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Prospects for Detecting Cryovolcanic Activity in Exoplanetary Systems

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Introduction

"Ocean planets" are a class of water-rich exoplanets [1-7] that could resemble larger versions of the icy satellites of the outer planets [2-3, 8-9]. Geophysical processes operating on these cold, low-density worlds may be similar to processes operating on our solar system's icy moons. Chief among these processes is explosive cryovolcanism [10-14] (Fig. 1). Cryovolcanic activity on icy satellites may indicate the presence of a subsurface fluid reservoir, possibly, an internal ocean. By analogy, surface venting on cold ocean planets could be indicative of fluid reservoirs within. Given the limits of current instrumentation, spectroscopic detection of H_2O and other molecules explosively vented onto planetary surfaces may be the the only way to infer the presence of subsurface oceans in these bodies. Detections of cryovolcanism on cold, H_2O-rich worlds could therefore be used as a proxy to constrain their habitability. Here, we discuss the prospects for detecting this dynamic processes using next-generation telescopes. Our results suggest that searches for plume activity on icy exoplanets should be a priority in the coming decades.

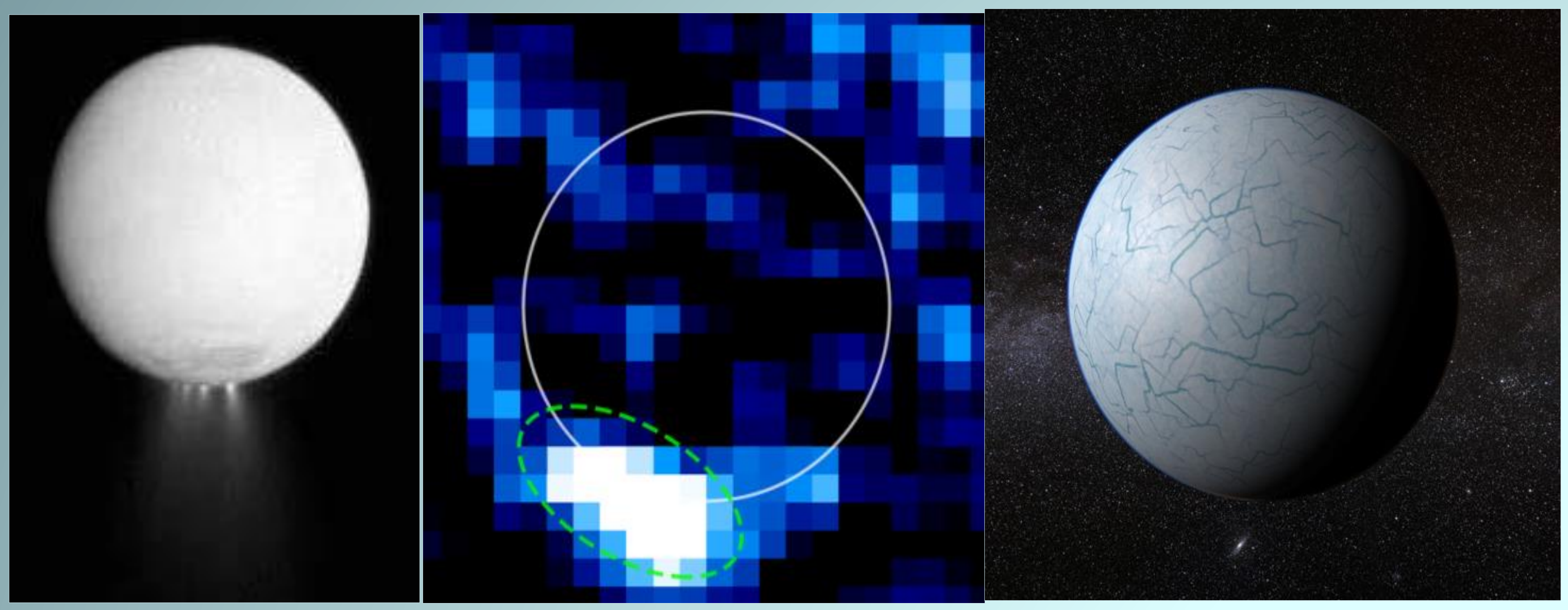

Figure 1. Explosive cryovolcanism in the outer solar system. **Left:** Geyser-like plumes erupting from the south pole of Enceladus (Credit: NASA/JPL-Caltech/SSI). **Middle:** HST UV observations of putative plumes at Europa's south pole from [13]. **Right:** Would next-generation telescopes be able to detect similar activity on water-rich exoplanets?

Theory

- The moons in our solar system that exhibit cryovolcanism in the form of geyser-like plumes are believed to harbor subsurface oceans [15-17].

- For terrestrial silicate eruptions, the ratio of intruded to erupted magma may be as much as 10:1 [18]. Extending this ratio to icy bodies suggests that the subsurface intrusion of melt pockets in the form of liquid H_2O and other aqueous solutions may be much more common than extrusive cryovolcanic activity in the form of geyser-like plumes and surface flows [19]. It is therefore likely that any planetary body exhibiting geyser-like plumes at least has subsurface pockets of liquid H_2O.

- Fagents et al. [20] and Quick et al. [21] have investigated eruption dynamics for potential geyser-like plumes on Jupiter's moon Europa (Fig. 2). Here, we apply these models to explore the dynamics of explosive cryovolcanism on H_2O-rich exoplanets.

- We consider 0.05 M_E, 0.5 M_E, 2.5 M_E, and 5 M_E water-rich exoplanets (Table 1) with the following parameters:
  - ❖ Planets orbit a 0.5 M_{Sun} M-dwarf star
  - ❖ 0.05 M_E planet is a "Super-Ganymede"; 0.5 M_E planet is a "Super-Mars"
  - ❖ Planet densities = 2 g/cm³
  - ❖ Surface temperature = 270 K
  - ❖ Planets have no atmosphere
  - ❖ Plumes are composed of H_2O, CO_2, and SO_2 [13-14, 20, 22-23] and erupt at T = 273 K.

Table 1. Planetary Characteristics Planetary radii are calculated from the relationship, $R_{planet} = \left({}^{3M_p}/_{4\pi\rho}\right)^{1/3}$

M_p	$0.05\ M_E$	$0.5\ M_E$	$2.5\ M_E$	$5\ M_E$
R_{planet}	$0.52\ R_E$	$1.1\ R_E$	$1.9\ R_E$	$2.4\ R_E$
g (m/s²)	4	6.8	8.5	1.8

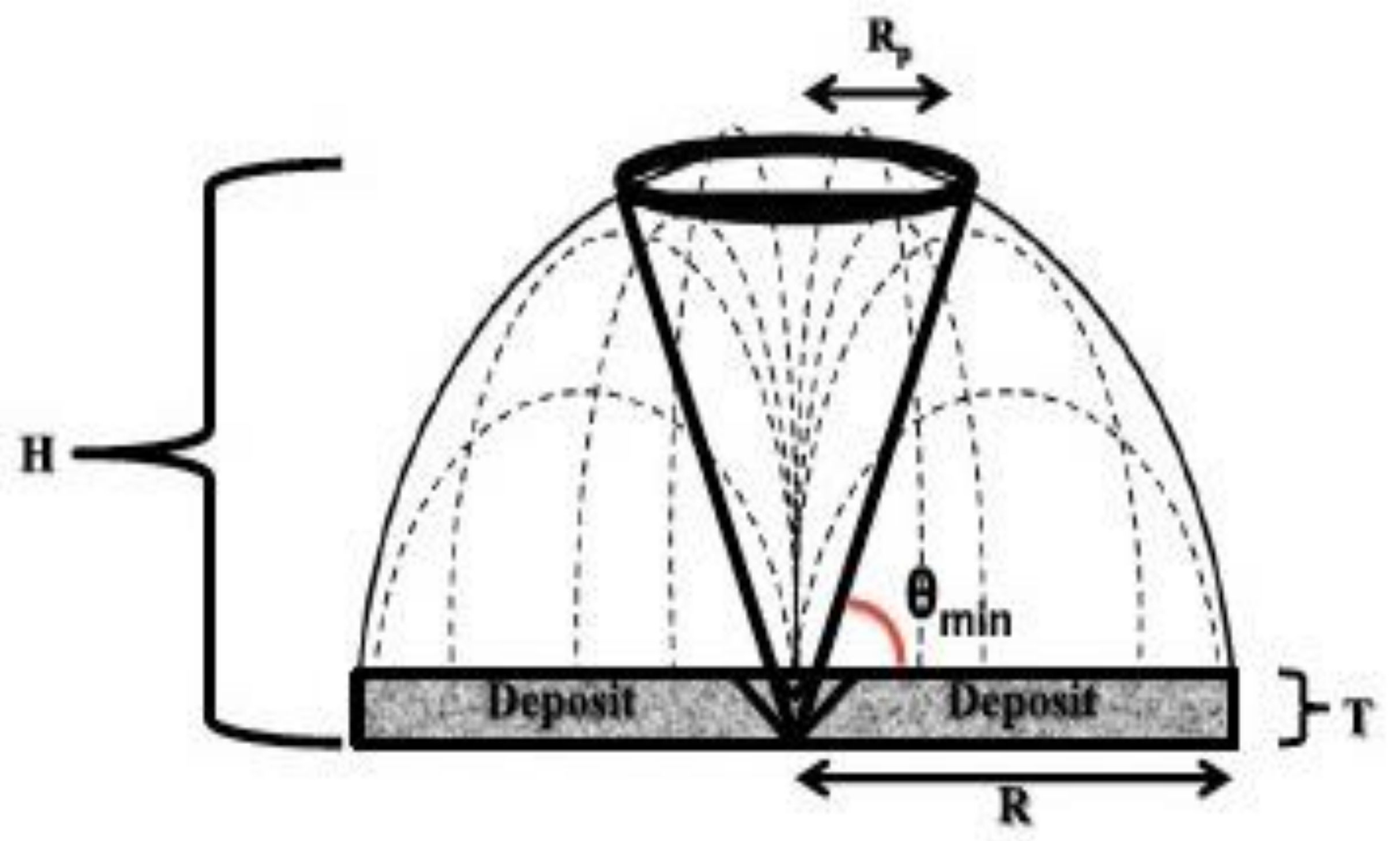

Figure 2. The central, densest portion of a plume that will be visible to observers has been modeled as an inverted cone with radius R_p. *H* is plume height. Figure from Quick et al., 2013 [21].

Governing Equations

Eruption Velocity

$$V = \sqrt{\frac{2nR_GT\kappa}{m(\kappa-1)}} \qquad (1)$$

Plume Height

$$H = V^2/2g \qquad (2)$$

Where n is the weight percent of the driving gas, R_G is the universal gas constant, T = 273 K is the eruption temperature, and κ and m are the ratio of specific heats of the entrained gas, and the molar mass, respectively.

References

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Results

I.   Plume Parameters

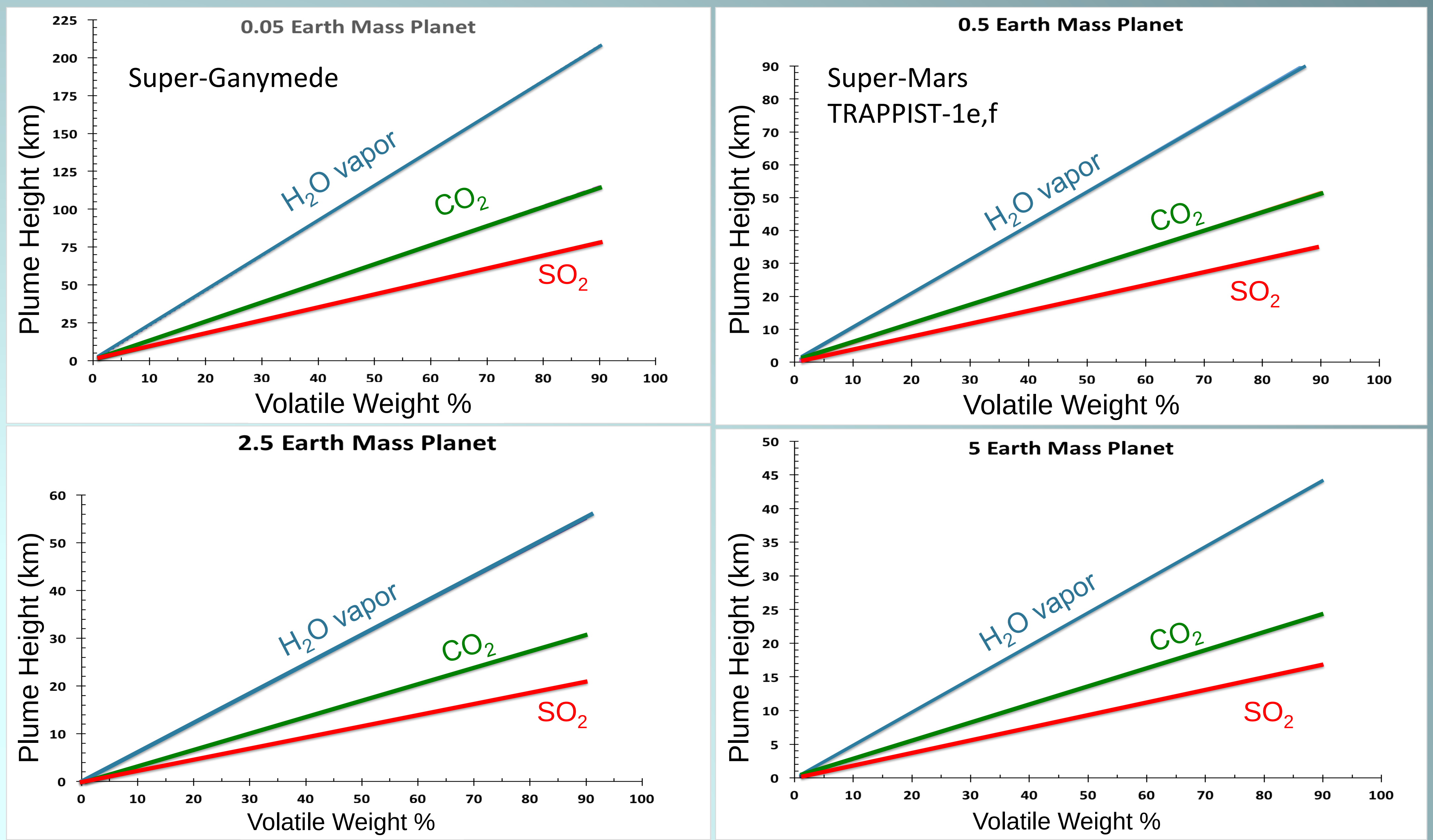

Figure 3. Plume height as a function of weight percentage of driving gas for each planet investigated. In all cases, eruptions on smaller planets will extend higher above the surface than those on larger planets. In addition, plumes with H_2O vapor as the primary volatile constituent will reach higher above planetary surfaces than plumes composed of CO_2 or SO_2, and may therefore be more easily detected by space telescopes.

Plumes with water vapor as the primary volatile constituent would reach higher above planetary surfaces than their counterparts with CO_2 or SO_2 as the primary gas (Fig. 3). Our results suggest that plumes erupting on a Super-Ganymede (0.05 M_E) would be the most expansive, and therefore easiest for next-generation telescopes to detect. With water vapor as the driving volatile, these plumes could extend > 200 km above the surface (Fig. 3). If eruptions are continuous over a 5 month timespan, and if water vapor exists in a 1:1 ratio with erupted cryoclastic particles, the methods of [21] suggest that a maximum concentration of 1 x 10^{37} H_2O molecules/second would be produced. Conversely, plumes on larger exoplanets would be more diminutive owing to the higher surface gravities they encounter (Fig. 3 & Table 1). As a result, they would likely be more difficult to detect. For example, geyser-like plumes on a 2.5 M_E water-rich exoplanet that have water vapor as their driving volatile would extend no more than 55 km above the surface (Fig. 3). Assuming continuous eruptions for 5 months, and a 1:1 ratio between vapor and icy particles, a maximum of 4 x 10^{35} H_2O molecules/second would erupt from these plumes.

II. Detection Prospects

We use NASA-Goddard's Planetary Spectrum Generator (PSG) (http://ssed.gsfc.nasa.gov/psg/) [24] to simulate spectra of cryovolcanic eruptions on icy exoplanets. We consider a 2.5 M_E water-rich exoplanet with a surface layer of 100 µm thick Ice Ih [25], and an albedo of 0.8. We assume that the planet orbits a 0.5 solar mass M-dwarf star with an effective temperature = 3735 K. We also assume active cryovolcanic eruptions would produce a spectra akin to that of an expanding coma with an "atmosphere" primarily composed of water vapor. To account for the potential presence of other volatile species, we assume the driving gases for the eruption are composed of of 95 % H_2O and 5% CO_2, similar to the composition of the plumes on Enceladus [22, 26]. We also assume an emissivity = 1 and a 1:1 particle to vapor ratio, as before. We calculate spectra from 0.4 to 20 microns assuming observations with 3 hours of data on JWST (6.5m diameter).

We find that next-generation space telescopes such as JWST can detect eruptions producing ≥ 10^{42} molecules per second (see Fig 4). For a 2.5 M_E water-rich exoplanet, this would require > 300 plumes producing at least 10^{39} molecules/second in just 30 minutes' time. For a Super-Ganymede, this would require about 100 plumes producing 10^{39} molecules/second in about 10 hours' time. This is comparable to the total mass of material erupted by Mt. Pinatubo during its four-day explosive eruption in 1991 [27]. Enceladus may have ~100 jets erupting from its south pole [28], but the eruptions there and on Europa seem to produce, on average, 10^{25}-10^{28} H_2O molecules/second [14, 22, 26].

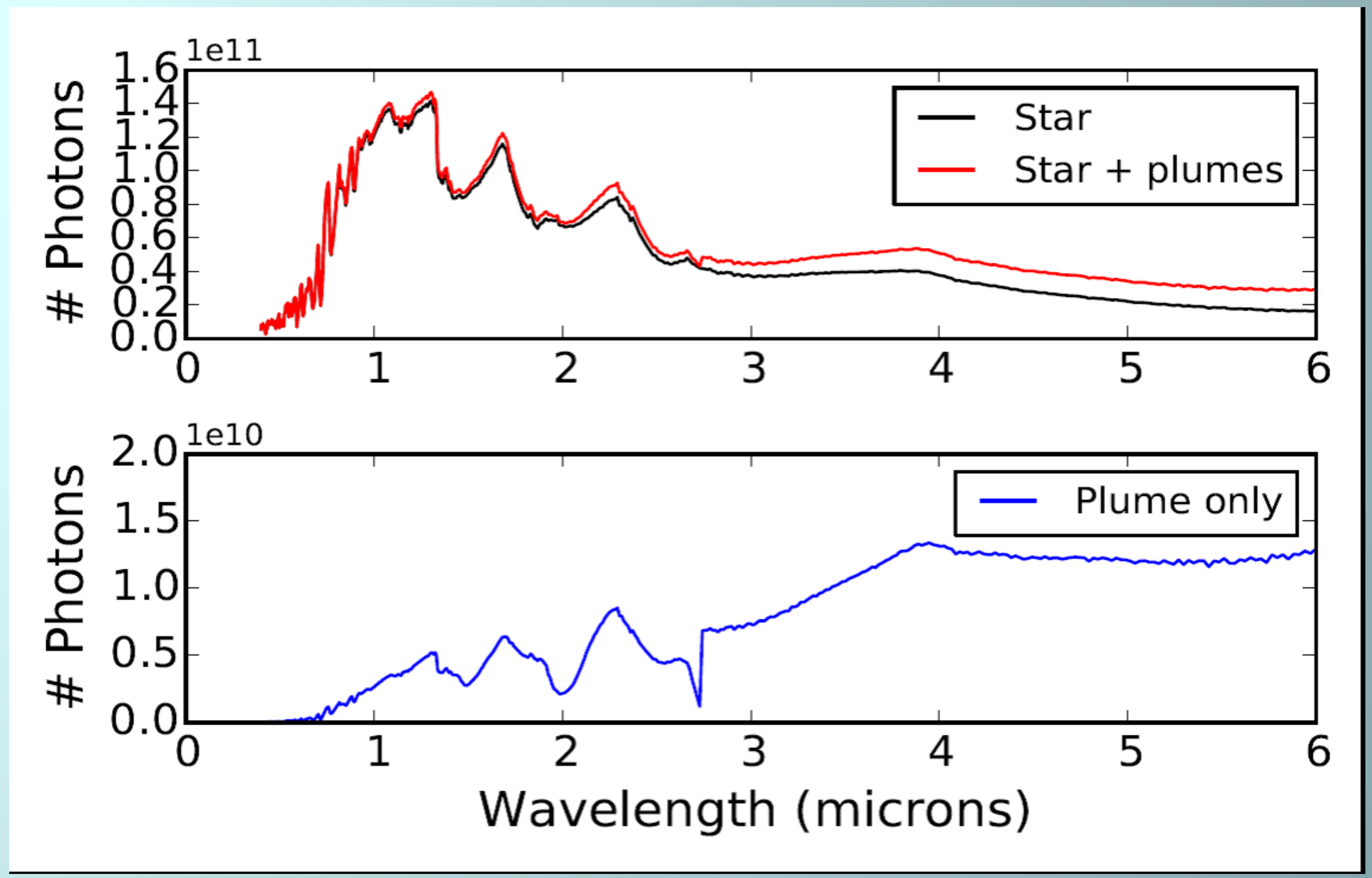

Figure 4. Simulated spectra of a cryovolcanic eruption on an H_2O-rich, 2.5M_E exoplanet. This eruption releases 10^{42} molecules/s. Such an eruption would be many orders of magnitude larger than what has been observed on our solar system's icy moons.

Future Work: Understanding the interior evolution of ice/rock bodies between Super-Ganymede to Super-Earth sizes will shed light on the eruption rates and frequencies that could be expected for bodies in other systems. In our solar system, cryovolcanism is thought to be driven by tidal heating, where the cyclical tidal flexing of the ice shells of Europa and Enceladus are heated from within by dissipation of their orbital energy. Extrasolar planets may experience tidal heating if they are in eccentric orbits and are close to their parent stars. For plume and geyser activity to occur, the planet must have enough internal energy to create pockets of subsurface liquid water, and sufficient tidal or internally generated tectonic stresses to permit the surface to rupture, providing a pathway for pressurized water to erupt. In our future work, we will consider the orbital and geodynamic settings in which such large eruptions may be possible. This will help observers to determine which systems are most likely to harbor planets with detectable plumes.

Conclusions

Cryovolcanic eruptions may be most easily detected on small, < 0.5 M_E, water-rich exoplanets. Using cryovolcanic processes in our solar system as a baseline, our results suggest that spectroscopic detection of geyser-like plumes with practical eruption rates will require next-generation telescopes > 10 m in diameter. In addition, direct detection of explosive cryovolcanism during transit may be possible with a next-generation, 10-meter class, *Kepler*-like space telescope. Plumes that are concentrated in one hemisphere on a planet with no atmosphere (e.g., Fig. 1) would block extra starlight during the ingress or egress of the planetary transit. For a Super-Ganymede with 100 plumes that are 200 km high and >50 km wide, the plumes would block in excess of an additional 1.3 ppm of starlight, or greater than 1.5% of the total transit depth. This would be observable as an asymmetric light curve shape that would also vary over the lifetime of the plumes.