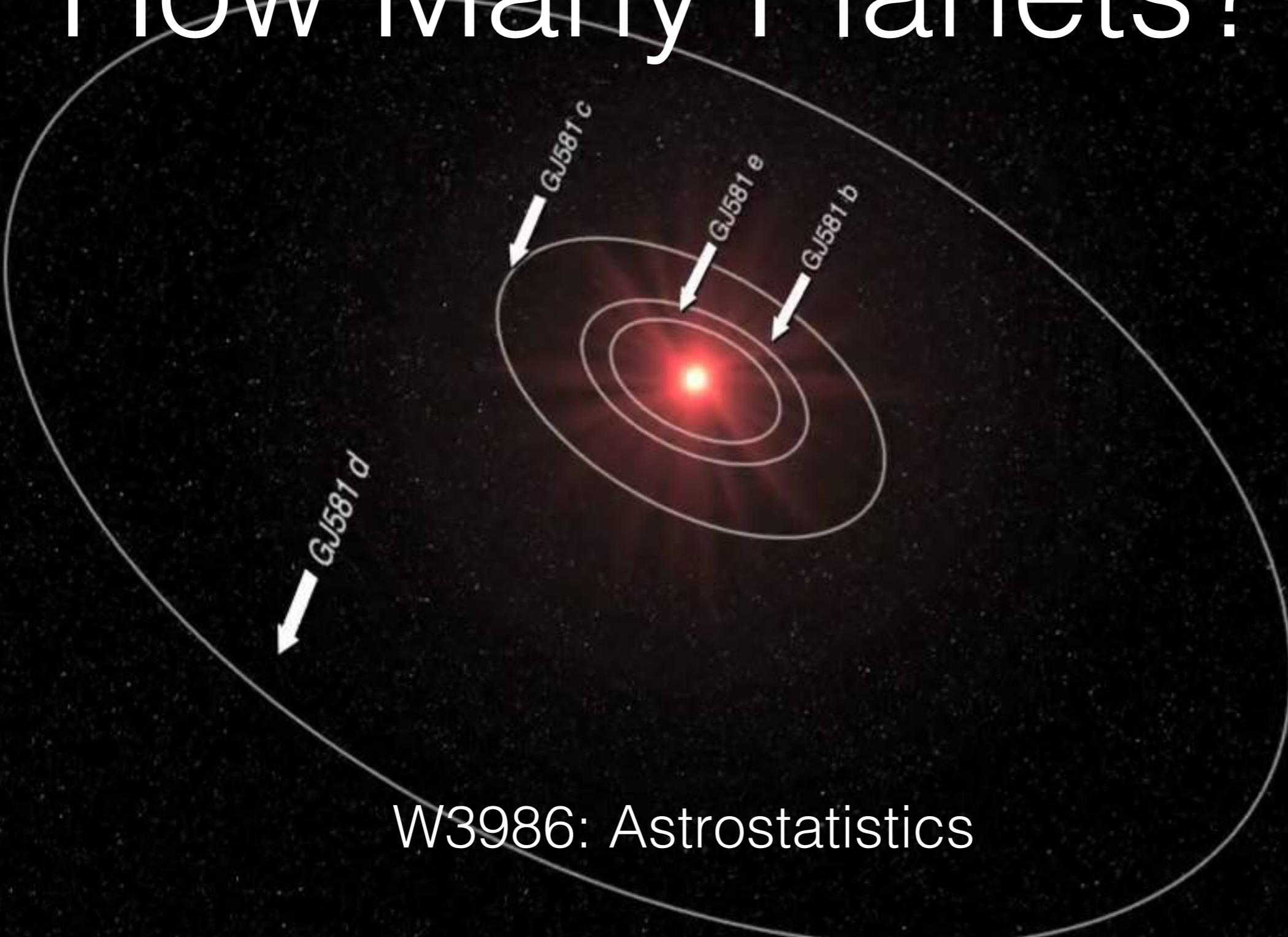


LAB 4

How Many Planets?



W3986: Astrostatistics

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

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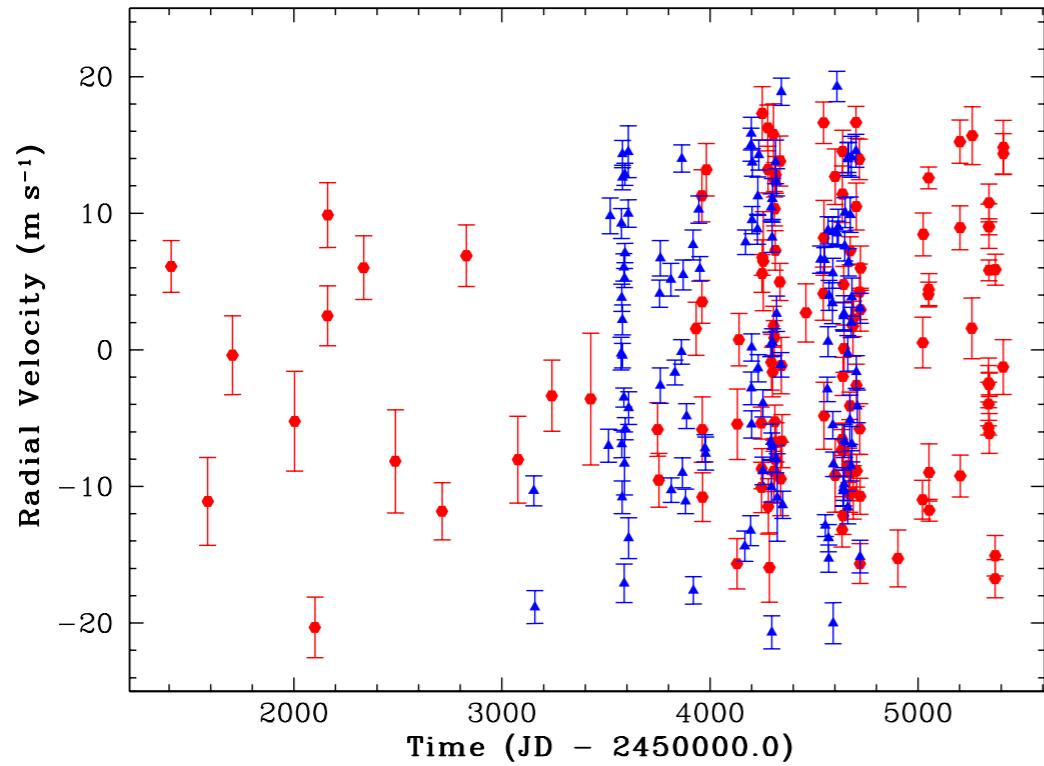
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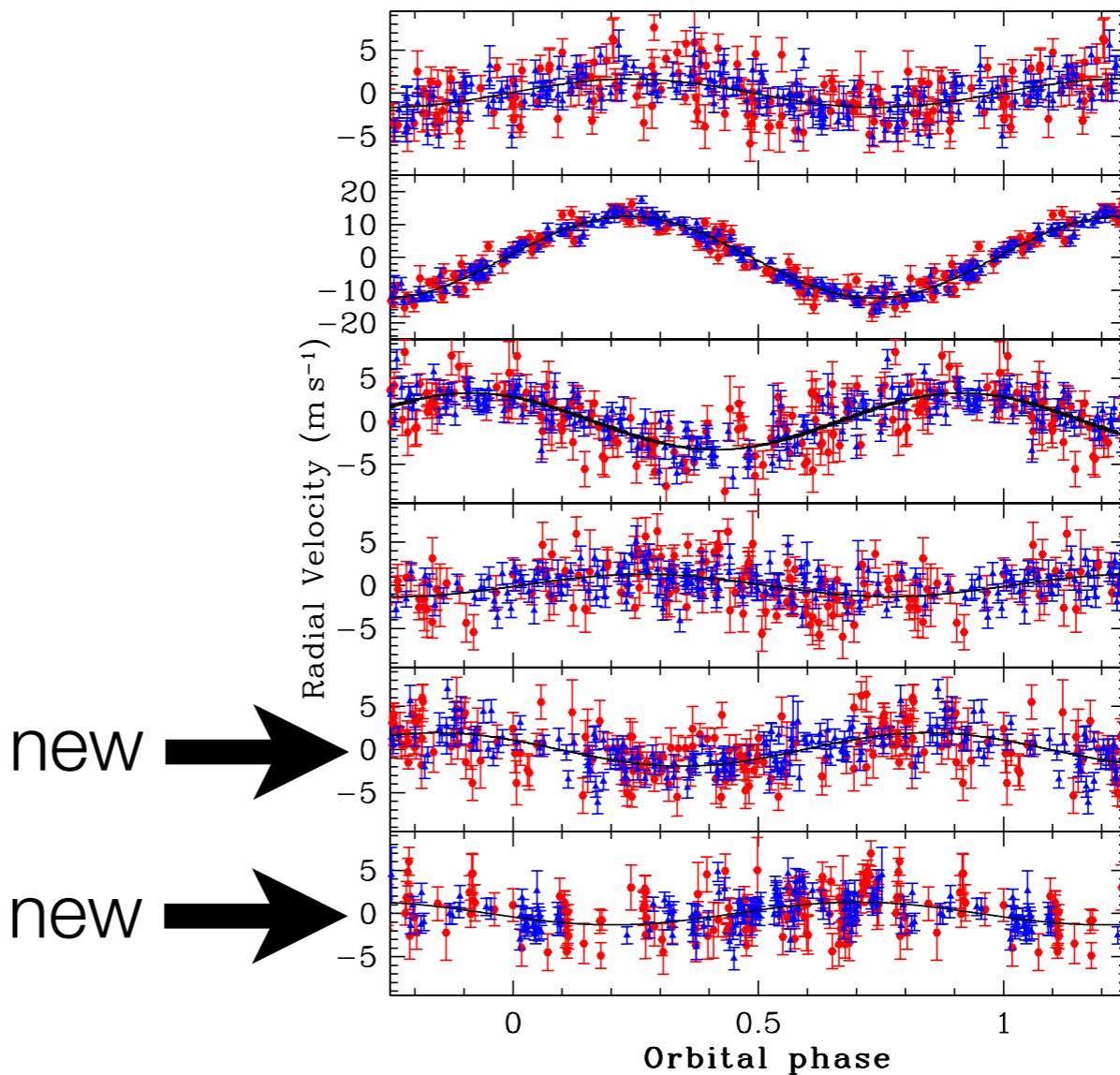
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The sixth panel down in Figure 3 shows the periodogram of the residuals to the 5-planet fit. A lone dominant peak remains near 37 days. This peak shows the extreme narrowness expected of a truly coherent signal, that, if Keplerian and real, would have 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

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

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.

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TIME

Found: An Earthlike Planet, at Last

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

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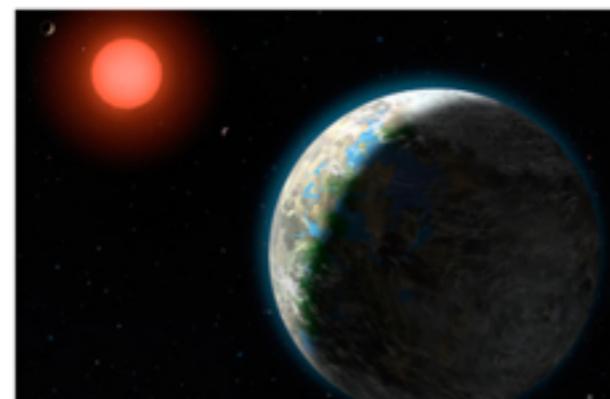
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The star known as Gliese 581 is utterly unremarkable in just about every way you can imagine. It's a red dwarf, the most common type of star in the Milky Way, weighing in at about a third of the mass of the sun. At 20 light years or so away, it's relatively 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

the guardian

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

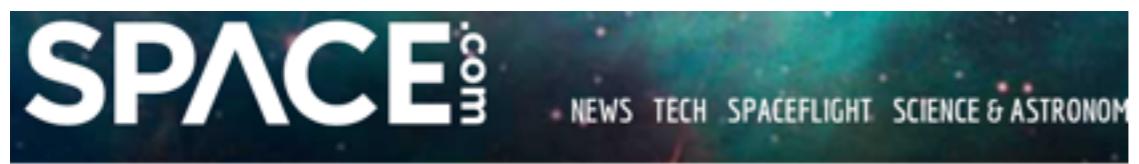
Astronomers have discovered a potentially habitable planet of similar size to Earth in orbit around a nearby star.



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



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



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...

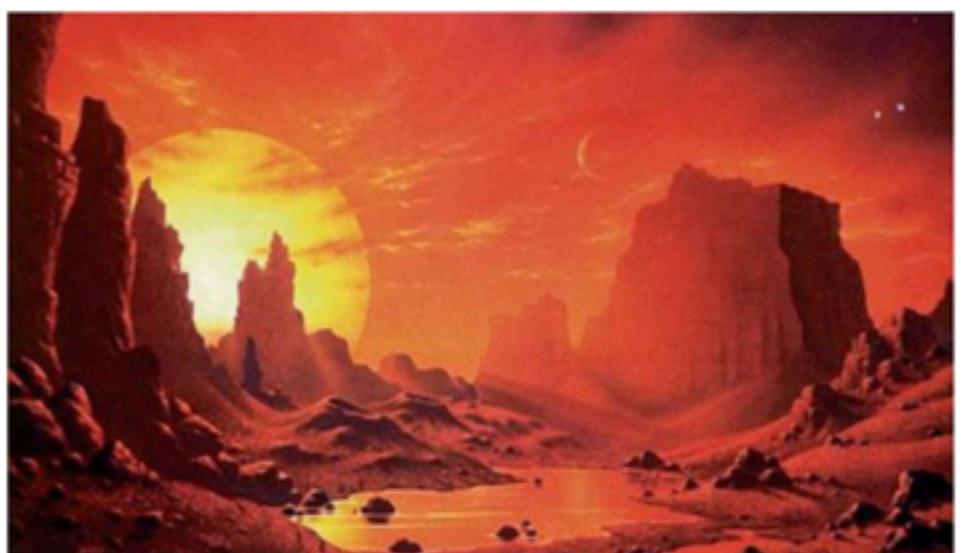
The astrophysicist who discovered Zarmina describes life on "second Earth"



Annalee Newitz

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

102.3K



just two weeks later...

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

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Most Read in News



things get worse for Gl 581g...

Bayesian Re-analysis of the Gliese 581 Exoplanet System

Philip C. Gregory^{1*}

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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 H α line, we measure a stellar rotation period of 130 ± 2 days and a correlation for H α 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.

The HARPS search for southern extra-solar planets *

XXXII. Only 4 planets in the Gl 581 system

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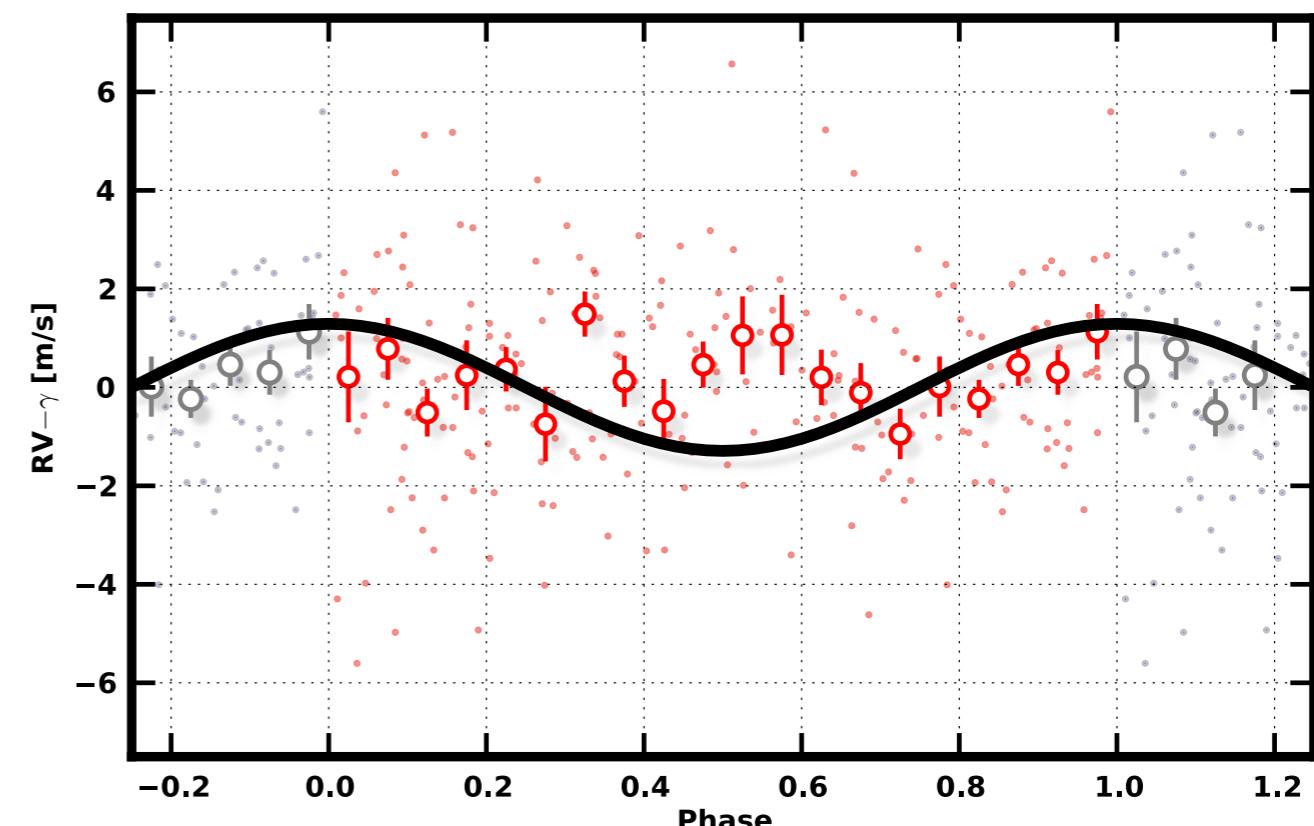
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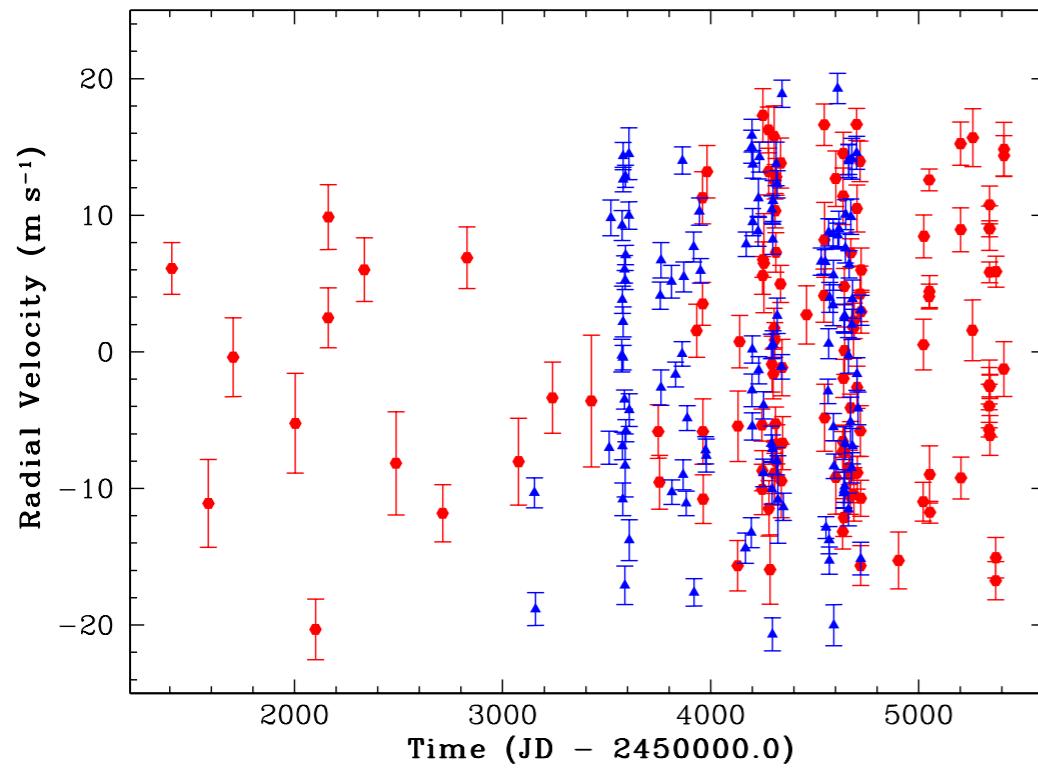
¹² Departamento de Astronomía y Astrofísica, Pontificia Universidad Católica de Chile, Casilla 306, Santiago 22, Chile



Another team use new data to show planet is disfavored

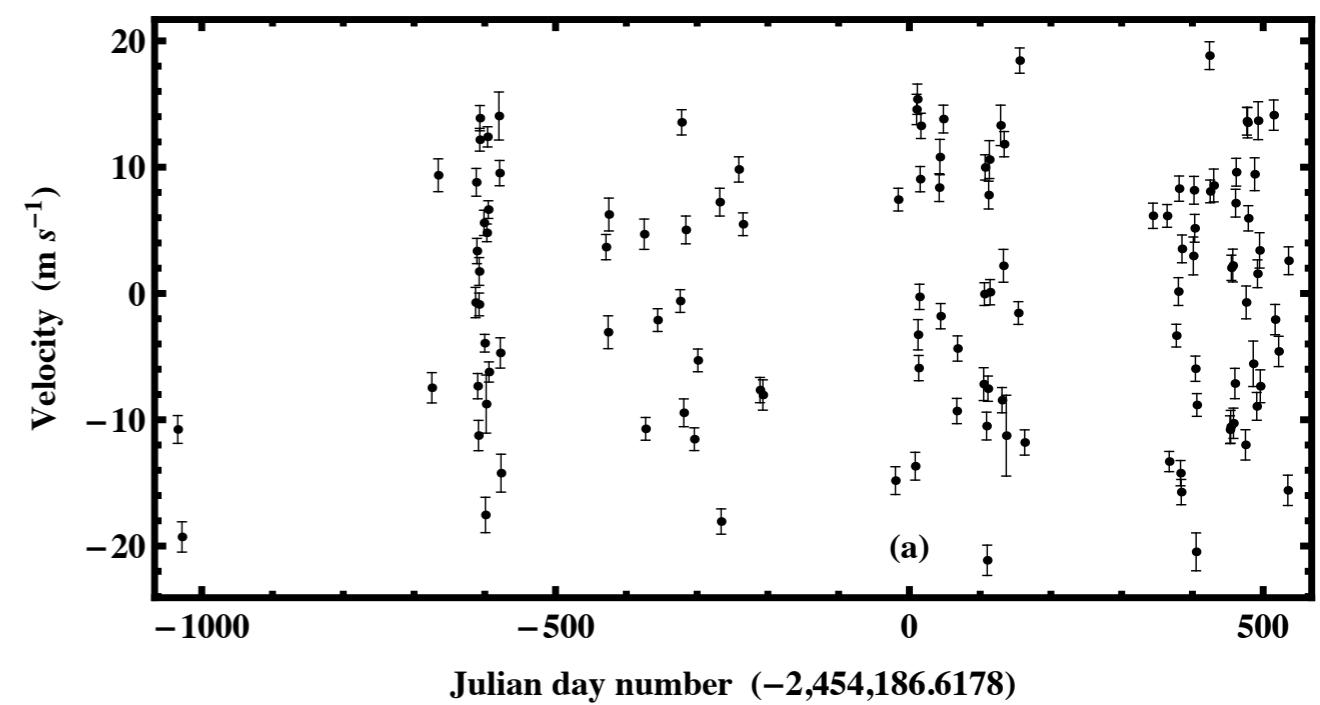
follow-up data killed Gl 581g, but was it even really necessary?
you are going to repeat the model selection on the original data!

“discovery” data



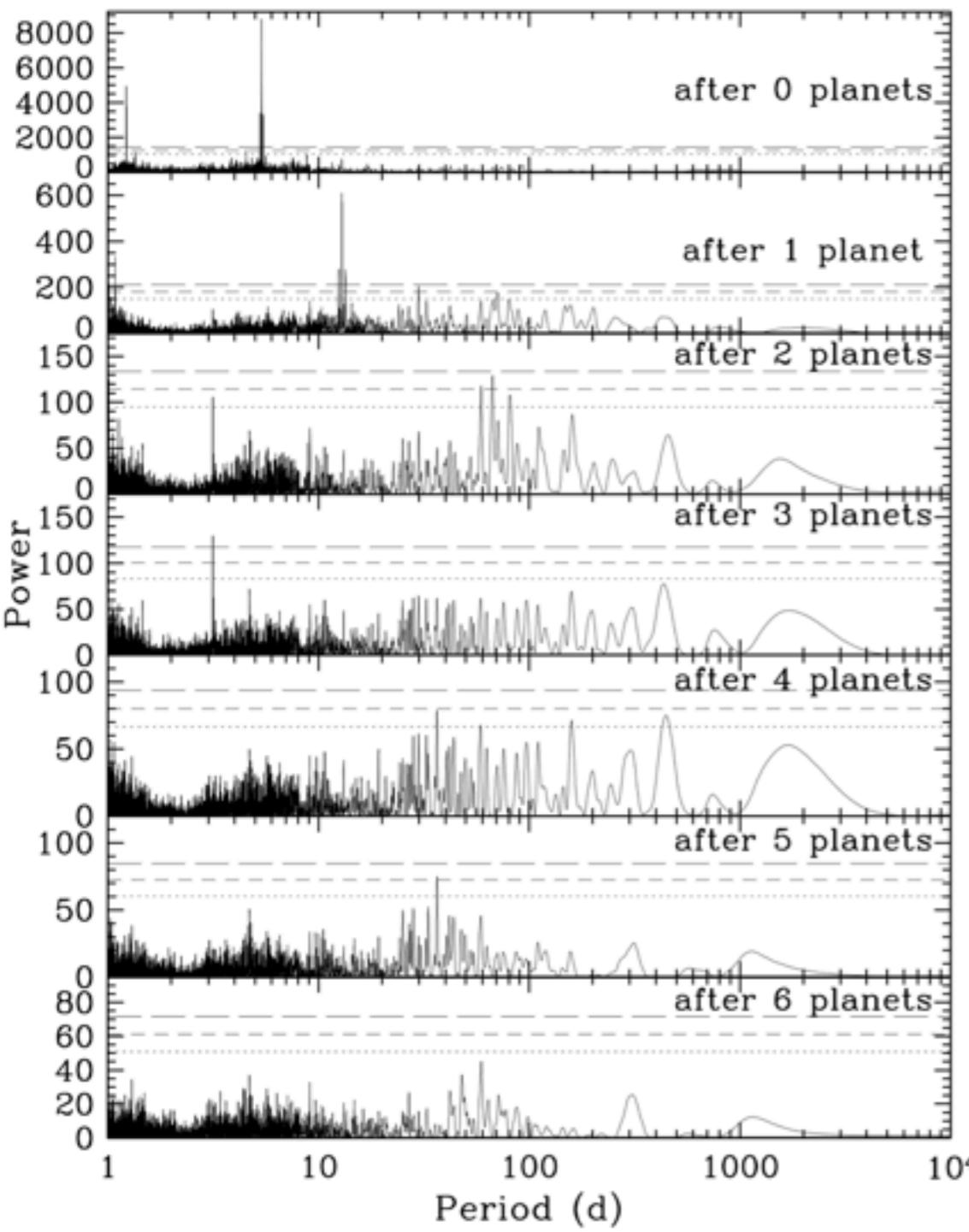
122 HIRES points
119 HARPs points
= 241 data points

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

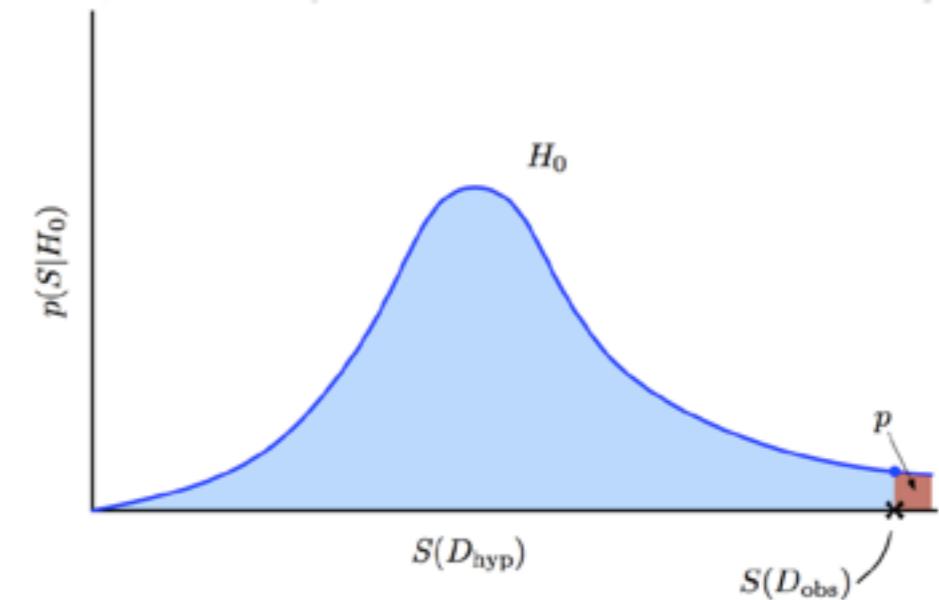
Vogt et al. made several statistical errors in their analysis...

2. p-value \neq FAP

The FAP is the chance that a peak as high as, or higher than, that observed in the periodogram would occur by chance,

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 $S > S_{\text{obs}}$

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

$$p_0 = \frac{(N - 2)}{2} \frac{(\chi_{\text{constant}}^2 - \chi_{\text{circ}}^2)}{\chi_{\text{circ}}^2}, \quad (2)$$

where χ_{circ}^2 is the reduced chi-squared for a circular fit at/near the period implied by the peak and χ_{constant}^2 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!

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

max likelihood

of data points

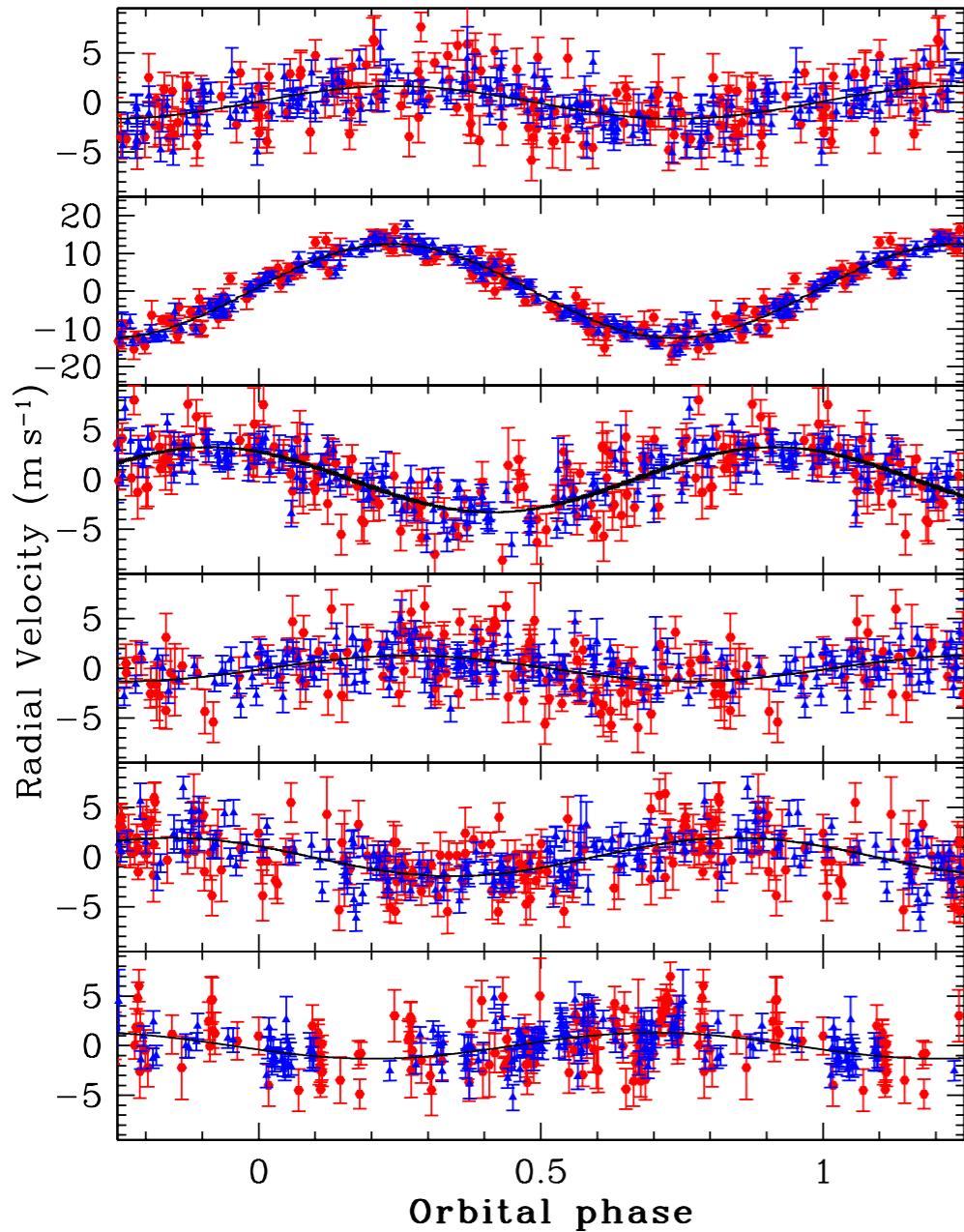
of parameters

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

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

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...

M₀: 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 (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 e, what do you think?
- 5] Write up your slides!

two weeks deadline!