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Introduction: The possibility that Venus had an earlier temperate period at some point in its history has been supported in a number of works [1,2,3]. Yet how Venus went from habitable to hellish remains a largely unexplored parameter space. This transition may also be relevant to Earth's deep time future, but also to exoplanetary worlds being discovered around nearby stars.

Early work proposed that the gradual brightening of our sun over the eons would be sufficient to drive the planet into a runaway greenhouse state [4]. Yet Venus at 4.2Ga received 1.4 times the incident flux that Earth receives today. Given that Earth is already considered to be near the inner edge of the habitable zone [5, Fig 8] this does not seem a tenable option for Venus. Early work showed that a high cloud albedo feedback was required to maintain temperate conditions on Venus [6]. More recent work [3,7] has demonstrated that a slowly rotating Venus can provide such clouds and that the cloud albedo feedback is so effective that it may work even at Venus' present-day insolation (nearly 2x Earths!). The question remains, how can a world like Venus transition to a hot-house state? We propose that the mechanism may be one that has been observed here on Earth, Large Igneous Provinces (LIPs) [8,9]. As documented in [8] LIPs have taken place throughout Earth's history and have been responsible for a number of mass extinction events via global climatic change [10]. Where the LIP is emplaced may be critical since a large LIP emplaced in carbonate/volatile rich sediments [11] may release more CO_2 than one emplaced at the bottom of the ocean where a more muted impact is likely. The ambient surface temperature into which the LIP is emplaced is also critical. There is some evidence [12] that the bottom ocean water temperatures 3.5Ga could have been 50-60C higher than those today! Finally, there is the possibility that Earth has been fortunate that there have never been two large LIP events in the same temporal period. It is this last possibility that we investigate herein. We use Earth as our proxy since it has a similar size, density and assumed geochemistry to that of Venus [13].

Methods: We start with the most complete record of LIP events through time on Earth [8] going back to 2.8 Ga. We examine the record and find that it appears to be consistent with approximately random and uniformly distributed through time by comparing to a purely Poisson cumulative distribution function. Even if there is periodicity in the record as some studies have shown [14] it only increases the likelihood of overlapping LIPs. We then do a large number of Monte Carlo simulations based on this record and examine the likelihood of overlapping events using a bootstrap like method on the simulations.

Conclusions: In our analysis of the Earth LIP record we find that pairs and triplets of LIP events closer in time than 0.1 to 1 x 10^6 years are likely. We chose these times given that the environmental impact of some LIPs span this range [15]. We also examined the LIPs with the largest areal extent and again we find overlap highly probable. In future we will examine how a temperate climate evolves in such a scenario, using General Circulation Models similar to those modeling LIP climatic impacts [15].

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References: [1] Grinspoon, D.H. & Bullock, M.A. (2007) AGU https://doi.org/10.1029/176GM12. [2] Way, M. J. et al. (2016) GRL 43, 8376–8383. [3] Way, M. J. and Del Genio, A D. (2020) JGR Planets 125, e2019JE006276. [4] Kasting J. F., Pollack J. B. and Ackerman T. P. (1983) Icarus*, 57,* 335-355. [5] Kopparapu, R.K. et al. (2013) ApJ 765, 131. [6] Pollack (1971) Icarus 14, 295. [7] Yang, J. et al. (2014) ApJ 707, L2. [8] Ernst R. E. et al. (2021) AGU Geophys. Mon. 255, pp. 3-26. [9] Coffin M. F. and Eldholm O. (1997) Reviews of Geophysics, 32, 1, pp. 1-36. [10] Wignall, P. (2001) Earth Science Reviews, 53 (1-2), 1-33. [11] Svensen et al. (2009) EPSL 277, 490. [12] Tartese R, et al. (2017) Geochem Perspect Lett 3, 55 [13] Treiman, A. H. (2009). In Venus geochemistry: Progress, prospects, and new missions, Vol. 1470, pp. 47–48. [14] Prokoph et al. (2013) Geosci. Front. 4, 263. [15] Black B. A. et al. (2018) Nat Geo, 11, 949