BOREALIS: Milliarcsecond–Scale Stellar Characterization via Bayesian Analysis of Lunar Occultations

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Lunar Occultation (LO) fundamentals

When the lunar limb occults a star, a diffraction pattern arises, analogous to light passing a narrow slit. The fringes, described by the Fresnel diffraction equation, have non–uniform spacing and drift with the Moon's motion:

$$F(w) = I \times \frac{1}{2}\left[\left(C(w)+\frac{1}{2}\right)^2 + \left(S(w)+\frac{1}{2}\right)^2\right], \quad w = x\sqrt{\frac{2}{\lambda d}}$$

with Fresnel integrals

$$C(w) = \int_0^w \cos\left(\frac{\pi}{2}t^2\right)\mathrm{d}t, \quad S(w) = \int_0^w \sin\left(\frac{\pi}{2}t^2\right)\mathrm{d}t$$

In practice, the observed light curve is modified by stellar profile, telescope aperture, instrument response, sky background, and scintillationRichichi 1989:

$$I(t) = \beta + [1+\xi]\int_{-\infty}^{\infty}\mathrm{d}\phi\int_{-\frac{A}{2}}^{\frac{A}{2}}\mathrm{d}\alpha\int_{\lambda_1}^{\lambda_2}\mathrm{d}\lambda\int_{\Delta\tau}^{0}\mathrm{d}\tau\cdot F(w)S(\phi)O(\alpha)\Lambda(\lambda)T(\tau)$$

BOREALIS pipeline

We developed BOREALIS[a], a Python–based pipeline for high–precision analysis of lunar occultation events at Bosscha Observatory. It incorporates all relevant parameters a priori and provides the following features::

- synthetic data generator for testing purposes
- event type auto detection (e.g. disappearance, reappearance)
- N_{stars} auto detection, could be adjusted manually
- pre–compute grid to avoid unnecessary loops: wavelengths, lunar velocity
- robust init values taken from various sources e.g. Hipparcos catalogue (colors, to estimate T_{eff}), JPL ephemerides (lunar distance, position, and velocity)

Test using synthetic data

Check for robustness was conducted by deploying our pipeline to the synthetic datasets generated from a particular model, with various parameter combinations. The goal is to derive best–fit parameters for that particular dataset.

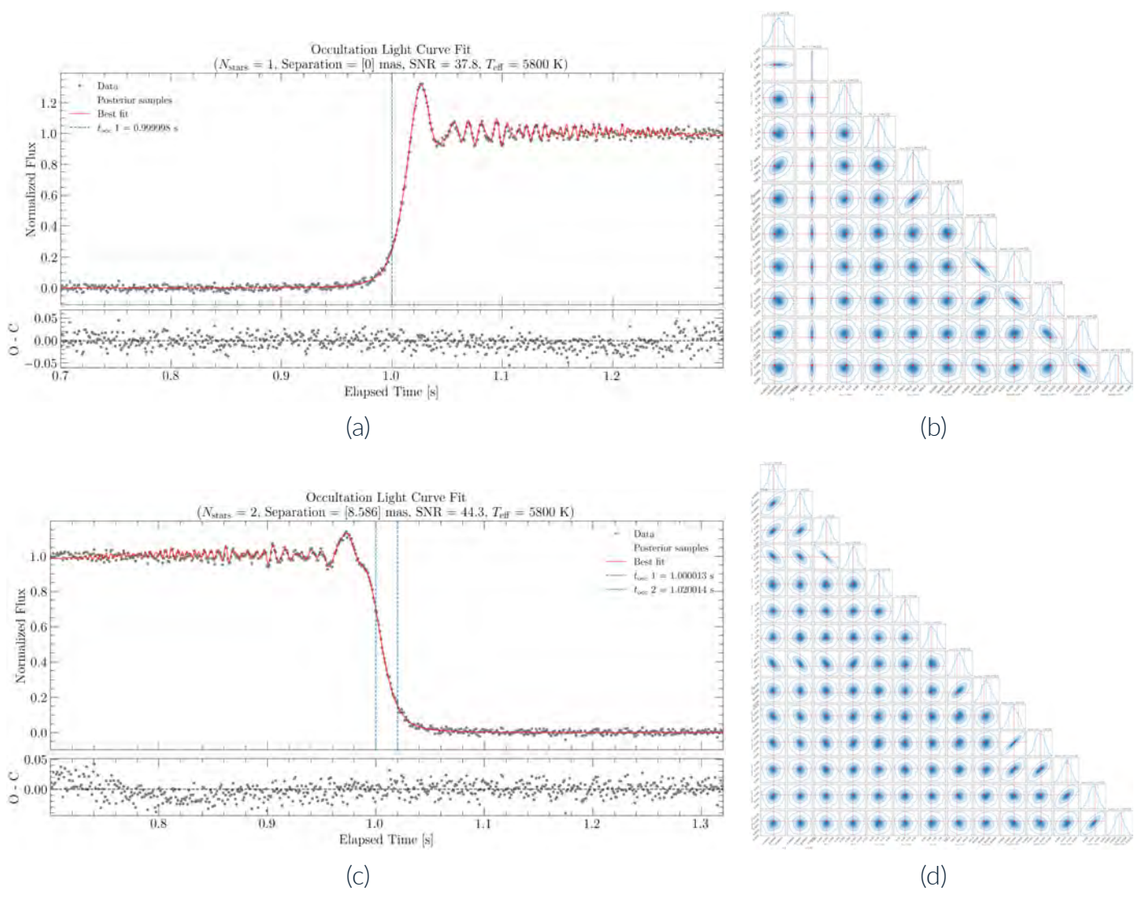


Figure 1. Synthetic dataset with the corresponding best–fit model (a, c) and posterior probability distributions of the model parameters (b, d). The top row is a single–star dataset, and the bottom row is a binary–star dataset.

[a]Bosscha Occultation Reduction and Analysis of Integrated Light Curve System

Real data application

All data were obtained with an 11–inch telescope using a GPS–synchronized QHY 174M CMOS camera.

SAO 158379

Also known as HD 123523, this star is relatively bright ($V = 6.85$). Observations on 8 July 2022 with a 20 ms sampling time yielded an SNR ~ 6, insufficient to detect binarity or multiplicity.

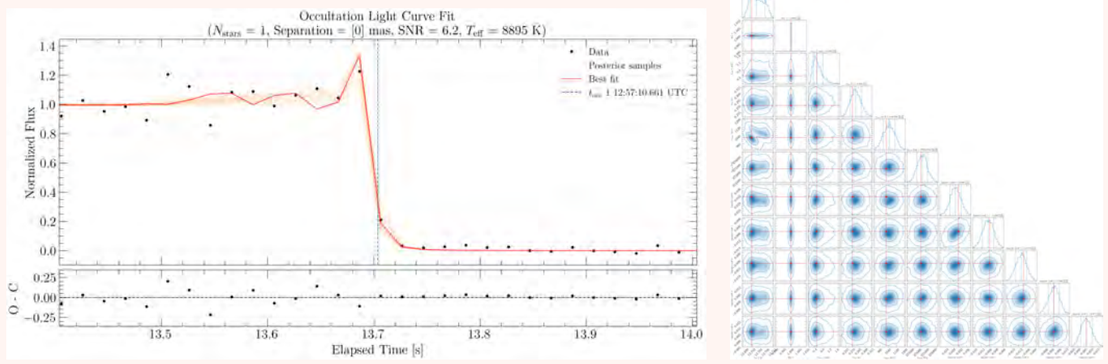


Figure 2. (a) Best–fit model and (b) posterior distributions for SAO 158379.

1 Gem

This object was observed on 15 November 2019 with a 15 ms sampling time. It is a triple system, with components AB separated by 0.1" and AC by 107". Despite the modest SNR, a distinct step in the light curve indicates the detection of the binary components.

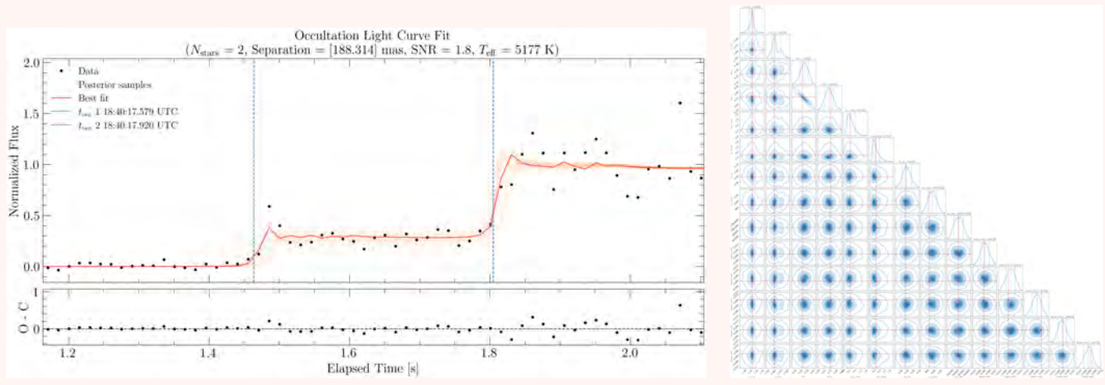


Figure 3. (a) Best-fit model and (b) posterior distributions for 1 Gem.

Conclusion

The results for the two events are summarized below.

Parameters	SAO 158379	1 Gem
Occultation time 1, $t_{\mathrm{occ},1}$	$12{:}57{:}10.6611^{+0.0027}_{-0.0038}$ UTC	$18{:}40{:}17.5790^{+0.0254}_{-0.0150}$ UTC
Occultation time 2, $t_{\mathrm{occ},2}$	-	$18{:}40{:}17.9201^{+0.0074}_{-0.0142}$ UTC
Flux 1, f_1	$1.00^{+0.00}_{-0.00}$	$0.29^{+0.06}_{-0.05}$
Flux 2, f_2	-	$0.71^{+0.05}_{-0.06}$
Star diameter 1, $\varnothing_1$	$0.50^{+0.19}_{-0.32}$ mas	$0.49^{+0.20}_{-0.32}$ mas
Star diameter 2, $\varnothing_2$	-	$0.48^{+0.17}_{-0.35}$ mas
Projected separation, $\Delta\theta$	-	$188.314^{+15.348}_{-15.348}$ mas

We conclude that BOREALIS represents a major step toward automated, high–precision lunar occultation analysis at Bosscha Observatory, enabling milliarcsecond–scale measurements of stellar diameters and binary separations. SAO 158379 remains unresolved within our detection limits, while for 1 Gem we derive a projected separation of 188.3 ± 15.3 mas at a position angle of 283.3°.

Acknowledgement

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References

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