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Introduction Atmospheric evolution and escape, when coupled to a magma ocean, leads to metallic gas and plasma tori in our solar system and beyond (Oza et al. [1]; Charnoz et al. [2]). The recent technique of *evaporative* transmission spectroscopy has enabled the study of escaping metals and grains in gas absorption via radiative transfer simulations during transit (Seager and Sasselov [3]; Gebek and Oza [4]).

Here, with keen interest for the newly launched JWST spacecraft to capture evaporating magma oceans and volcanism in the mid-infrared with MIRI [5], we develop a toy model to assess the average abundance of $\sim \mu\text{m}$ grains at close-in rocky exoplanet and exomoon systems.

Candidate Volcanic Systems Candidate systems are identified based on their prodigious heating rates by the stellar tide Quick et al. [6] or their sodium and potassium (Na/K) signatures Oza et al. [1]. For their stark similarities to Io, these systems are often referred to as Super-Ios (super-Earth sized exoplanets) and exo-Ios (evaporating/disintegrating exomoons).

Surface-Atmosphere Model We employ two independent magma ocean vaporization codes (Oza et al. 2019b; Charnoz et al. 2021) to study the Hill sphere and Roche limit of close-in rocky exoplanets. This exercise illuminates possible circumplanetary environments immediately accessible in the thermal infrared based on reasonable geophysical assumptions.

Atmosphere-Exosphere Model The secondary atmosphere of a close-in rocky exoplanet not only experiences extreme outgassing but also extends far beyond to a length scale dR . This length scale is *independent* the scale height of the atmosphere. This length scale is the pull from the star on the planet, similar to the Earth's tide on the proto-Moon. Gas escape is calculated via energy-limited escape easily $\dot{M} \sim Q/U$, but the dust escape of grains of $r_g \sim 0.1 \mu\text{m}$ size is more difficult to probe, motivating this volcanically-coupled model.

Given a broadband flux decrease of (dF/F) the observed occulting cloud radius is:

$$dF/F = \left(\frac{R_c}{R_*}\right)^2 \quad (1)$$

The above radius is of course of unknown geometry but we assume the differential area is that of a circle so

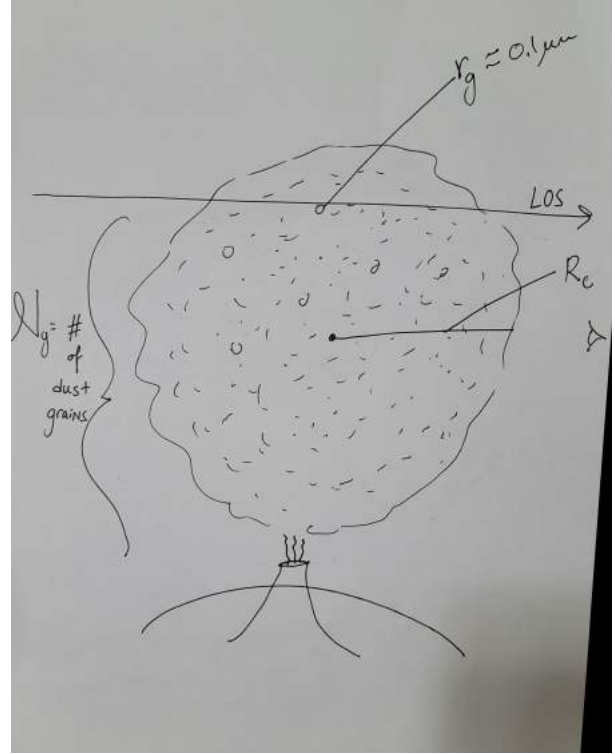


Figure 1: Schematic diagram of the surface-atmosphere system. A volcanic cloud of radius R_c evaporated into the orbit of a tidally-heated close-in exoplanet. N_g is the total number of dust grains derived from Eqn. 2. The radius of a dust grain, r_g is set to be $\approx 0.1 \mu\text{m}$, which is used as a free parameter depending on the wavelength to be probed along the line-of-sight (LOS).

that $dA_c \approx \pi R_c^2$. An occulting cloud of dust grains of quantity N_g will be of the same geometry, so that

$$dA = N_g \pi r_g^2 \pi R_c^2 = N_g \pi r_g^2 \Rightarrow N_g = \left(\frac{R_c}{r_g}\right)^2 \quad (2)$$

This permits us to easily derive the average line-of-sight (LOS) column density of grains during transit (Johnson Huggins 2006; Oza 2019):

$$\bar{N}_{LOS} = \frac{N_g}{\pi R_*^2} \quad (3)$$

where geometry dictates the average vertical column density N_v is related to the LOS column via the Chapman enhancement factor so that:

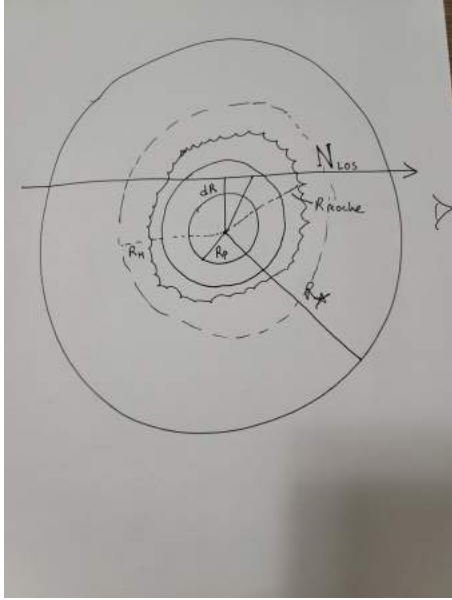


Figure 2: Schematic diagram of atmosphere-exosphere system highlighting several lengthscales during relative to the stellar radius R_* : The Hill sphere R_H , Roche limit, R_{Roche} , the observed photometric radius of the planet R_p , and finally a canonical gas at altitude $\sim dR$ above the planet.

$$\bar{N}_{LOS} = N_v \sqrt{2\pi \frac{R_p}{dR}} \quad (4)$$

These two geometrical derivations of the LOS column density are independent of each other and can therefore be used to derive either the scale height of the atmosphere, or the vertical column densities N_v via $\bar{N}_v \approx \bar{N}_{LOS}$. The observations require one assumption either on the magnitude of N_v (sourced by vaporization of a magma ocean or volcanism) or dR (a length scale that has a minimum due to either the isothermal scale height $H = k_b T / \mu m g$ or the tidal length scale $dR_T \sim U_T / g$, both of which are ≈ 100 km).

Discussion All giant planets (icy & gaseous) possess rings in our solar system. Neptune’s rings for instance were predicted before the Voyager 2 flyby by Rawal [7]. Burns et al. [8] was also able to describe the origin and formation of Jupiter’s gossamer rings by the impact and evaporation of Amalthea, ongoing today. Dust grains at close-in exoplanet systems should be the same.

Summary Exorings appear to be inevitable at close-in rocky exoplanet systems. Extreme temperatures coupled with atmospheric loss or ionization will result in vaporized magma ocean atmospheres whose gas will orbit the parent planet. As current visible and ultraviolet data appear to suggest the presence of a variable cir-

cumstellar torus sourced by volcanic escape at a rocky-exoplanet system (Oza 2021). This companion paper suggests that future infrared spacecraft may reveal the presence of variable circumplanetary tori. The ballistic and orbital timescale of the dust grains we study show that these volcanic exorings may pulsate, and if atmospheric escape is sufficient, drive a plasma tail ahead of the planet. Evidence of exorings so far appear at J1407b Kenworthy et al. [9] and several alkali-rich gas giant systems Oza et al. [1]. Monitoring close-in rocky exoplanets may be far more efficient with particular interest to the newly launched JWST/MIRI spectrograph [5].

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