Measurement of Spin-Orbit Alignment in an Extrasolar Planetary System

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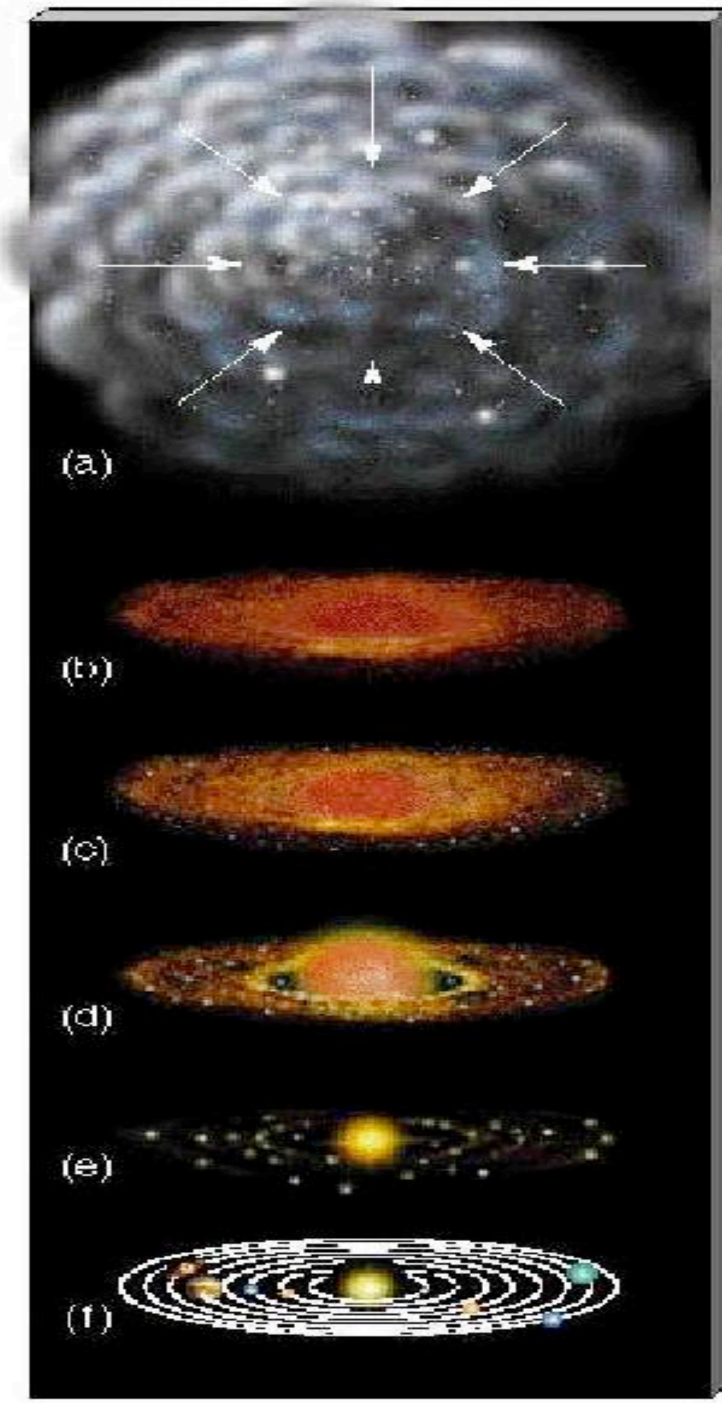
Outline

- Background on our theory on Solar System Formation
- Motivation for determining Spin-Orbit Alignment
- The Rossiter-McLaughlin Effect
- Data & Orbital Parameters
- Models
- Fitting the Data
- Rapidly Rotating Stars

Solar System Formation*

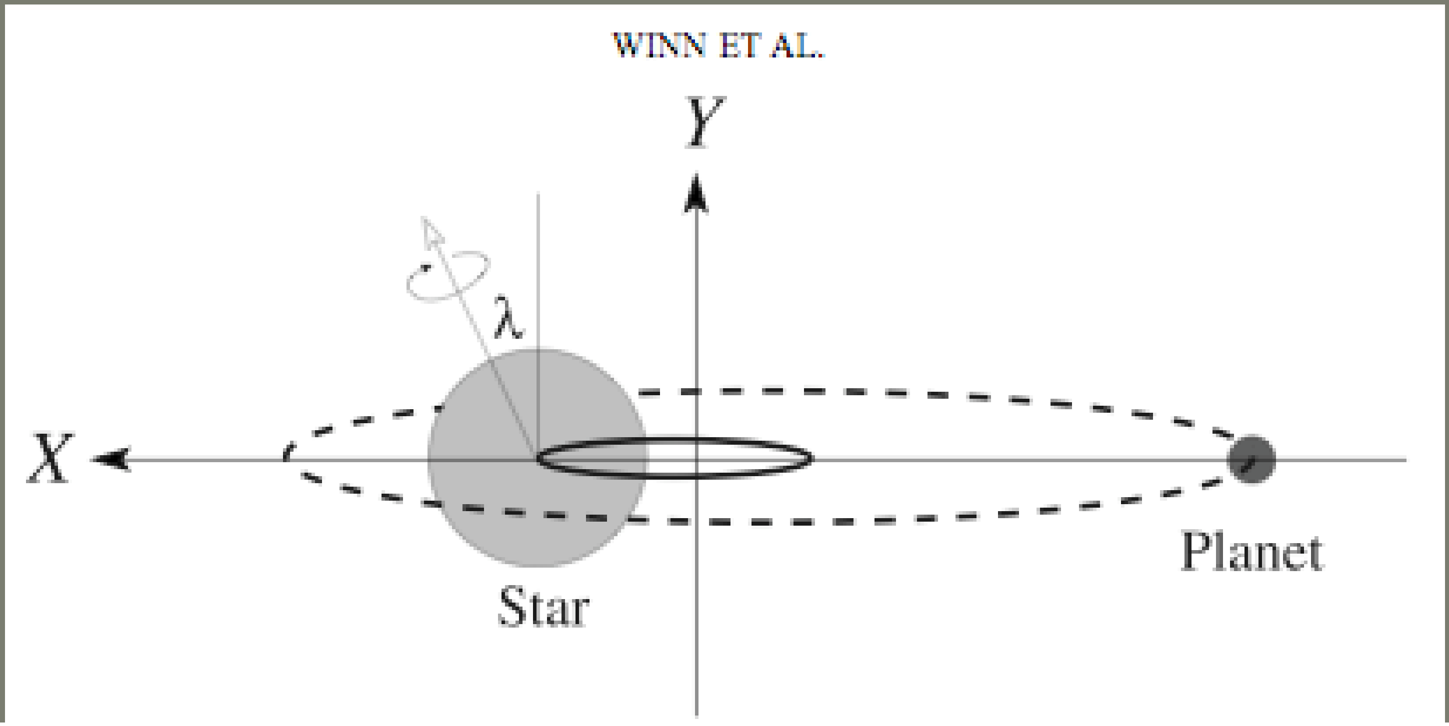
- Initial rotation (angular momentum) requires initial cloud to collapse to disk

*See "Solar System Formation" by Mark Richardson



Motivation

- The leading theory on solar system formation predicts a common angular momentum vector for the initial and final constituents of the cloud.
- A significant example of this is that the net orbital angular momenta is expected to point in the same direction as the solar rotation angular momentum



Motivation Continued

- To find support for this theory, we can determine the angular difference (ψ) between the orbital angular momentum vector (Ω) and the star's rotation vector (Ω_*).
- Question: Is ψ roughly zero? Compare with the sun: ~6^o (Winn et. al. 2005)

Further Motivation

- Finding $\psi \approx 0$ would support the leading theory.
- Also it would suggest a way to determine Ω provided Ω_* can be found (consider line broadening, rotation period, and stellar radius).

More Motivation

- Also if ψ is not ~0, this is of significance:
  - Could indicate inhomogeneities in the initial angular momentum distribution.
  - Possible torque from the T-Tauri phase due to magnetic fields/outflows
  - Interactions with stellar neighbours
  - Due to migratory phase

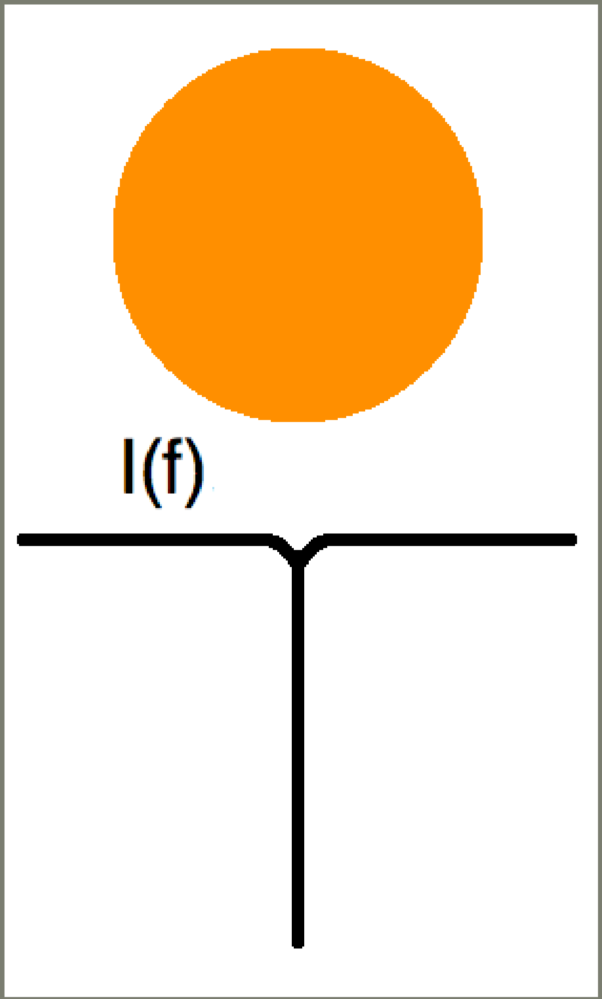
Methods

- There are two methods to determine ψ that will be discussed here:
  - For slowly rotating stars, we can take advantage of The Rossiter-McLaughlin Effect*.
  - For rapidly rotating stars,we can consider the von Zeipel Theorem*

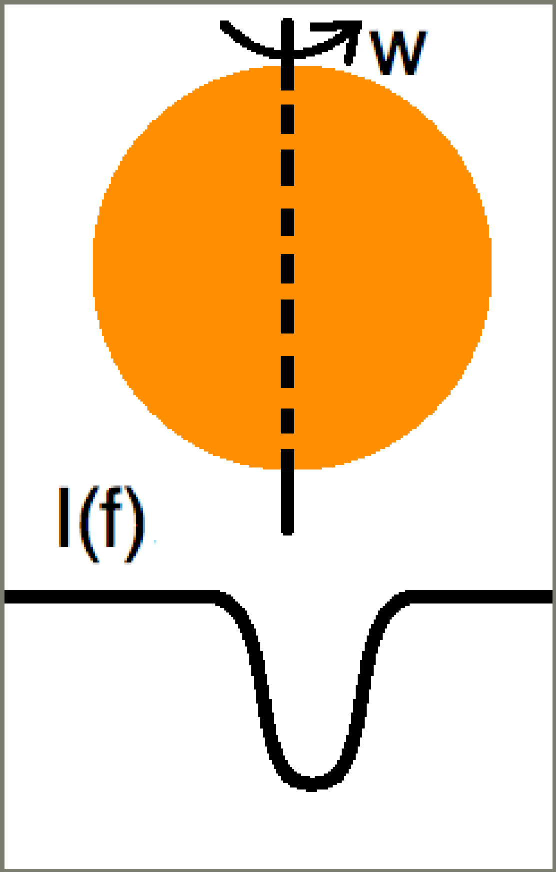
*Description to come

The Rossiter-McLaughin Effect

- $V_{rot} = 0$

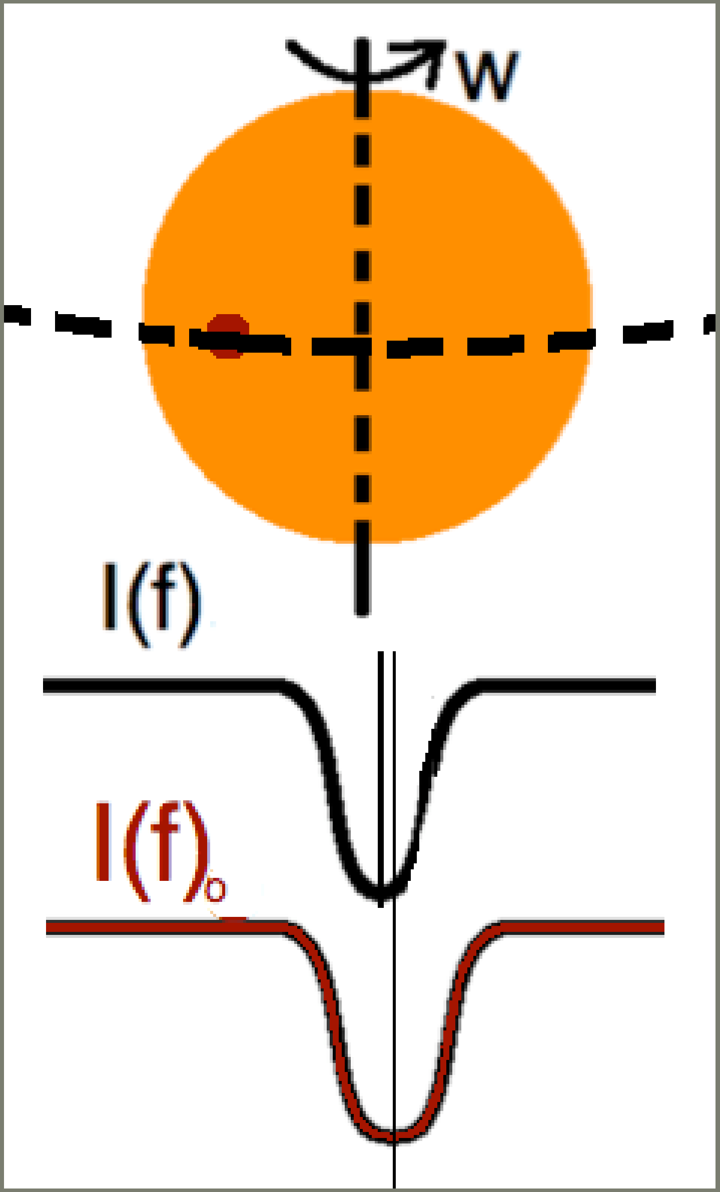


$V_{rot} = R_* w$



RM Effect

- The obstruction of the blue shifted frequencies result in an apparent skewing of the wave towards the red.
- This results in an apparent velocity (velocity anomaly) Δv



Finding ψ

- So what does this have to do with ψ … this is not an easy answer although it is somewhat intuitive … due to technological difficulty I must turn to the whiteboard.

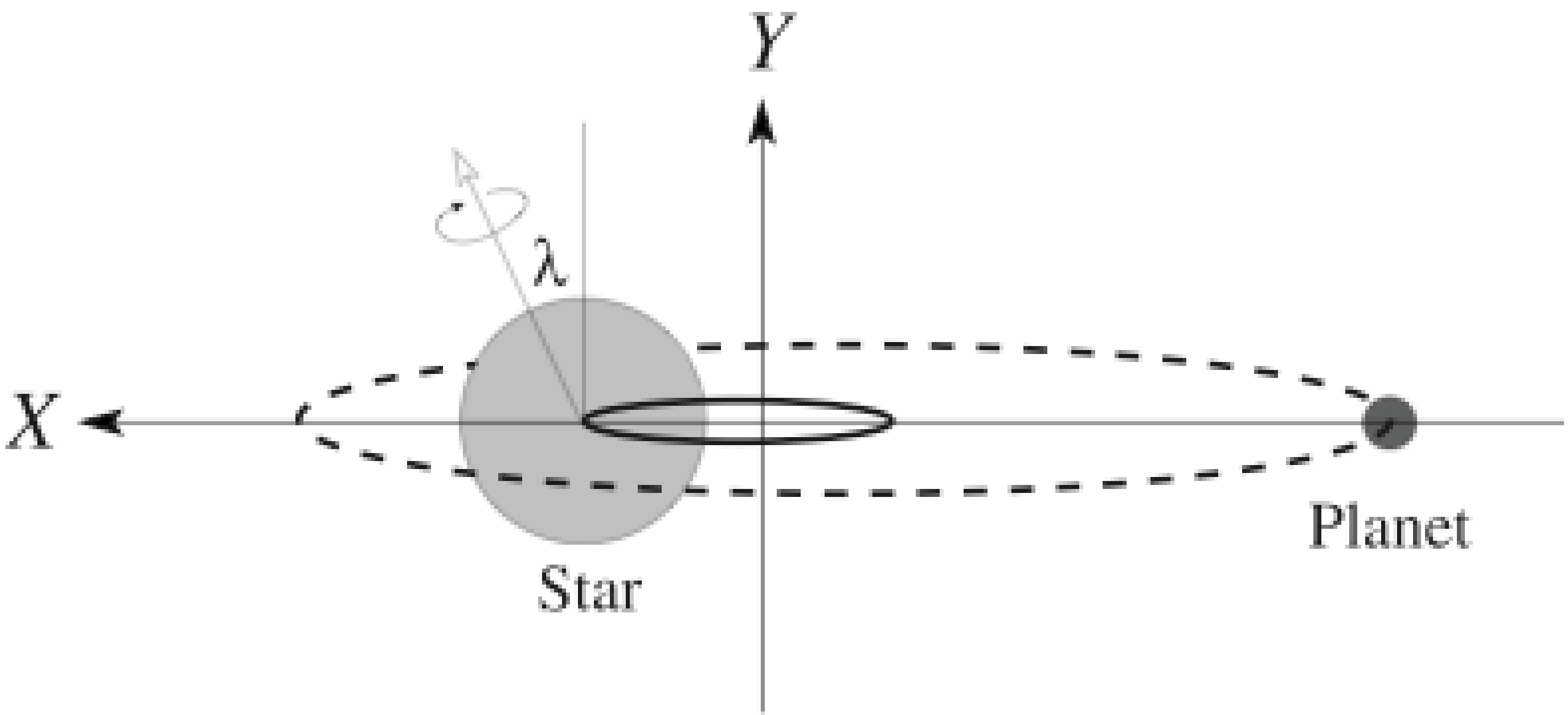
Finding ψ

- So the 3D angle, ψ, is related to the 2D projected angle, λ, by:

  $\cos\psi = \cos I_* \cos I + \sin I_* \sin I \cos\lambda$
- I = inclination between orbital plane and sky plane
- I_* = inclination between star rotation axis and sky plane

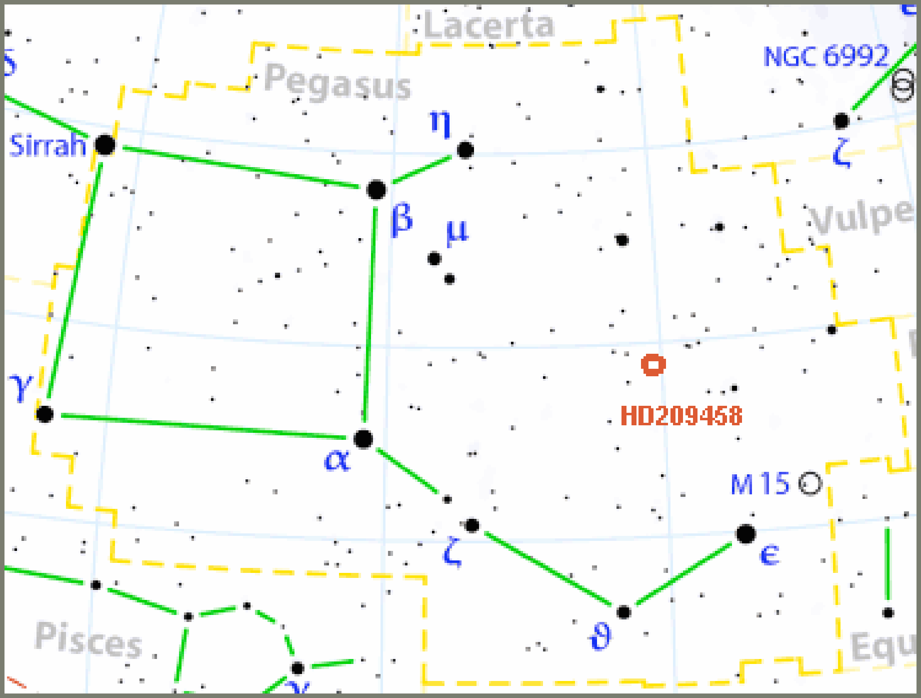
Caveats

- Everything is hampered by I and I_* (for example can only find $v_{rot}\sin I_*$).
- Will only detect a lag-time between $t(\Delta v=0)$ and $t(dI/dt=0)$ provided $I \neq 90^o$ and $I_* \neq 0$.
- The velocity anomaly is small relative to the radial velocity observed for the orbital motion, thus a bright host star is required to allow for high precision data.


Y
λ
X
Star
Planet

HD 209458

- HD 209458 is the brightest star known to host a transiting planet.
- From wikipedia:
  - G0V star
  - T ~ 6000K
  - M ~ 1.13 Solar Masses
  - R ~ 1.14 Solar radii
  - First known transiting planet



Data

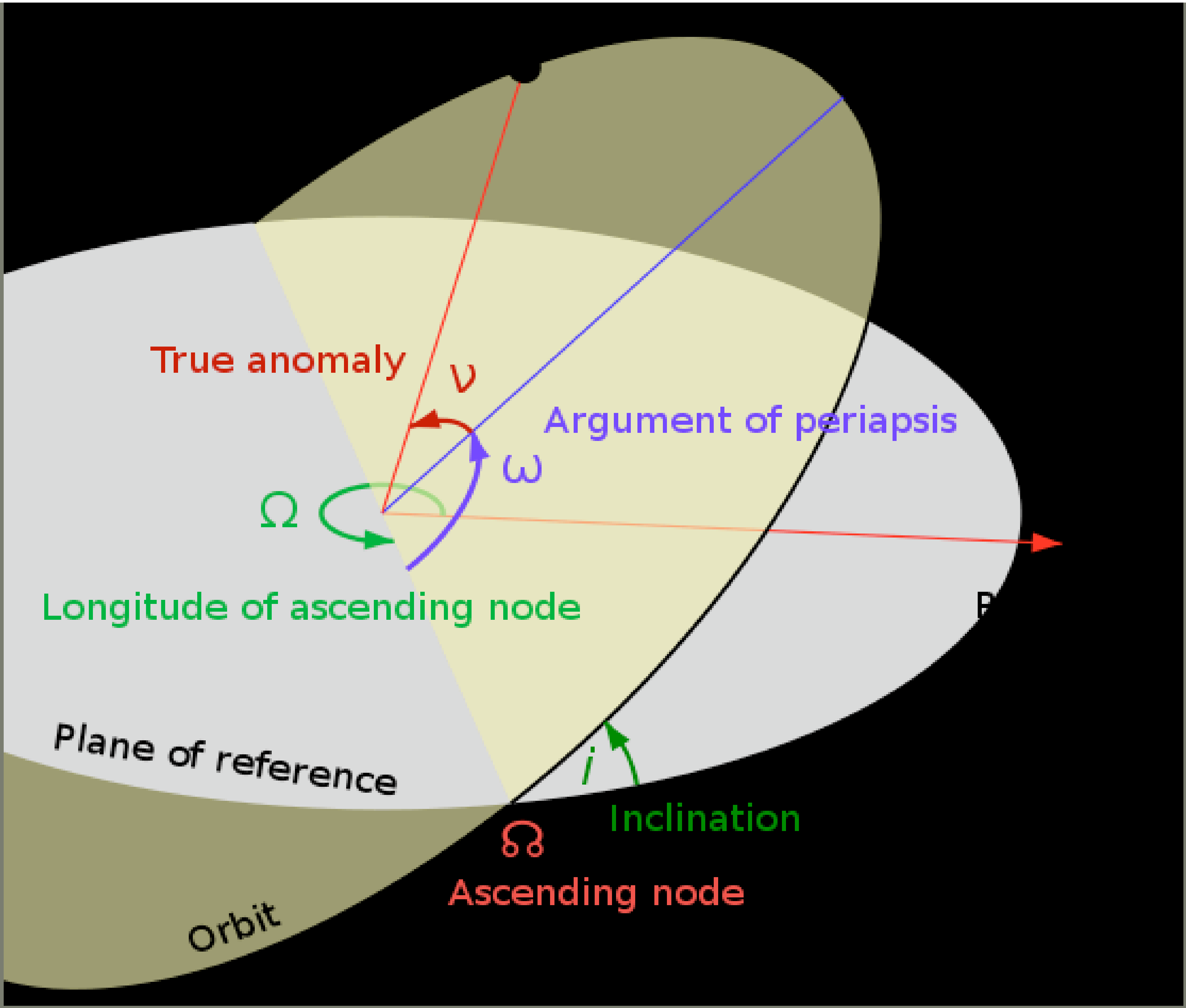
- 1) 85 sets of spectra data from Laughlin et al. (2005) between Nov 1999 and Dec 2004. Used technique from Butler et. al. (1996) to determine radial velocities with ~3 to 4m/s accuracy
- 2) 417 photometry datasets from Brown et. al. (2001) with 10^{-4} relative flux precision, including transit data.

Data continued

- 3) IR observations of the secondary eclipse with signal to noise ratio of ~5 to 6.

Parameters

- The article discusses several parameters. Quickly listed:
  - Orbital: M_p, P, *e*, ω,I,λ, Δt_I, X, Y, Z
  - Flux: R_P, R_*, u_1, u_2
  - Star: $M_{*,}$ $v_{rot}\sin I_*$



Courtesy Wikipedia

The Models

- Orbit: Two-Body Keplerian Orbit (see your favourite textbook!)
- Flux of star: Limb darkening using:

  $I(\mu) = 1 - u_1(1-\mu) - u_2(1-\mu)^2$ (6)

  – μ is the cosine of the angle between the sight line and the surface normal

  – From this can calculate the flux from a region of the star (when/where planet is transiting)

  – $I = 1$ when the planet is not transiting

The RM Effect

- Winn et. al. have made a new way to simulate the RM effect depending on the planet's position in front of the star.
- Their algorithm is as follows:
  - A: Take solar spectra and modify it to fit HD 209458 properties
  - B: Repeat A, only Dopler Shift by v_p and stretch according to f_p.
  - Take A - B, multiply by solar iodine absorption
  - Convolve with 'point-spread' function and put in to method used to get radial velocities Butler et. al. (1996)

RM Effect

- Winn et al argue that this result should be more accurate than a previous model by Ohta et al (2005).
- Argued that new method compares ‘apples to apples’, compared to finding the ‘first moment’
- Determined the following polynomial for Δv:

$$\Delta v = -f v_p \left[1.33 - 0.483 \left(\frac{v_p}{4.5 \text{ km s}^{-1}} \right)^2 \right], \qquad (7)$$

- Question about u_1 and u_2

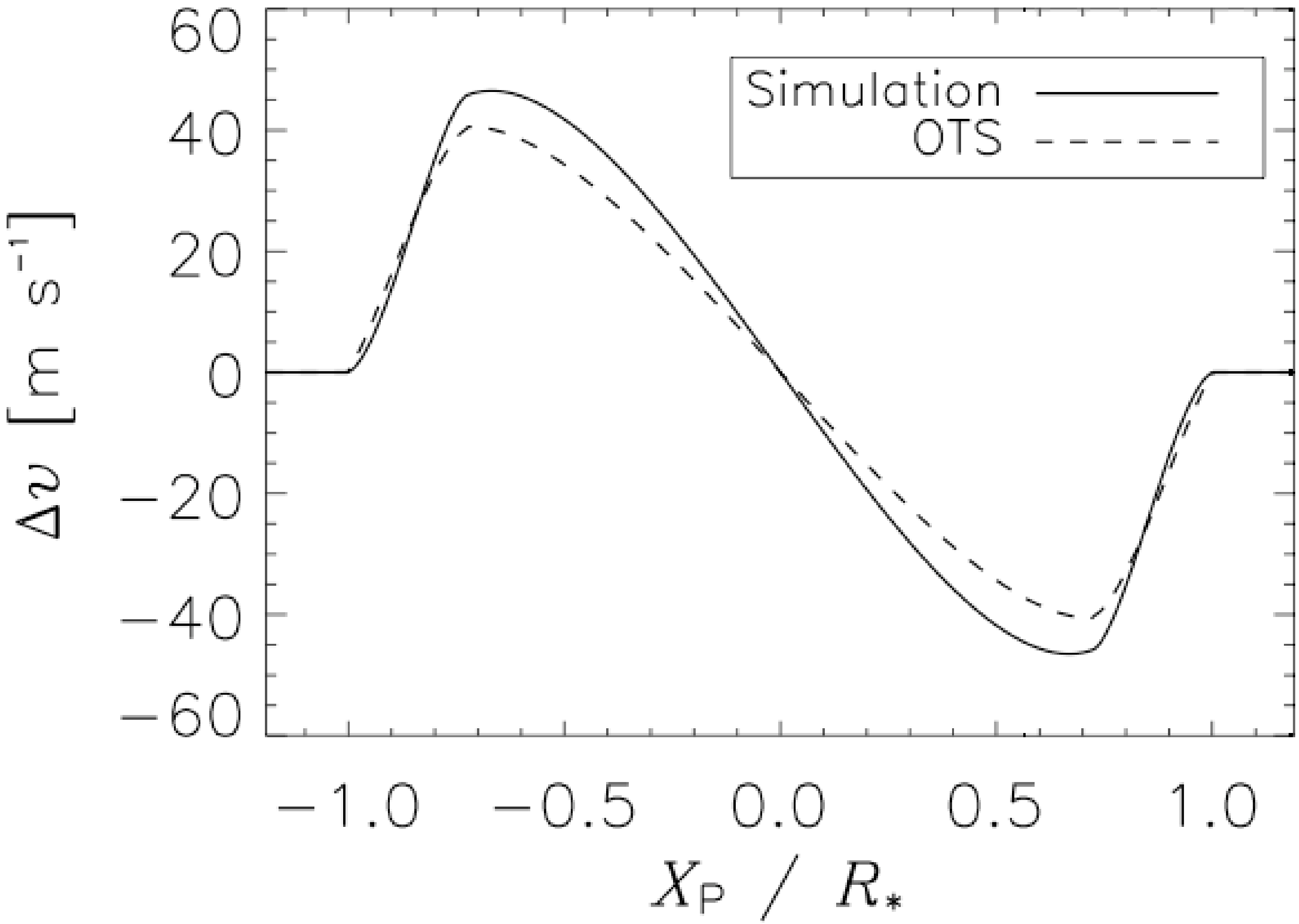


FIG. 2.—Radial velocity anomaly due to the Rossiter-McLaughlin effect, as calculated via our simulations (*solid line*) and the formula of OTS (*dashed line*). The horizontal axis gives the distance from the planet to the projected axis of the stellar spin. The orbital, planetary, and stellar properties were chosen to be approximately those of HD 209458: $R_p/R_\star = 0.12$, $Y_p/R_\star = 0.5$, $e = 0$, $\lambda = 0^\circ$, $v \sin I_\star = 4.5$ km s^{-1}, and $u_1 + u_2 = 0.64$.

Fitting the Data

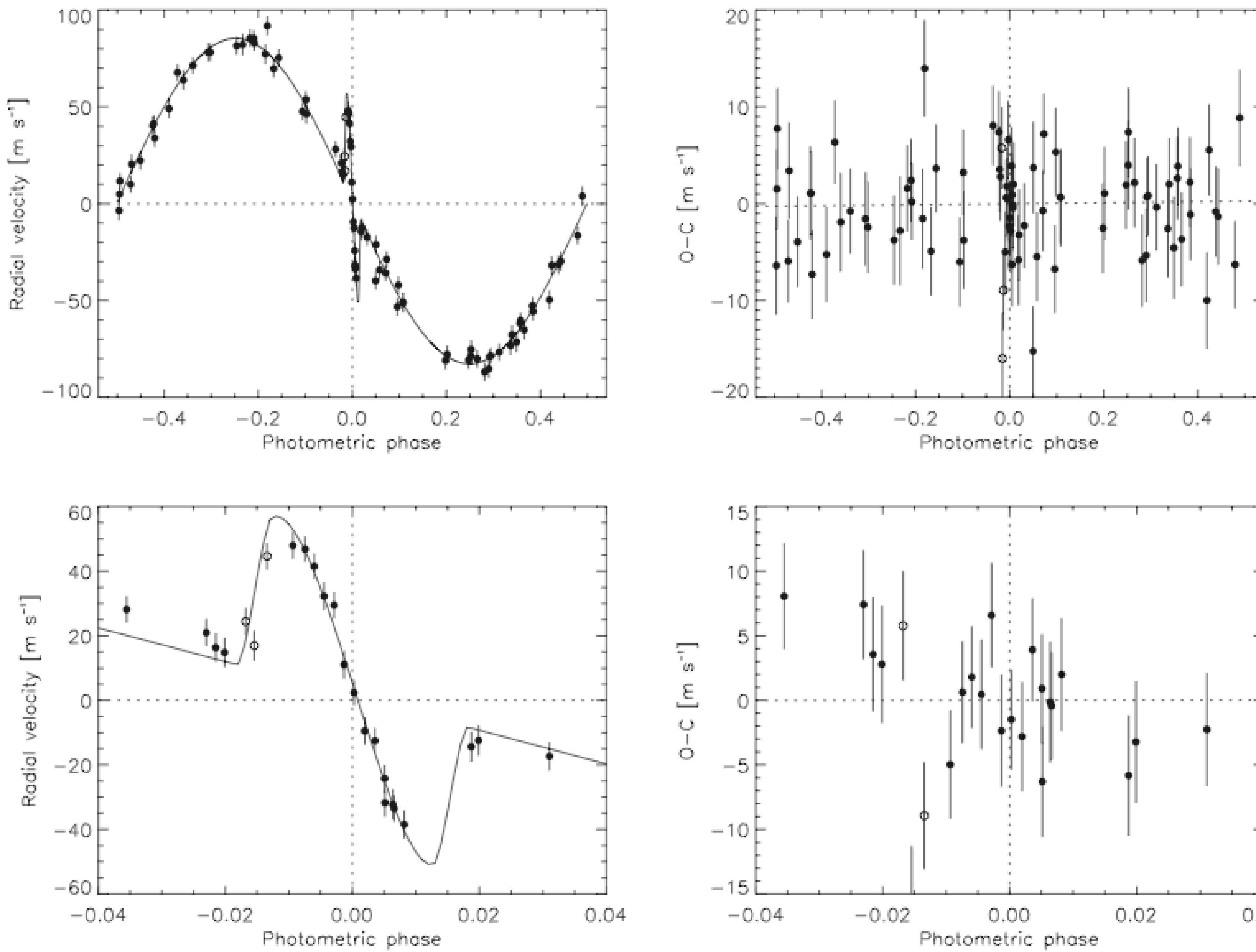
- Winn et al are now set to produce simulated data once they set the parameters described before.
- Method:
  - Set M_*
  - perform simulations for some set of parameters (12 of them!)
  - Determine simulated observations at the same time as the data
  - Determine χ^2 (to be defined), keep if min. Repeat

Fitting the Data

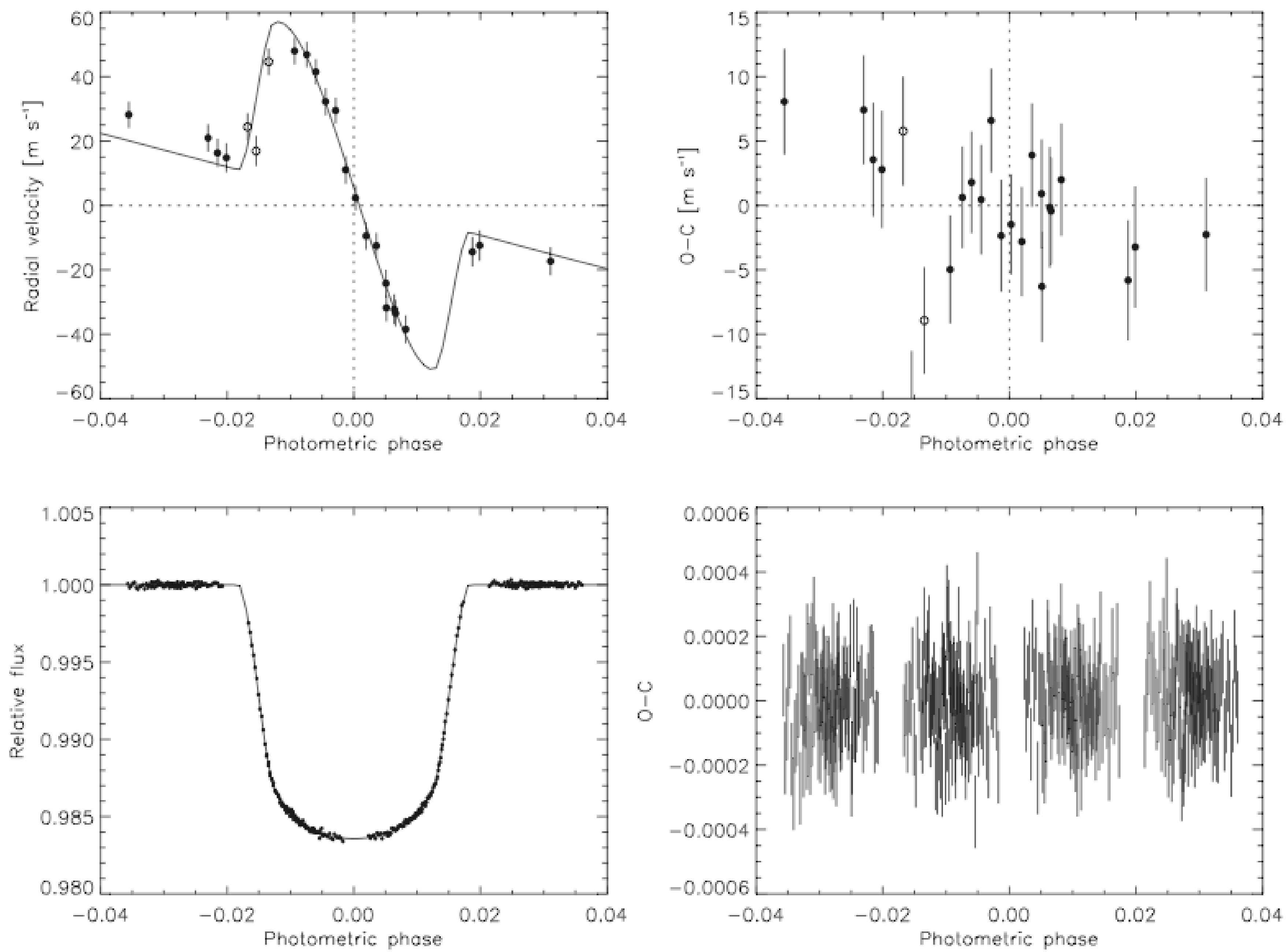
$$\chi^2 = \sum_{n=1}^{N_v}\left(\frac{v_o - v_c}{\sigma_v}\right)^2 + \sum_{n=1}^{N_f}\left(\frac{f_o - f_c}{\sigma_f}\right)^2 + \left(\frac{t_{\mathrm{II},o} - t_{\mathrm{II},c}}{\sigma_t}\right)^2 \quad (8)$$

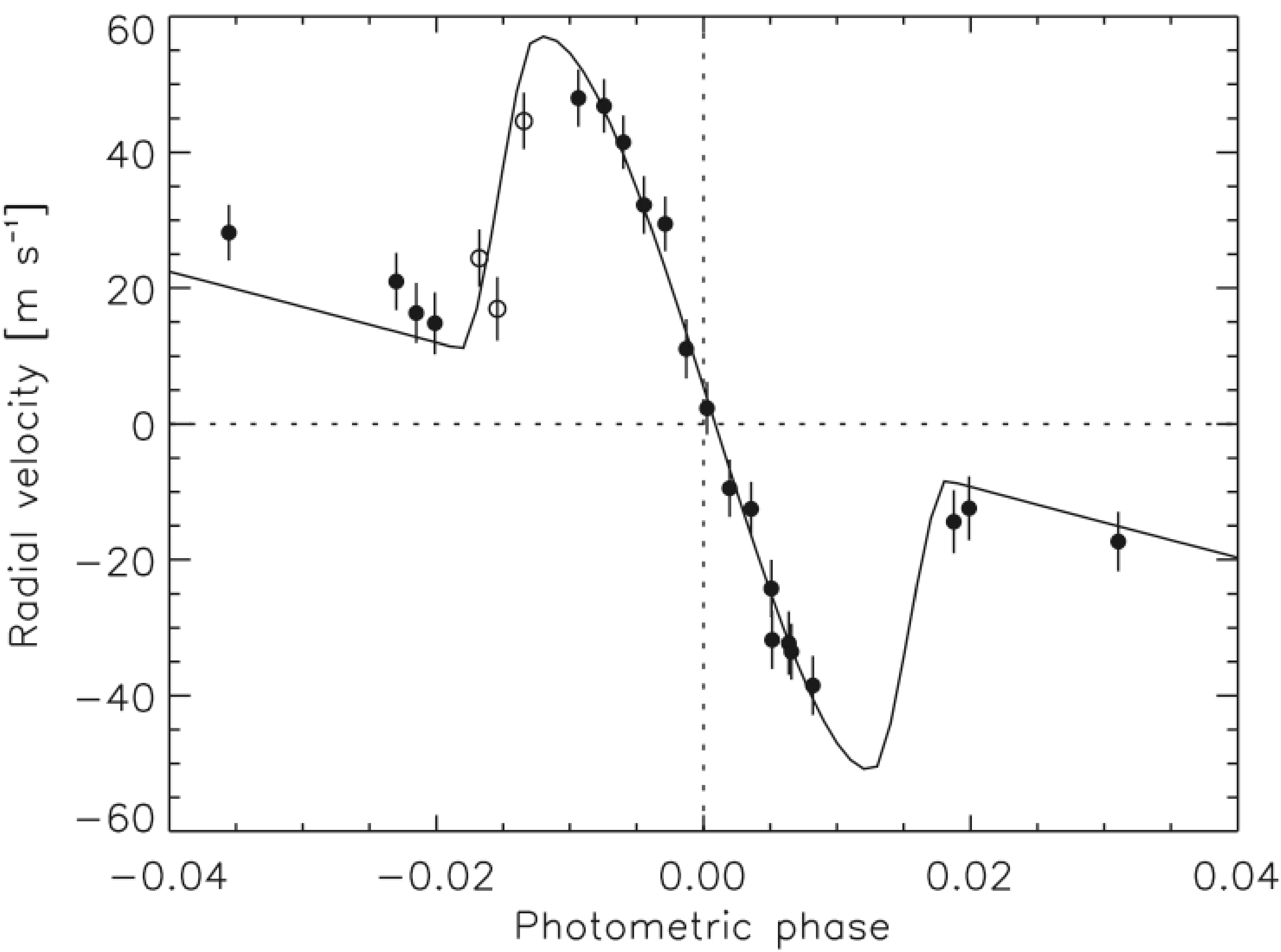
- The set of parameters that minimize χ^2 are taken as the best fit.
- Confidence levels are determined by 'bootstrap Monte Carlo analysis'
  - Mark: This one's on you …
- Did this for 100 000 synthetic datasets

Results


Radial velocity [m s⁻¹]
Photometric phase
O−C [m s⁻¹]
Photometric phase
Radial velocity [m s⁻¹]
Photometric phase
O−C [m s⁻¹]
Photometric phase

Results


Radial velocity [m s^{-1}]
Photometric phase
O−C [m s^{-1}]
Photometric phase
Relative flux
Photometric phase
O−C
Photometric phase



60
40
20
0
−20
−40
−60
Radial velocity [m s⁻¹]
−0.04
−0.02
0.00
0.02
0.04
Photometric phase

Results

TABLE 1

ORBITAL, STELLAR, AND PLANETARY PROPERTIES OF HD 209458

Parameter	Best Fit (mean)	Uncertainty (σ)	Lower 90% Confidence Limit	Upper 90% Confidence Limit	Notes
M_p (M_{Jup})	0.657	0.006	0.647	0.668	1
M_p (M_{Jup})	0.657	...	0.594	0.721	2
$R_\star$ ($R_\odot$)	1.148	0.002	1.143	1.152	1, 3
$R_\star$ ($R_\odot$)	1.15	...	1.09	1.20	2, 3
R_p (R_{Jup})	1.355	0.002	1.350	1.358	1, 3
R_p (R_{Jup})	1.35	...	1.29	1.41	2, 3
$R_p/R_\star$	0.12096	0.00025	0.12056	0.12141	
$e \cos\omega$	0.0014	0.0022	−0.0021	0.0049	
$e \sin\omega$	0.0141	0.0055	0.0037	0.0232	3
e	0.0147	0.0053	0.0057	0.0234	3
ω (deg)	84	11	56	99	3
γ (m s^{-1})	1.11	0.63	0.08	2.12	
Δt_I (s)	−5.7	2.0	−9.0	−2.6	
I (deg)	86.55	0.03	86.49	86.61	3
$v \sin I_\star$ (km s^{-1})	4.70	0.16	4.44	4.97	
λ (deg)	−4.4	1.4	−6.8	−2.1	
$v_1 \equiv u_2 + (5/3)u_1$	0.825	0.010	0.808	0.842	3
$v_2 \equiv u_2 - (3/5)u_1$	0.181	0.074	0.058	0.289	3

NOTES.—(1) Based on the assumption $M_\star/M_\odot = 1.06$. (2) Incorporates the uncertainty in the stellar mass. The lower confidence limit is for $M_\star/M_\odot = 0.93$, and the upper confidence limit is for $M_\star/M_\odot = 1.19$. (3) Depends on our particular choice of limb-darkening law. In reality, e is probably consistent with zero (see § 4.4).

Further Results and Discussion

- Found the best fit for λ: ($-4.4^{o} \pm 1.4^{o}$)
  - Could be subject to errors if 'stellar jitter' was present --> Get more v_r data
- Estimate $\psi \sim 0.1$ rad (for various reasons)
- There were no significant discrepancies between the determined parameters and previous studies.
- Limb-darkening law may have effect on e --> Winn et al suspect e is much closer to zero.

Further results

- The ψ result gives support for there to be agreement between Ω and Ω_* even for smaller orbits (the planet in question has a semi-major axis ~ 1/9 Mercury's)

Cause of ψ

- Winn et al discuss several causes of developing the angle ψ in a planetary system - determine most are improbable due to very long timescales.

Rapidly Rotating Stars

- Rapidly rotating stars (Earlier than ~F6) are particularly difficult to measure the RM effect (strong stellar winds due to B-field make v_r difficult to measure)
- We can still measure spin-orbit (mis) alignment though!
- Two things to consider:
  - Oblateness
  - Von Zeppel effect

Oblateness

- Rapidly rotating stars will have a larger radius at the equator than at the pole.
- Effect of oblateness on transit curves
  - significant different transit times depending on I
  - ‘weird’ transit curves based on intensity of surface.
- Barnes defines $f \equiv (R_{eq}-R_{pole})/R_{eq}$

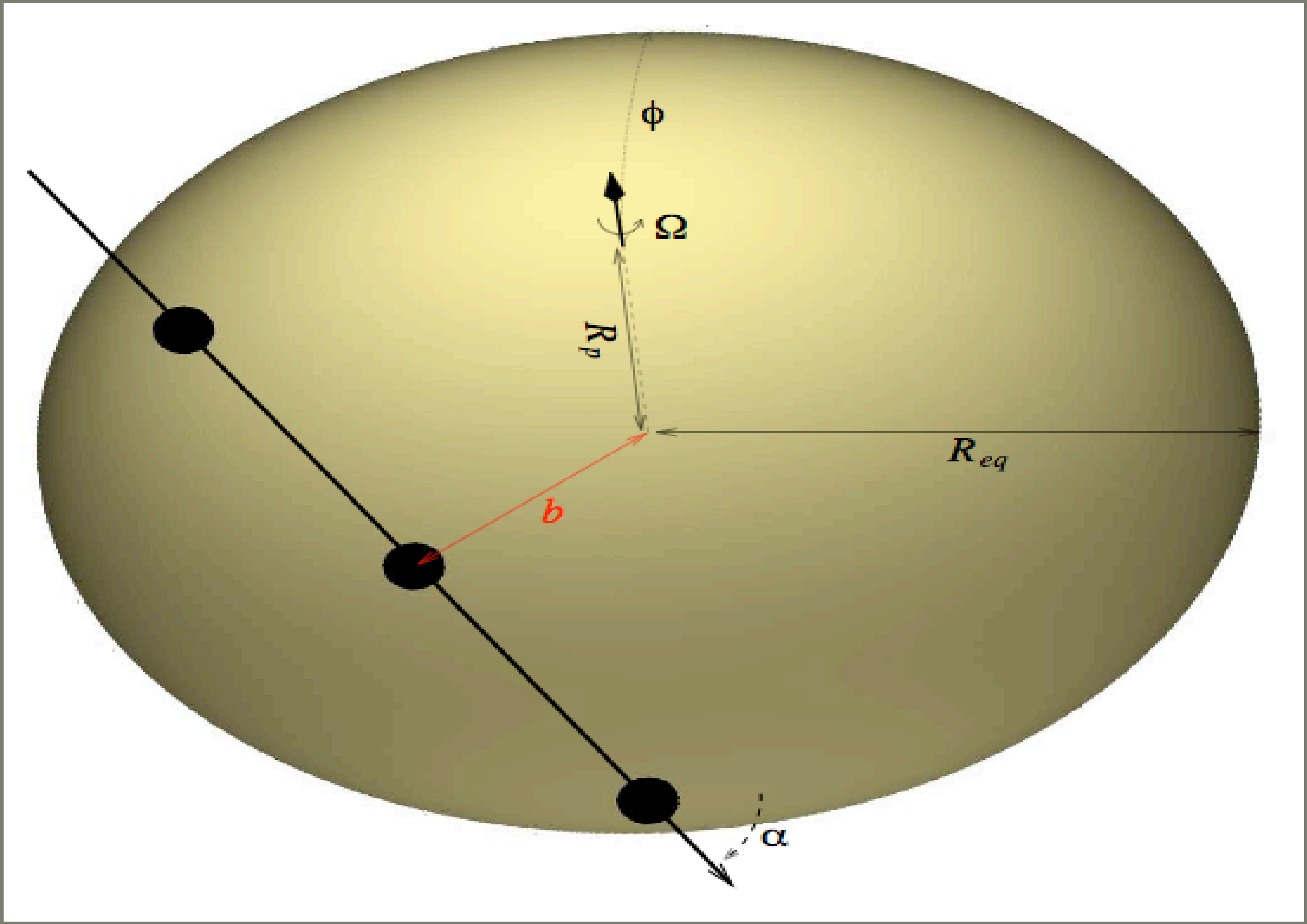
Intensity

- Barnes determines surface flux by integrating over the oblate star (not assuming spherical symmetry)
- Attains this by ‘popping’ the coordinates into coordinate space. Only real effect on relative transit fluxes is lumped into the Intensity in the new coordinates.

Von Zeppel Effect

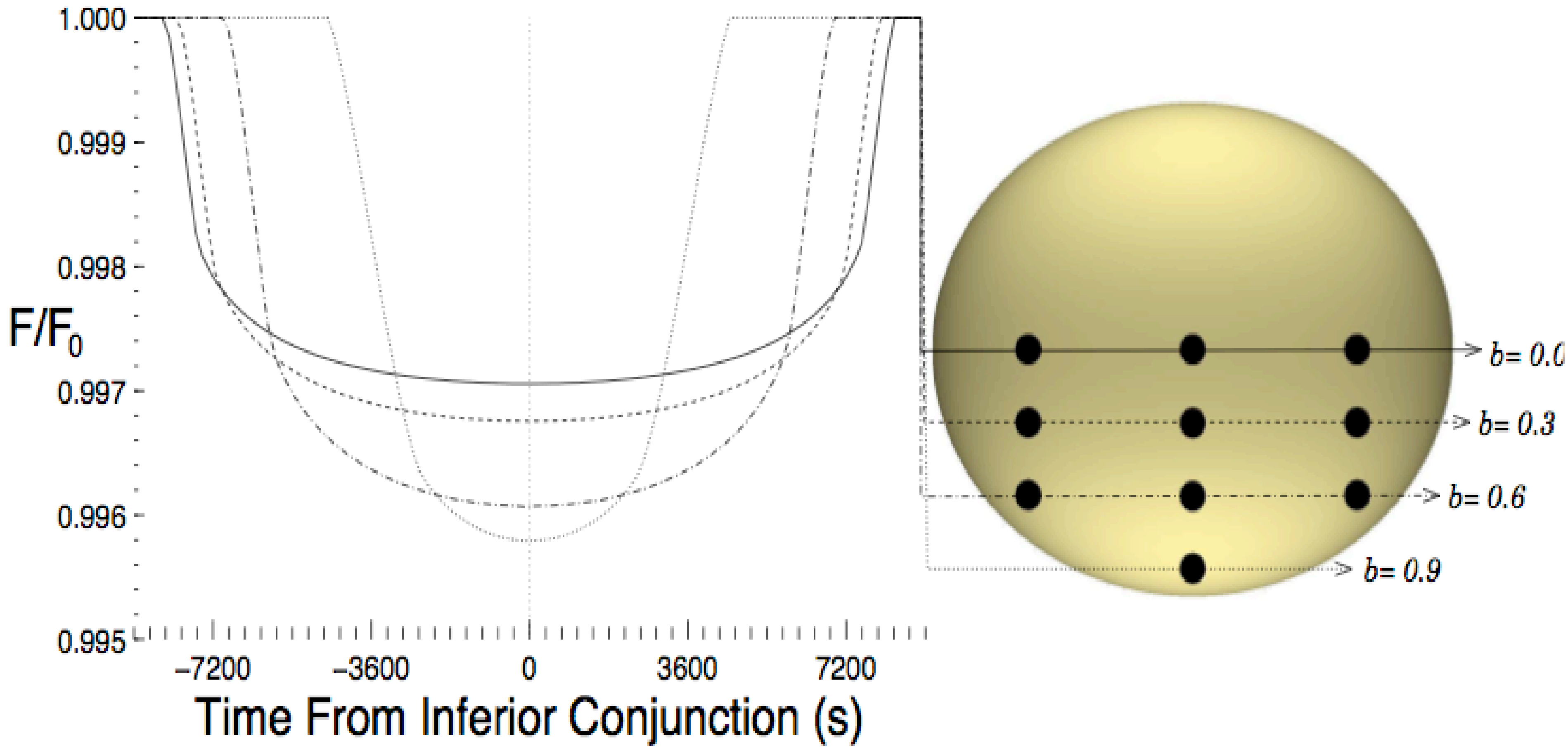
$$T = T_{\text{pole}} \frac{g^{\beta}}{g_{\text{pole}}^{\beta}}$$

- Where g is the surface gravity, and β is 0.25 for a pure radiative star.
- g is dependant on both gravity and the centrifugal term.
- From here just use Steffan-Boltzmann's law



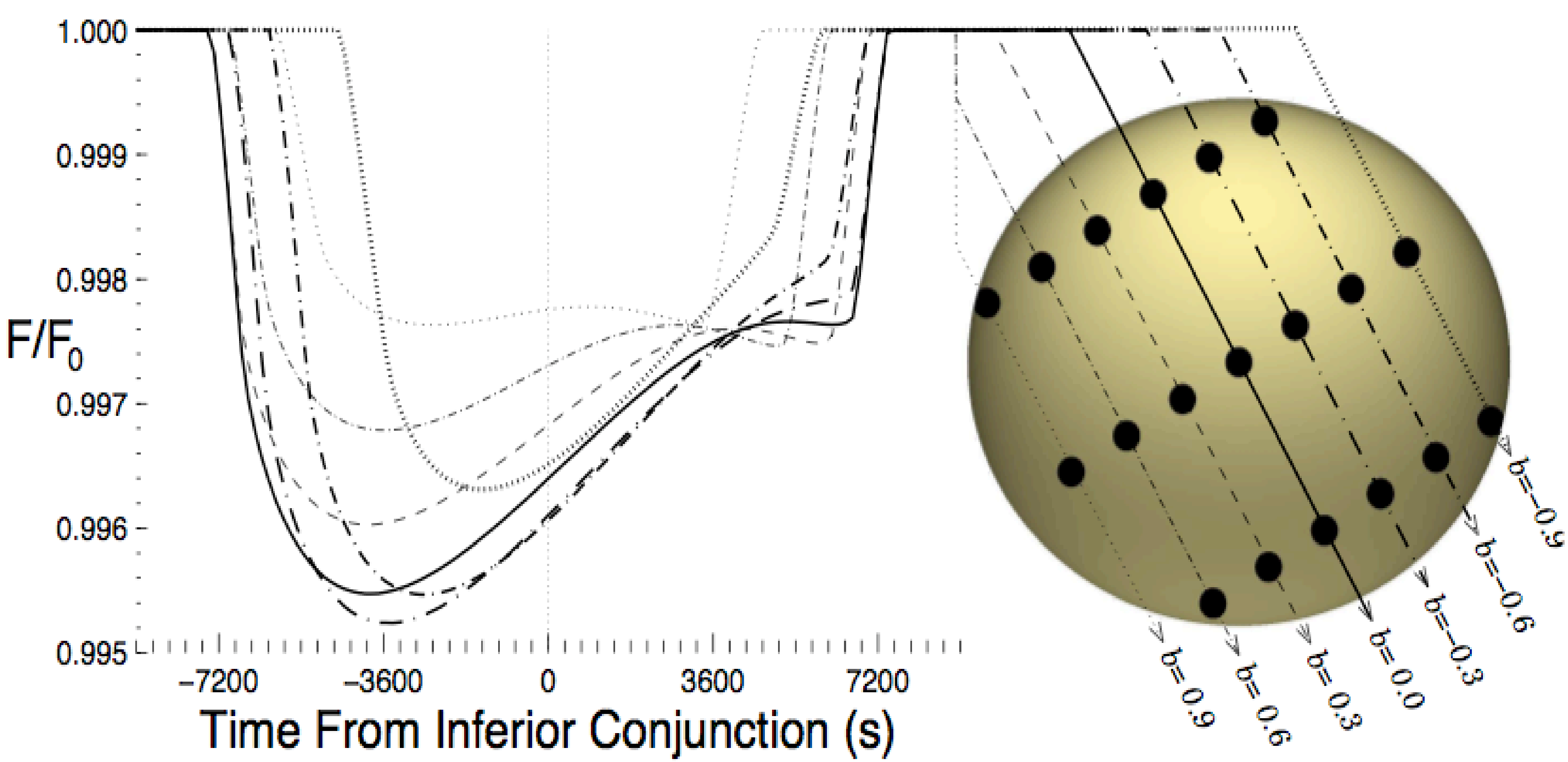
From Barnes, 2009.

α = 0, ϕ=0



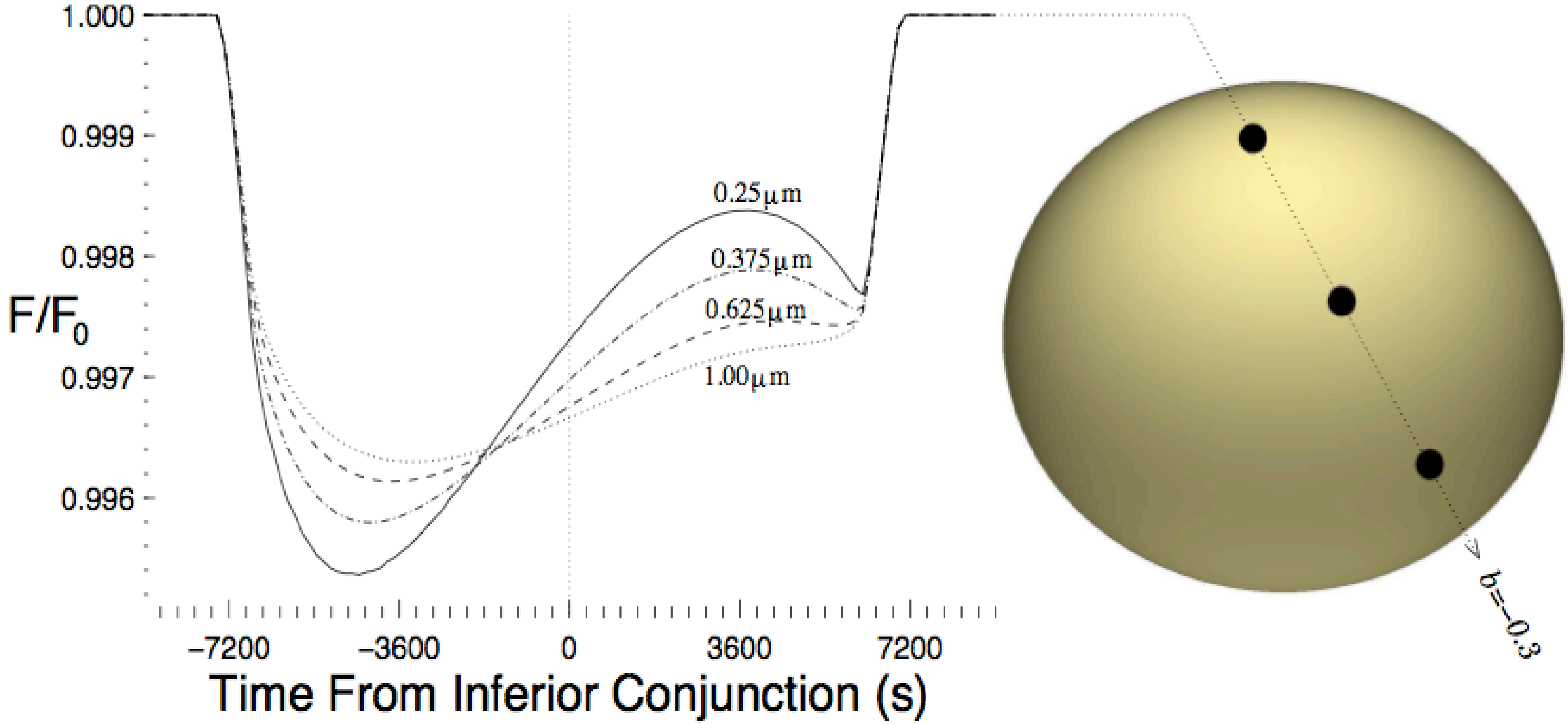
1.000
0.999
0.998
0.997
0.996
0.995
F/F0
-7200
-3600
0
3600
7200
Time From Inferior Conjunction (s)
b= 0.3
b= 0.6
b= 0.9

α = 60, ϕ=30°



1.000
0.999
0.998
0.997
0.996
0.995
F/F0
−7200
−3600
0
3600
7200
Time From Inferior Conjunction (s)
b=−0.9
b=−0.6
b=−0.3
b= 0.0
b= 0.3
b= 0.6
b= 0.9

α = 60, ϕ=30°



Conclusion

- Barnes has produced intensity plots at various wavelengths for an assortment of orbital parameters. It is his hope that these will allow for quick comparison with results from the Kepler mission.
- I'm curious why he went for such significant variation in α. I see it as more beneficial to do this detailed work for $\alpha \sim 0$ as is expected from our theory.

Conclusions

- We now have seen simulated observations for spin-orbit (mis)alignments for both slowly and rapidly rotating stars.
- The RM effect is an efficient tool to analyze the spin-orbit alignment and has been used for subsequent stars (see list in Barnes)

Thanks!

- Discussion???

Ecentricity