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Direct imaging of magma oceans in nearby young stellar associations

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Abstract

During their formation and early evolution, terrestrial planets experience repeated global melting events (so-called magma oceans) from interactions with other protoplanets, similar to the Moon-forming giant impact in Earth's history. The detection and characterization of post-collisional afterglows provides 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 observational prospects to detect magma oceans in nearby young stellar associations with future direct imaging facilities. We find that probabilities of detection significantly increase when focusing on young and close stellar targets, and are highest for the β Pictoris association.

1. Introduction

With the advent of a number of imminent ground- and space-based missions, a comprehensive assessment of the potential detectability of bodies in their formation stage is desired. The present study aims to quantify the likelihood of observing magma ocean planets inside ten 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 within the pre-existing atmosphere exerts a thermal blanketing effect that inhibits heat radiation to space and slows down the cooling of the interior. 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 [1].

2. Methods

The probability P_{MO} of detecting at least one magma ocean event in each of the stellar associations is calculated using

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

for a given telescope filter central wavelength λ_{cen}, distance d of the stellar association from the Sun, age of the stellar sample τ_*, and planetary atmospheric emissivity ϵ. 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 ($\Delta t_{\mathrm{bin,i}}$ = 20 Myr), which accounts for the age of the considered stellar association. $\Delta t_{\mathrm{obs_{\bar{R}},i}}$ indicates the time interval within which a magma ocean planet with radius $\bar{R}$ is bright enough to be detected.

The telescope parameters used for the detectability assessment are the inner working angle (IWA) and the sensitivity. A planet is considered as 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 consider two filters each for a space-based interferometer similar to the ESA Darwin concept, and ESO's ground-based Extremely Large Telescope (ELT).

We use the N-body code GENGA [2] to constrain the occurrence rate and timing of magma ocean-inducing impacts during terrestrial planet formation around different star types. For every collision we calculate the specific impact energy Q [3] and determine the size of the resulting post-impact body.

The thermal evolution of magma ocean planets is investigated using an energy balance model with self-consistent thermodynamics of melt and solid silicate phases [4]. We track the surface temperature evolution for various planetary sizes using two different models for the efficiency of heat transport in the atmosphere, namely (1) a gray body, where the insulating effect of the atmosphere is parameterized using an effective emissivity ϵ , and (2) a steam atmosphere parameterization [5].

3. Results

The probabilities of detecting at least one magma ocean planet in young nearby stellar associations (calculated according to Equation 1) within an observation time of 30 hours are shown in Figure 1 for different observation strategies and planetary parameters.

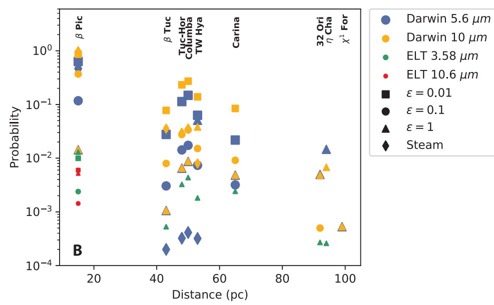

Figure 1: Probability of detecting at least one magma ocean planet in nearby stellar associations for 30 hours integration time with either the Darwin or ELT observing concepts. The colors and shapes refer to different telescope filters and planetary atmospheric emissivities, respectively.

A young stellar age translates into a high number of expected giant impacts. Therefore, the younger a stellar association and the more stars of a given type it contains, the higher the probability of detecting at least one magma ocean planet. Planets with lower emissivities are the most likely to be directly observed due to their long-lived magma oceans, but the atmosphere could be sufficiently dense to prevent the surface from being imaged at all. 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.

In general, ELT/METIS displays only low detection probabilities, even for bodies with negligible atmospheric effects (i.e. high emissivity). Contrarily, due to its higher resolution and sensitivity, a space-based interferometer similar to the ESA Darwin concept is the preferred instrument for magma ocean exploration. The most promising stellar targets to be explored are β Pictoris, Columba, Tucana-Horologium and TW Hydrae.

4. Summary and Conclusions

Our work provides first-order predictions of 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 models of magma ocean cooling for bodies of various sizes and atmospheric emissivities. Overall we find that:

- 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 to fully exploit the number of planetary systems, the β Pictoris association is best suited for future observations of magma ocean bodies.

These findings motivate the need for a large space-based mid-infrared interferometer alike Darwin for future explorations devoted to the study of the formation and early evolution of planetary bodies.

References

[1] Massol, H., Hamano, K., Tian, F., et al.: Formation and Evolution of Protoatmospheres, Space Sci. Rev. 205, 153–211, 2016.

[2] Grimm, S. L. and Stadel, J. G.: The GENGA code: Gravitational encounters in N-body simulations with GPU acceleration, Astrophys. J. 796, 23–39, 2014.

[3] Leinhardt, Z. M. and Stewart, S. T.: Collisions between Gravity-dominated Bodies. I. Outcome Regimes and Scaling Laws, Astrophys. J. 745, 79–106, 2012.

[4] Bower, D. J., Sanan, P. and Wolf, A. S.: Numerical solution of a non-linear conservation law applicable to the interior dynamics of partially molten planets, Phys. Earth Planet. Inter. 274, 49–62, 2018.

[5] Zahnle, K. J., Kasting, J. F. and Pollack, J. B.: Evolution of a steam atmosphere during Earth's accretion, Icarus 74, 62–97, 1988.