Direct imaging of magma oceans in nearby young stellar associations

Irene Bonati [a,b], Tim Lichtenberg [*,b], Dan J. Bower [c], Sascha P. Quanz [d], Miles L. Timpe [e]

[a] Earth-Life Science Institute, Tokyo Institute of Technology, Japan
[b] Institute of Geophysics, ETH Zürich, Switzerland
[c] Center for Space and Habitability, University of Bern, Switzerland
[d] Institute for Particle Physics and Astrophysics, ETH Zürich, Switzerland
[e] Institute for Computational Science, University of Zürich, Switzerland
* *Presenter*, now at: University of Oxford, United Kingdom

irene.bonati@elsi.jp

Motivation

- Terrestrial planets are thought to undergo **multiple magma ocean (MO) stages** as a result of heat released during **accretion (giant impacts)**, **decay of short-lived radioisotopes** and **core formation**.
- Processes taking place during MO solidification set **initial conditions** for the planetary **chemical structure**, **atmospheric composition**, **tectonic behavior**, and **habitability**.
- **Next-generation direct imaging techniques** could lead to the detection of such bodies, thus providing observational constraints for theoretical models and insights into the origin and diversification of planets in our Solar System and beyond.
- We present a **quantitative assessment of the observability of MO planets in nearby young stellar associations (SA)** via future direct imaging facilities.

Methodology

I. N-body simulations[1]
→ **Occurrence rate of giant impacts (GI)** during planet formation around **A**, **G** and **M-stars**

II. 1D MO interior model[2]
→ **Surface temperature evolution** after GIs
→ MO cooling through **atmospheres** of **different emissivities ($0 \leq \varepsilon \leq 1$) + steam atmosphere**

III. Telescope parameters: IWA + sensitivity
- ELT ground telescope[3]
- Darwin-like space telescope[4]

→ Explore optimal **target selection strategy**
→ Constrain potential **detectability of MO bodies**

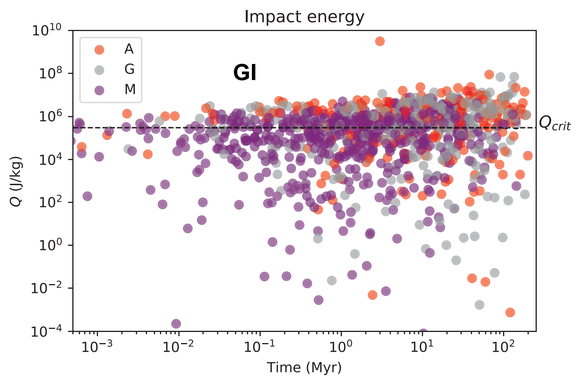
IV. Probability of detecting at least one magma ocean planet in nearby stellar association[5]

Association	d (pc)	Age (Myr)	No. stars A	G	M
β Pictoris	15	23	4	18	21
AB Doradus	20.1	150	0	23	8
β Tucanae	43	45	4	0	1
Tucana Horologium	48	45	2	27	5
Columba	50	42	2	37	1
TW Hydrae	53	10	2	0	33
Carina	65	45	0	22	0
32 Orionis	92	22	2	7	2
η Chamaeleontis	94	11	1	0	11
χ1 For	99	50	2	0	0

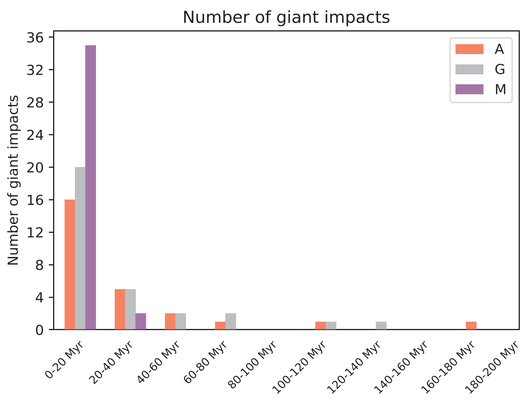
$$P_{\mathrm{MO}}(\lambda_{\mathrm{cen}}, \mathrm{d}, \tau_*, \epsilon) = 1 - \prod_{i=1}^{i=n_*} \left(1 - \frac{\bar{n}_{\mathrm{GI,i}} \cdot \Delta t_{\mathrm{obs}_{\bar{\mathrm{R}}},\mathrm{i}}}{\Delta t_{\mathrm{bin,i}}}\right)$$

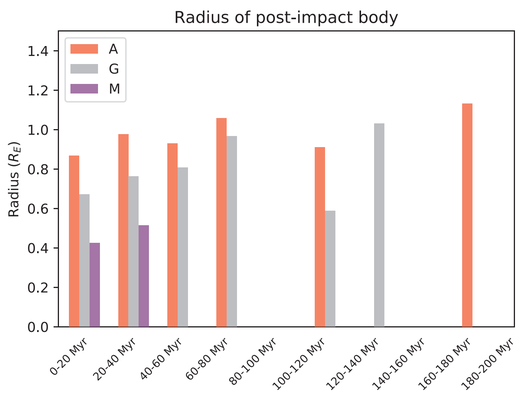
Results

I. Timing and energy of giant impacts

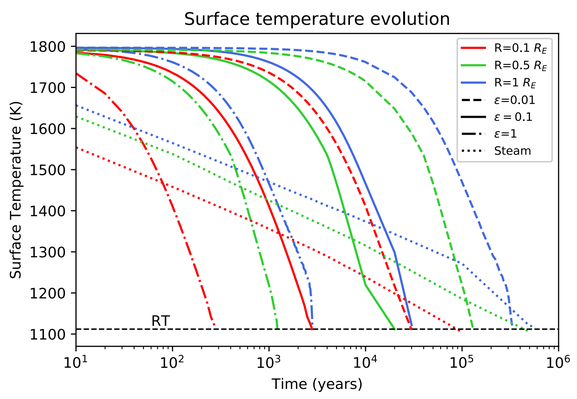


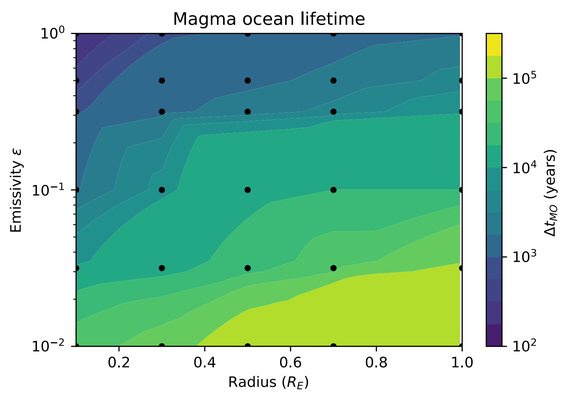
- $Q > Q_{crit}$ → **giant impact (GI)**
- Most GIs occur within the **first 20 Myr** of planet formation.
- Post-impact bodies have radii **$0.4\ R_{E} \leq R \leq 1.1\ R_E$**.





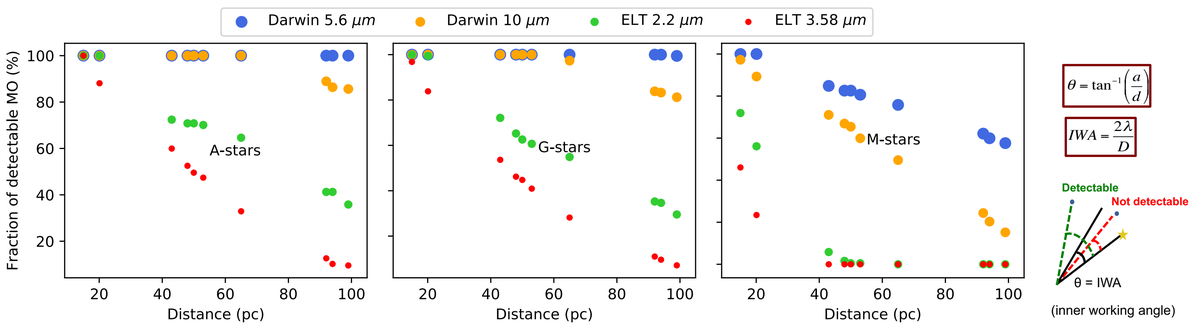
II. Magma ocean (MO) cooling timescales





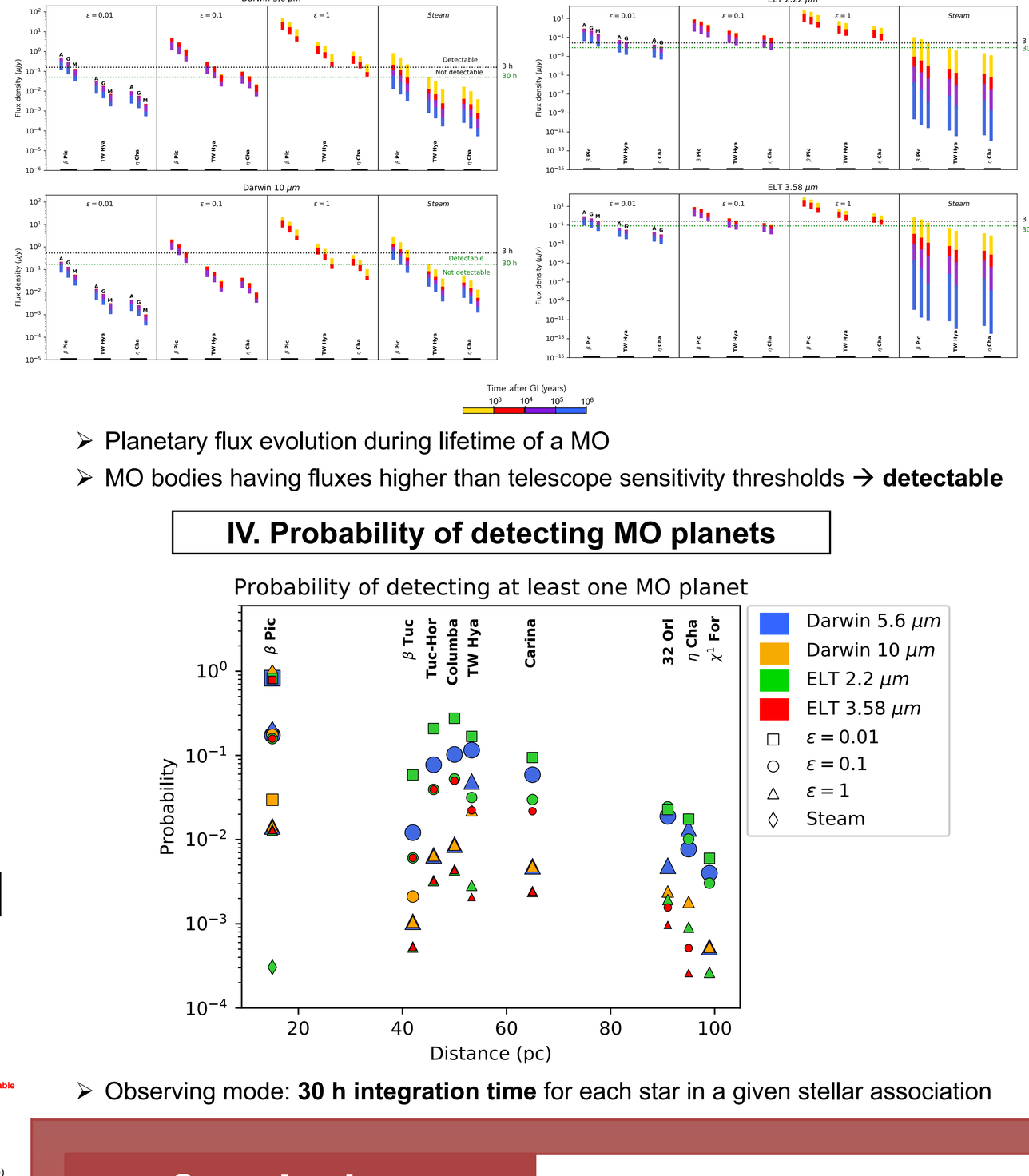
- Large planetary radius + low atmospheric emissivity → **long MO lifetime**
- Evolution of **steam atmosphere** results in longer sustained MO

III a. Detectability assessment: Inner Working Angle (IWA)



- MO planets at angular separations **θ ≥ IWA** → **detectable**

III b. Detectability assessment: sensitivity



- Planetary flux evolution during lifetime of a MO
- MO bodies having fluxes higher than telescope sensitivity thresholds → **detectable**

IV. Probability of detecting MO planets

- Observing mode: **30 h integration time** for each star in a given stellar association

Conclusions

- Target selection favoring **young** and **close** stellar associations containing a **large amount of stars** significantly **increases the likelihood of detecting a MO event**.
- **β Pictoris** is the association best suited for potential future observations of collision-induced magma oceans, both with Darwin and ELT configurations.

References

[1] Grimm & Stadel, ApJ, 796, 23 (2014)
[2] Bower et al., Phys. Earth Planet. Inter., 274,49-62 (2018)
[3] Brandl et al., SPIE (2016)
[4] Kammerer & Quanz, A&A, 204 (2018)
[5] Mamajek, Proc. IAU Symp. (2015) + ref. therein