VOLCANISM ON MAGMA PLANETS: EXTREME VOLCANISM IS REGULATED BY PLANET MASS, TEMPERATURE, AND INITIAL COMPOSITION.

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Summary: The daysides of short-period rocky exoplanets, which are now being observed [1-3], are long-lived surface magma pools. We provide estimates of magma-planet outgassing rates and magma composition. Atmospheric pressure tends toward vapor-pressure equilibrium with surface magma, and surface composition is set by the competing effects of fractional vaporization and surface-interior exchange. We use basic models to show how surface-interior exchange is controlled by the planet's mass, temperature, and initial composition. We find:- (1) atmosphere-interior exchange is fast enough to buffer surface composition when the planet's bulk-silicate FeO concentration is low, and slow when FeO concentration is high; (2) magma pools are compositionally well-mixed for substellar temperatures $\lesssim$2400 K, but compositionally patchy and rapidly variable for substellar temperatures $\gtrsim$2400 K; (3) magma currents within the magma pool cool the base of the magma pool ("tectonic refrigeration"), so the usual upper boundary condition for modeling the solid-mantle circulation of hot rocky exoplanets is too warm; (4) contrary to earlier work, many magma planets have time-variable surface compositions.

Background: Over one hundred exoplanets have masses or radii in the rocky-planet range, and substellar equilibrium temperatures hot enough to melt peridotite rock (e.g. CoRoT-7b, Kepler-10b, and WASP-47e) [4-6].These molten surfaces are tantalizing because they are relatively easy to detect and characterize [1-3] - what sets molten-surface composition? The melt-coated dayside is exposed to intense insolation, sufficient to remove H_2 [7] and to maintain a thin silicate atmosphere [8] (Fig. 1). The most-volatile rock-forming element constituents of the melt (e.g. Na, K, Fe) preferentially partition into the atmosphere. These atmospherically transported volatiles are cold-trapped on the permanent nightside, or lost to space (Fig. 1). If trans-atmospheric distillation is faster than mass exchange between the melt pool and the solid interior, then surface composition will differ from bulk-planet silicate composition. But if mass exchange between the melt pool and solid interior is fast, then surface composition will be repeatedly reset towards bulk-planet silicate composition.

In the first (compositionally evolved) case, with relatively slow atmosphere-interior exchange, preferential loss of volatiles (Na, K, Fe ...) creates a refractory Ca-Al-rich lag [9]. The lag armors the vulnerable volatile-rich interior, as on a comet. After lag formation, atmospheric pressure will be everywhere $\lesssim O(1)$ Pa. In the second (compositionally buffered) case, Na, K, and Fe are replenished by surface-interior exchange; the exosphere fills with Na and K; and surface compositional evolution is extremely slow: it is buffered by the whole planet's silicate mass.

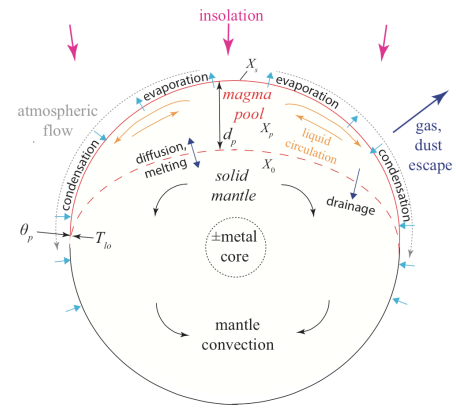

Fig. 1. Processes shaping the surface composition of a hot rocky exoplanet. Magma pool (depth d_p, mean composition X_p, surface composition X_s) overlies a solid mantle (composition X_0). d_p is shown greatly exaggerated. T_{lo} corresponds to the lock-up temperature that defines the edge of the melt pool. θ_p corresponds to the angular radius of the melt pool.

To what extent does fractional evaporation drive the hot rocky exoplanets' dayside surface composition? We set out to determine the rates of surface-atmosphere versus surface-interior exchange. To do this, we quantify the key controls on magma pool surface composition (Fig. 1): stirring of the melt pool by horizontal convection, chemical distillation of the pool through atmospheric flow, and (crucially) the buoyancy evolution of melt pools undergoing fractional evaporation (Fig. 2).

Model: In order for surface composition X_s to deviate from pool-average composition X_p (Fig. 1), the ocean mixing timescale τ_T must be shorter than the time (τ_X) needed for evaporatic ablation by fractional vaporization (advection). We use simple scalings for the ocean overturning circulation [10]. To find the fractional vaporization rate, we need a model of the winds, which we adapt from vertically-averaged models of Io's sublimation-driven atmosphere [11,12]. The ratio τ_X/τ_T decreases with temperature because evaporation increases much more quickly with temperature than thermal diffusion in the liquid. (Thermal diffusion in the liquid is needed to drive upwelling in horizontal-circulation). Neither winds nor currents much affect surface energy balance, which is set by radiative equilibrium (for $T \lesssim$ 3000K). Next, we use the MAGMA code [8,13], plus literature equations-

of-state [14], to investigate whether the density of the chemically-fractionated reservoir (the residual magma left behind during fractional evaporation) is less than initial density throughout fractional evaporation. This determines whether the fractionating reservoir is unstable to sinking (Fig. 2).

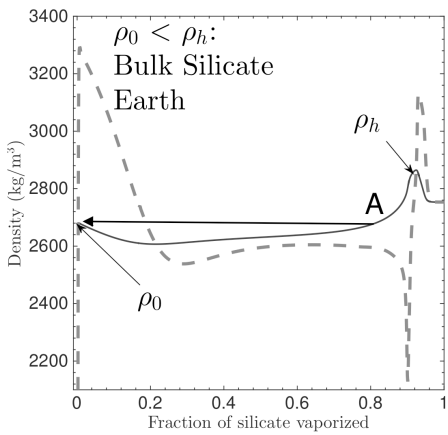

Fig. 2. Density evolution for fractional vaporization (at 2000K) of an initial composition corresponding to Bulk Silicate Earth. Thin black solid curve corresponds to the density of residual magma, and thick gray dashed curve corresponds to the density-upon-condensation of the gas. At point A, the surface boundary layer sinks into the interior. ρ_h corresponds to the maximum density at >70 wt % fractional vaporization. ρ_0 corresponds to unfractionated magma density.

Results: Results are summarized in Fig. 3. Magma-pool overturning circulation and differentiation can be viewed as a new tectonic mode for rocky planets at temperatures too high for plate tectonics, stagnant-lid convection, or heat-pipe recycling. Surface-interior exchange on magma planets is driven by near-surface contrasts in melt density (and can shut down if the surface layer becomes stably buoyant). In turn, these density effects are regulated by two factors (Fig. 3). (1) Relative vigor of winds and currents. For substellar temperature $\lesssim$2400K ("ocean-dominated" worlds), magma-pool overturning circulation outruns net evaporation, and pool surface composition tracks bulk pool composition. For substellar temperature $\gtrsim$2400K ("atmosphere-dominated" worlds), pool overturning circulation is slow compared to atmospheric transport, and fractional evaporation drives pool composition away from the composition of the bulk of the pool. (2) Exposure of the planet's building-blocks to H_2O. If we assume a radial temperature gradient similar to the solar nebula, then if the planetesimals that formed the planet grew >1 AU from the star, water rock reactions will lead to high Fe-oxide concentrations in the planet's silicate mantle. Close to the star, preferential evaporation of volatile and dense Fe favors stable stratification of the residual magma. This may allow a buoyant, stable lag to form a compositionally-evolved surface. However, if the planetesimals that formed the planet are reduced (low mantle FeO), fractionally-evaporated residual melt will sink. The concomitant resurfacing will repeatedly reset the surface composition to the planet-averaged silicate composition.

Tests: Magma composition may be constrained using atmospheric column densities of Na and K [15], surface spectra [16], and the properties of dust streaming from disintegrating magma planets such as K2-22b [17].

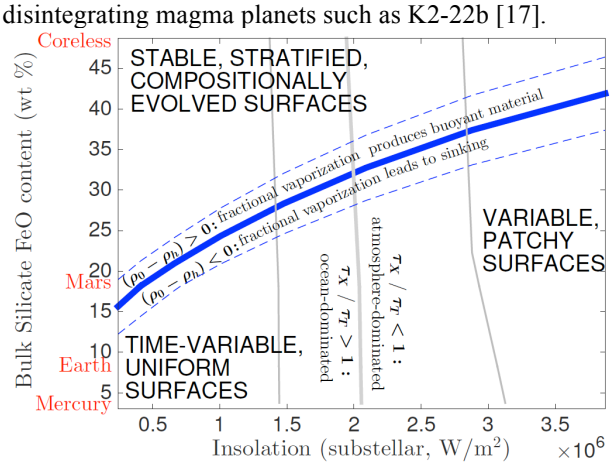

Fig. 3. Magma planet phase diagram. Stratification index (ρ_0 - ρ_h) is contoured at +50 kg/m^3 (top dashed blue line), 0 kg/m^3 (thick solid blue line), and -50 kg/m^3 (bottom dashed blue line). Planets below the line are unlikely to have CaO/Al_2O_3-dominated surfaces, planets above the line are likely to have CaO/Al_2O_3-dominated surfaces. Ocean-dominance index τ_X/τ_T is contoured at 10 (left gray line), 1 (thick gray line), and 0.1 (right gray line), for 50 wt% vaporization. Lower-left quadrant corresponds to magma pools with uniform, but time-variable surfaces, well-stirred by currents. Lower-right quadrant corresponds to atmosphere-dominated magma pools with variable, patchy surfaces driven by evaporative overturn. Upper two quadrants correspond to planets with stable, stratified, CaO/Al_2O_3-dominated surfaces. Calculations assume planet period 0.84 days, radius 1.5× Earth, and gravity 1.9× Earth (= Kepler-10b).

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