Update on b_occ for MCs and TPCs

b_occ distributions, e model and more

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Eclipse potential for transiting planets

The main goal of this project is to estimate the eclipsing potential for all the candidates within the current MCs and TPCs catalogues.

Although a planet is detected via the transit method, it does not guarantee that the planet will also eclipse its host star due to non-zero eccentricty from a pure geometric perspective.

We want to quantify and estimate the potential of those transiting planets to eclipse their host stars to maximize the budget for Ariel project.

What have been done (1/2)

In the MCs raw catalog, the eclipse column has flagged the planets to be "FALSE", "Grazing", "Semi-Grazing" and "TRUE".

Eclipse	Count
TRUE	766
Grazing	5
Semi-Grazing	26
FALSE	11

However, it is not clear how the flagging is done, and based on Edward et al. 2019, the assumed $\boldsymbol{b}_{\text{transit}}$ is 0.5.

What have been done (2/2)

In TPCs catalog, due to a lack of eccentricity and argument of periastron, there is no eclipse flagging.

Current Methodology: b_occ(1/2)

Just as b_{transit} defines the transit geometry, we can define b_{occ} as the impact parameter for eclipse geometry. According to Winn 2010,

$$b_{\text{occ}} = \frac{a}{R_\star} \cos i \left(\frac{1 - e^2}{1 - e \sin \omega} \right)$$

where:

- $a/R_\star$ = scaled semi-major axis (sampled as single parameter)
- i = orbital inclination
- e = eccentricity
- ω = argument of periastron

Current Methodology: b_occ(2/2)

According to Winn 2010, there could be three scenarios for eclipse geometry:

- $\boldsymbol{b}_{\rm occ} < \mathbf{1} - \boldsymbol{k}$: Eclipsing
- $\mathbf{1} - \boldsymbol{k} < \boldsymbol{b}_{\rm occ} < \mathbf{1} + \boldsymbol{k}$: Grazing
- $\boldsymbol{b}_{\rm occ} > \mathbf{1} + \boldsymbol{k}$: Beyond

where $\boldsymbol{k} = \boldsymbol{R_p}/\boldsymbol{R_\star}$.

Current Methodology: MCMC(1/2)

In MCs catalog, the $a/R_\star$, i, e and ω are provided with uncertainties.
In TPCs catalog, the same columns exist. However, $a/R_\star$ does not have uncertainties, and $i = 90$, $e = 0$ and $\omega = 0$ are set to constant.

I propose to use MCMC to sample those parameters and calculate the b_{occ} distribution for each planet in both catalogues, and see how the b_{occ} distribution matches the definition of "eclipsing", "grazing" and "beyond".

Current Methodology: MCMC(2/2)

MCMC samples 4 parameters to propagate uncertainties through $\boldsymbol{b}_{\text{occ}}$ calculation:

Parameter	Prior Distribution	Bounds
$\boldsymbol{a/R_\star}$	Gaussian (transit fit)†	$\mathbf{(0, \infty)}$
$\mathbf{cos}\ \boldsymbol{i}$	Gaussian (transit fit)†	$\mathbf{[-1, 1]}$
$\boldsymbol{e}$	Beta(α=0.867, β=3.03) + Gaussian*	$\mathbf{[0, 1)}$
$\boldsymbol{\omega}$	Uniform + Gaussian*	$\mathbf{[0^\circ, 360^\circ)}$

*Additional Gaussian constraint if RV measurements available

†Asymmetric error bounds from database are averaged for symmetric Gaussian prior

Configuration: 32 walkers, 3000 steps, 500 burn-in steps

MCMC Results (1/2)

MCMC Results Summary (808 MCS + 1638 TPC = 2446 total systems):

Statistic	MCS	TPC	All
b_{occ} Distribution			
Mean	0.452	0.000	0.128
Median	0.424	0.000	0.001
Std Dev	0.281	0.004	0.252
Min	$\mathbf{-0.948}$	$\mathbf{-0.026}$	$\mathbf{-0.948}$
Max	1.845	0.037	1.845
Acceptance Fraction			
Mean	0.513	0.496	0.501
Std Dev	0.045	0.002	0.025

TPC systems have near-zero $\boldsymbol{b}_{\mathrm{occ}}$ due to assumed circular orbits ($\boldsymbol{e = 0}$, $\boldsymbol{i = 90^\circ}$)

MCMC Results (2/2)

Visualization Strategy:

For each planet, we plot the posterior $\boldsymbol{b}_{\text{occ}}$ distribution showing:

- Median value (central estimate)
- $\pm\mathbf{1}\boldsymbol{\sigma}$ and $\pm\mathbf{2}\boldsymbol{\sigma}$ intervals (68% and 95% credible regions)
- Eclipse boundaries: $\mathbf{1}-\boldsymbol{k}$ (grazing threshold) and $\mathbf{1}+\boldsymbol{k}$ (beyond eclipse)

Key Insight: Comparing the $\boldsymbol{b}_{\text{occ}}$ distribution shape to the $\mathbf{1}\pm\boldsymbol{k}$ boundaries reveals the eclipse probability for each system, accounting for observational uncertainties in orbital parameters.

Visualization: MCs (1/2)

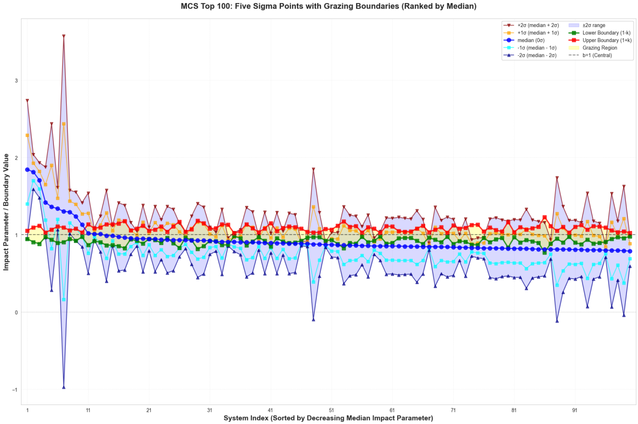


Figure: $\boldsymbol{b}_{occ}$ *distributions for top 100 MCS systems (violin plots)*

Visualization: MCs (2/2)

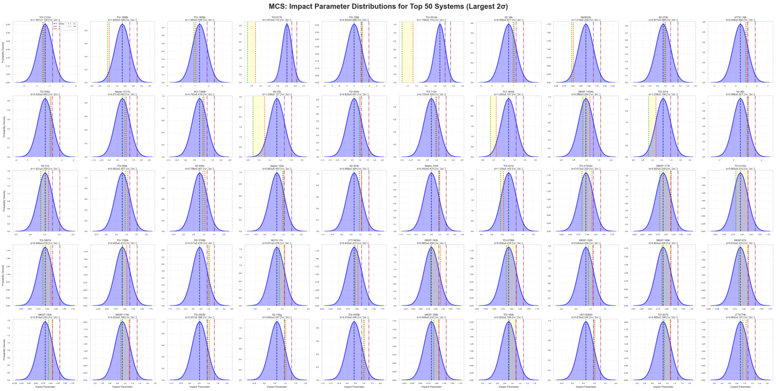


Figure: $\boldsymbol{b}_{occ}$ *distributions for top 50 MCS systems with eclipse boundaries*

Analysis: MCs (1/4)

MCS Systems Summary (808 systems with impact parameter data):

Level	**Central**	**Grazing**	**Beyond**
Median (0σ)	775 (95.9%)	23 (2.8%)	10 (1.2%)
$+1\sigma$	686 (84.9%)	83 (10.3%)	39 (4.8%)
$+2\sigma$	571 (70.7%)	101 (12.5%)	136 (16.8%)

Analysis: MCs (2/4)

Eclipse Depth by Impact Parameter Category (808 MCS systems):

Level	Category	Total	Observed	Mean Depth [%]
0σ	Central	775	97 (12.5%)	0.0383
	Grazing	23	2 (8.7%)	0.0482
	Beyond	10	0 (0.0%)	—
$+1\sigma$	Central	686	88 (12.8%)	0.0388
	Grazing	83	10 (12.0%)	0.0385
	Beyond	39	1 (2.6%)	—
$+2\sigma$	Central	571	76 (13.3%)	0.0307
	Grazing	101	16 (15.8%)	0.0820
	Beyond	136	7 (5.1%)	0.0365

Note: Mean depths calculated from systems with measured eclipse observations. Impact parameter uncertainty shifts systems from Central to Grazing to Beyond categories.

Analysis: MCs (3/4)

Eclipse Depth by Impact Parameter Category (808 MCS systems):

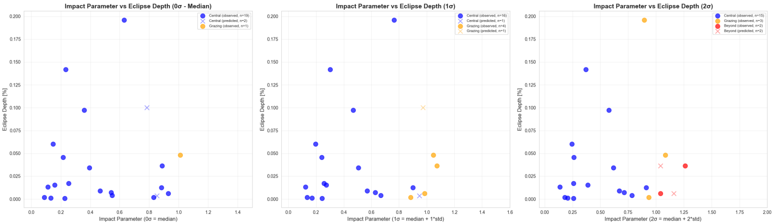


Figure: *Impact parameter vs eclipse depth across uncertainty levels (0σ, 1σ, 2σ)*

Analysis: MCs (4/4)

Cross-match: Original Eclipse Flagging vs Calculated b_{occ} Categories

0σ (Median)

Original	Cnt	Grz	Bey
TRUE	766	0	0
Semi-Grz	8	18	0
Grazing	0	5	0
FALSE	1	0	10
Total	775	23	10

$+1\sigma$

Original	Cnt	Grz	Bey
TRUE	685	62	19
Semi-Grz	1	19	6
Grazing	0	2	3
FALSE	0	0	11
Total	686	83	39

$+2\sigma$

Original	Cnt	Grz	Bey
TRUE	570	93	103
Semi-Grz	1	7	18
Grazing	0	1	4
FALSE	0	0	11
Total	571	101	136

Cnt = Central, Grz = Grazing, Bey = Beyond. Semi-Grz = Semi-Grazing.

As uncertainty increases, systems migrate from Central → Grazing → Beyond.

Analysis: MCs (4/4)

Original Eclipse Categories: Distribution Across Calculated b_{occ} Categories (%)

Level	Original	Central	Grazing	Beyond
0σ	TRUE	100.0%	0.0%	0.0%
	Semi-Grazing	30.8%	69.2%	0.0%
	Grazing	0.0%	100.0%	0.0%
	FALSE	9.1%	0.0%	90.9%
+1σ	TRUE	89.4%	8.1%	2.5%
	Semi-Grazing	3.8%	73.1%	23.1%
	Grazing	0.0%	40.0%	60.0%
	FALSE	0.0%	0.0%	100.0%
+2σ	TRUE	74.4%	12.1%	13.4%
	Semi-Grazing	3.8%	26.9%	69.2%
	Grazing	0.0%	20.0%	80.0%
	FALSE	0.0%	0.0%	100.0%

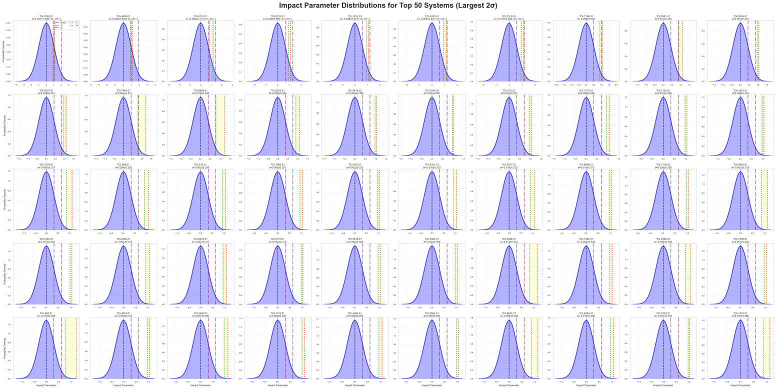
Key Findings:

- At 0σ (median): Near-perfect agreement for TRUE (100%) and FALSE (90.9%)
- At 1σ: Balanced uncertainty - TRUE 89.4% Central, FALSE 100% Beyond
- At 2σ: Conservative - 74.4% of TRUE systems still Central, 13.4% migrate to Beyond

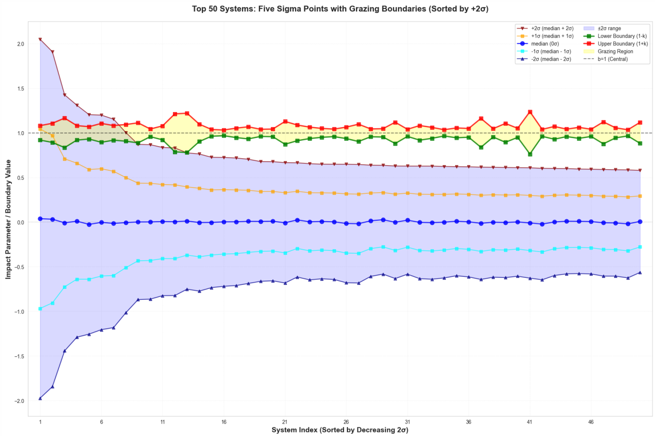
Issues encountered

- In TPCs catalog, $a/R_\star$ does not have uncertainties, and $i = 90$, $e = 0$ and $\omega = 0$ are set to constant. This leads to near-zero $b_{\rm occ}$ values and underestimates eclipse probabilities.
- Essentially their b_occ is almost like b_transit. And as they are sampled through transit detection, this doesn't help with target selection.
- How do I incorperate the geometric eclipse probability to Tiers, which is defined against SNR and has nothing to do with b_occ?

Visualization: TPCs



Visualization: TPCs



Option 1: Eccentricity Refinement (1/3)

Currently we adopted the beta distribution from Kipping (2013) as the prior for eccentricity sampling. Recent studies from Stevenson et al. (2025) suggested two local models for Rayleigh + Exponential (α, λ σ) might have a better estimation for planet with short period. It also tends to return a higher value for lower eccentricity.

Option 1: Eccentricity Refinement (2/3)

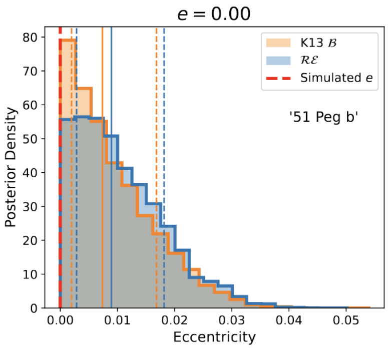


Figure 15. As for Figure 14, but with RVs simulated for an exactly circular 51 Peg b Keplerian. Neither posterior shows significant difference from the circular orbit interpretation, and shows that the new prior is not overly biasing results away from $e = 0$.

Option 1: Eccentricity Refinement (3/3)

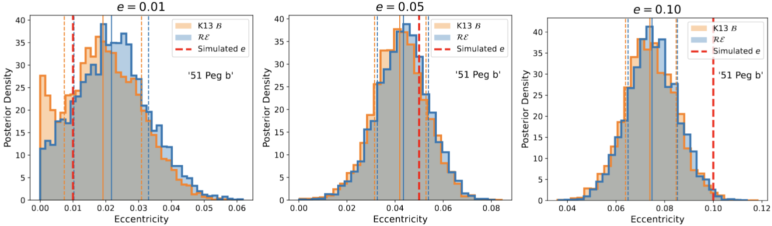


Figure 14. Eccentricity posterior histograms for KIMA runs of 51 Peg b, with two different priors. RVs are simulated in an attempt to recover ground truth eccentricities. Results are shown for signals with $e = 0.01, 0.05, 0.10$ (**left to right**).

Option 2: Eccentricity Probability

Winn (2010) also provided a geometric probability for eclipse:

$$P_{\text{eclipse}} = \left(\frac{R_\star + R_p}{a}\right)\left(\frac{1 + e\sin\omega}{1 - e^2}\right)$$

But this uses the same parameters as b_occ. Not sure whether this would provide additional information.

Option 3: Individual System Analysis

Analyze those with actual eclpises with lightkurve to validate the method. However, if it does have eclipse, what matter is transit depth and not much about b_occ, and as shown in previous MCs slides, there is no strong correlation between b_occ and eclipse depth. Not sure whether this methodlogy is valid.

More Options

Need more brainstorming...