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# Direct imaging of molten protoplanets in nearby young stellar associations

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## Abstract

During their formation and early evolution, terrestrial planets experience repeated global melting events from interactions with other protoplanets, similarly to the Moon-forming giant impact in Earth's history. The detection and characterization of such post-collisional afterglows (i.e., magma oceans) would provide direct observational constraints for theoretical models of planet formation, interior and atmospheric dynamics, as well as insights into the origin and diversification of planets in the solar system and extrasolar systems. Here, we quantitatively assess the prospects to directly detect molten protoplanets in nearby stellar associations with future direct imaging facilities. We find that the probability of observing magma ocean bodies significantly increases when focusing on young and close stellar targets, and varies significantly depending on the observation time and the distribution of atmospheric properties among rocky protoplanets [1].

## 1. Introduction

The late stage of planet formation is dominated by energetic impacts that can lead to extensive melting of planetary surfaces and mantles, resulting in global magma oceans. Processes taking place during the solidification of a magma ocean are of fundamental importance for the subsequent evolution of a planet, as they determine its early thermal and chemical structure, atmospheric composition, tectonic behavior, and ultimately its habitability [2].

The present study aims to quantify the likelihood of observing magma ocean planets in young stellar associations that are located within 100 pc from the Sun. The observability of hot molten planets is strongly controlled by the coupled evolution of a magma ocean and its outgassed atmosphere. The accumulation of over-saturated volatiles from degassing within the pre-existing atmosphere exerts a thermal blanketing effect that inhibits heat radiation to space and slows down the cooling of the interior [3]. Prolonged solidification timescales increase the probability of detection because a planet remains hotter for longer. However, the presence of dense and optically thick atmospheres can make magma ocean bodies appear less bright, thus hindering the direct observation of planetary surfaces.

## 2. Methods

The probability of detecting magma oceans in each one of the stellar associations is calculated using

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

where $P_{\mathrm{MO}}$ is the probability of detecting at least one magma ocean for a given telescope filter central wavelength $\lambda_{\mathrm{cen}}$, distance $d$ of the stellar association from the Sun, age of the stellar sample $\tau_*$, and planetary atmospheric emissivity $\epsilon$. $n_*$ is the number of stars of a given spectral type located inside a given stellar association. $\bar{n}_{\mathrm{GI,i}}$ is the number of detectable giant impacts taking place within a specified time interval of planet formation ($\Delta t_{\mathrm{bin,i}}$) comprising the age of the considered stellar association. $\Delta t_{\mathrm{MO}_{\bar{\mathrm{R}}},\mathrm{i}}$ indicates the time interval within which a magma ocean planet with radius $\bar{R}$ is bright enough to be detected by a given telescope.

We use performance estimates for near- and mid-infrared instruments to be installed at ESO's Extremely Large Telescope (ELT), and a potential space-based mission called Large Interferometer for Exoplanets (LIFE) [4]. The telescope parameters used for the detectability assessment are the inner working angle (IWA) and the sensitivity. A planet is considered to be detectable if its angular separation exceeds the instrument's IWA, and if its total flux observed in a specific band is higher than the instrument's sensitivity.

We constrain the occurrence rate and timing of magma ocean-inducing impacts by simulating planet formation around A- (2 $M_\odot$), G- (1 $M_\odot$) and M-type (0.5 $M_\odot$) stars during 200 Myr of evolution. The thermal evolution of the resulting magma ocean is investigated using an energy balance model with self-consistent thermodynamics of melt and solid silicate phases [5]. We track the planetary surface temperature evolution for various planetary sizes using two different models for the efficiency of heat transport in the atmosphere, namely (1) a grey body, where the insulating effect of the atmosphere is parameterized using an effective emissivity $\epsilon$ [6], and (2) a steam atmosphere parameterization [7].

## 3. Results

The probabilities of detecting at least one magma ocean planet in young nearby stellar associations are shown in Figure 1 for an integration time of 50 hours and various parameter combinations. A young stellar age translates into a high number of expected giant impacts, and thus a high detection probability. Planets with thick atmospheres (i.e, low atmospheric emissivities) are the most likely to be directly observed due to their long-lived magma oceans, although the atmosphere could be sufficiently dense to prevent the surface from being imaged. In contrast, a less dense atmosphere will pose less of a barrier to observing the planetary surface, but it will enable a magma ocean to cool faster, thus lowering the observation likelihood.

As a result of their favorable inner working angles and sensitivities, the highest detection probabilities are obtained for intensive reconnaissance using a K band (2.2 µm) ELT filter or a 5.6 µm LIFE filter. The most promising stellar targets to be explored in these scenarios are $\beta$ Pictoris, followed by Columba, TW Hydrae, and Tucana-Horologium.

## 4. Summary and Conclusion

Our work provides first-order predictions for the detectability of protoplanetary collision afterglows using performance estimates of next-generation direct imaging instruments, simulations of giant impact occurrence rates during planet formation around different star types, and magma ocean cooling models for bodies of various sizes and atmospheric properties. Overall we find that:

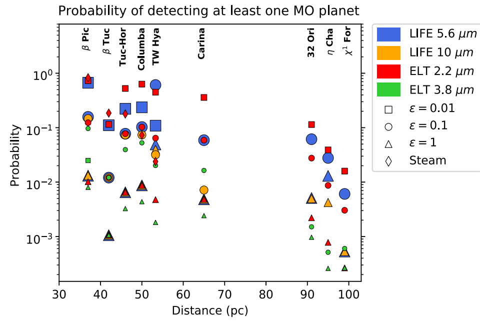


Figure 1: Probability of detecting at least one magma ocean planet in nearby stellar associations for an observation time of 50 hours. The colors and shapes refer to different telescope filters and planetary atmospheric properties, respectively.

- Target selection favoring young and nearby stellar associations containing a large amount of stars significantly increases the likelihood of detecting a magma ocean planet.
- For sufficiently long integration times with a K band (2.2 µm) ELT filter or a 5.6 µm LIFE filter, the $\beta$ Pictoris association is best suited for future observations of magma ocean bodies.

Our results inform the exploration of molten protoplanets in the solar vicinity using (near-)future ground- and space-based direct imaging facilities and motivate renewed efforts to explore the diverse thermal and atmospheric properties during the magma ocean phase of young rocky worlds.

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