Quantifying the effect of Mars obliquity on the intermittency of post-Noachian surface liquid water

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1. Table of contents	0
2. Scientific/Technical/Management	1
2.1 Summary	1
2.2 Goals of the Proposed Study	1
2.3 Scientific Background	2
2.3.1. Data: Climate supported intermittent surface liquid water relatively late in	1 Mars
history	2
2.3.2. Models: Obliquity's effect on climate intermittency is vital	
and poorly quantified.	2
2.3.3. Preliminary work: Coupling climate model output and obliquity change en	nables
simulation of post-Noachian liquid water intermittency	5
2.4 Technical Approach and Methodology	7
2.4.1. Compute an ensemble of 3.5 Gyr-long obliquity trajectories for Mars	7
2.4.2. Use MarsWRF and energy balance models to predict surface liquid water	8
2.4.3. Calculate climate evolution including surface liquid water intermittency	10
2.4.4. Select trajectories matching geologic constraints	12
2.4.5. Assumptions and caveats.	13
2.5 Perceived Impact of Proposed Work	14
2.6 Relevance of Proposed Work	15
2.7 Work Plan	15
2.8 Personnel and Qualifications	15
3. References	16
4. Biographical sketches	24
5. Current and Pending Support	29
6. Budget Justification	32
6.1.1. Personnel and Work Efforts	32
6.1.2. Facilities and Equipment	32
6.2 Budget Details	34
7. Jet Propulsion Laboratory Funding	35

2. Scientific/Technical/Management:

2.1 Summary. Obliquity variations are critical to post-Noachian climate on Mars (Toon 1980, Jakosky & Carr 1985, Kahn 1985, Jakosky et al. 1995, Laskar et al. 2004, Zent 2013) (Fig. 1). New analyses of Mars Science Laboratory and Mars Reconnaissance Orbiter data confirm that habitable conditions – surface liquid water – continued intermittently well after their Late Noachian / Early Hesperian peak, but habitable climates could not have been both long-lasting and global because post-Noachian terrain lacks deep weathering and erosion. Understanding the intermittency of post-Noachian Mars habitability requires better constraints on the role of stochastic, intermittent alternations between obliquity states that can help or hinder surface habitability (Fig. 1).



We will investigate obliquity forcing of intermittent bursts of late-stage habitability on Mars, employing a model of the coupled effects of obliquity change, solar brightening, and irreversible loss of CO₂. We will generate a statistically representative ensemble of possible obliquity histories for Mars, use these to drive forward models of Mars climate from 3.5 Ga (after the Noachian-Hesperian transition) to now, and predict the episodic presence and absence of surface liquid water for each possible history. Specifically, we will: (i) simulate an ensemble of possible 3.5 Gyr-long solar system dynamical histories, and the resulting variations in Mars' spin-orbit parameters; (ii) use a 3D Global Climate Model (MarsWRF; Mischna et al. 2013) assisted by a simple energy balance model (Kite et al. 2013) to generate spatially explicit $1^{\circ} \times 1^{\circ}$ look-up tables for liquid water availability; (iii) combine the liquid-water look-up tables with the ensemble of orbital histories to generate a range of climate trajectories, which shall include (iv) a variety of parameterizations of atmospheric CO₂ escape-to-space and carbonate weathering (which is a potentially important feedback on liquid water availability). We shall thus obtain a large number of trial climate-evolution tracks for Mars. From these trials, we will determine which ones fit observations. Our posterior distribution will thus contain only histories that self-consistently reproduce both the geologic observations and the present-day state of Mars. Each will predict the intermittency of surface liquid water at all timescales – diurnal, seasonal, Milankovitch, up through 3.5 Gyr - on a spatially-resolved grid. Our physical modeling will allow geologic and mineralogic observations that constrain liquid-water intermittency to be related to the longterm history of Mars' intermittently habitable surface. Therefore, the investigation will enhance our understanding of the creation and maintenance of habitable environments on Mars.

2.2 Goal of the proposed study.

The goal of the proposed work is to simulate the effect of obliquity on the intermittency of surface liquid water availability on post-Noachian Mars. Achieving this goal involves the following objectives:-

- Use an *N*-body code (HNBody) to compute >500 spin-orbital trajectories for Mars (§2.4.1).
- Use a global climate model (MarsWRF) to predict snow/ice pile-up locations (§2.4.2).
- Calculate climate evolution trajectories including surface liquid water (§2.4.3).
- Compare the climate evolution trajectories to geologic constraints (§2.4.4).

In order to define a focused, well-posed investigation of appropriate scope for a three-year study, we make several simplifying assumptions, which are explained and justified in §2.4.5.

2.3 Scientific background.

2.3.1. *Data:* Climate supported intermittent surface liquid water relatively late in Mars history.

Post-Noachian Mars was not always a global desert: fresh shallow valleys, alluvial fans, supraglacial valleys, and aqueous minerals all record surface liquid water. Much of this liquid water was supplied by top-down climate forcing (Howard et al. 2014, Williams et al. 2011, Milliken et al. 2008, Carter et al. 2013, Irwin et al. 2014, Grant & Wilson 2012, Mangold et al. 2004, Grotzinger et al. 2014, Morgan et al. 2014, Weitz et al. 2010). Habitable climates in the post-Noachian are surprising because most of the conditions for "warm/wet" climates no longer existed: Xe-, Kr-, and C-isotopes indicate massive pre-Noachian atmospheric loss, Mars' dynamo ceased around the mid-Noachian, and both Tharsis outgassing and large impacts were concentrated before the late Noachian (Phillips et al. 2001, Pepin 1994, Zahnle 1993, Segura et al. 2013. Webster et al. 2013. Stanley et al. 2014). Motivated by these constraints, a consensus is emerging that insolation-driven snow/ice melting was a significant water source (Clow 1987, Lee & McKay 2003, Irwin et al. 2014, Kite et al. 2013, Palucis et al. 2014), and unlike groundwater breakouts (e.g. Hauber et al. 2013) this can be used to constrain climate models. However, the mechanism, number, duration, and duty cycle of melt-permitting climates is not understood (Haberle 1998, Warner et al. 2010). In particular, the absence of deep weathering or deep erosion, and the fact that some basins fed by large rivers did not overflow, show that meltpermitting climates were intermittent (Tosca & Knoll 2009, Golombek et al. 2014, Irwin et al. 2014, Baker et al. 1991, Morgan et al. 2014), but the mechanism for this intermittency is poorly understood. Poor understanding of post-Noachian climates is in part due to the lack of a spatially explicit model that can simulate liquid water availability for 3.5 Gyr (Figs. 2-3), and so we propose to fill this gap.

2.3.2. Models: Obliquity's effect on climate evolution is vital and poorly quantified.

A long term habitability model should include the key controls on melt-permitting climates since 3.5 Gyr, which are (1) stochastic variations of Mars' obliquity, φ (Touma & Wisdom 1993), (2) a 30% increase in the Sun's luminosity L_{\odot} from 3.5 Gya to today (Bahcall et al. 2001), and (3) a decline of Mars' atmospheric CO₂ ($P_{CO2} \approx P$), where *P* is total atmospheric pressure) from ~(0.1-1) bar around the Noachian-Hesperian boundary to 0.006 bar today (Kahn 1985, Jakosky & Phillips 2001, Kite et al. 2014a, Catling 2009, Manga et al. 2012, Lammer et al. 2013). Impact energy does not seem to have driven global climate at this relatively late stage (Kite et al. 2011a,



10⁶

Timescale (yr)

10⁸

0.2

c)

0└ 10³





Irwin et al. 2014). Occasional contributions from other forcings (e.g. volcanism, changes in surface volatile inventory) can best be understood as perturbations relative to the effects of longterm forcings φ , L_{\odot} and P (Mischna et al. 2013).

Low φ favors globally-dry conditions because at low φ H₂O_(i) is trapped at the poles (which are likely never warm enough for surface melt; Fastook et al. 2012). Additionally, atmospheric collapse is more likely at low φ (Soto et al. 2014) (Fig. 1). Low φ helps to preserve Mars' inventory of CO₂ because surface carbonate formation is slow when water is trapped as polar ice (Forget et al. 2013). High φ drives ice and snow to low latitudes, where melting is more likely (e.g. Jakosky & Carr 1985, Mischna et al. 2003, Forget et al. 2006) (Fig. 1). The long-term episodicity of low- φ /high- φ transitions for Mars has never been systematically investigated (previous work on orbitally-driven climate change focuses on Late Amazonian glaciations; Christensen et al. 2003, Head et al. 2003, Laskar et al. 2004, Armstrong et al. 2004). A crucial recent finding is that only one-to-a-few transitions between low mean φ and high mean φ are expected since 3.5 Gya for a Moon-less planet in the inner solar system (Li & Batygin 2014, Lissauer et al. 2012). We have verified that this applies to Mars (§2.3.3, Fig. 2a). Oneto-a-few transitions are not enough to "average out" chaotic obliquity variations, and because the durations and intermittencies of potentiallyhabitable conditions predicted by equally likely forward-modeled histories can differ dramatically (Figs. 2a, 2b, 4), it is inappropriate to assume that φ variations "average out" over 3.5 Gyr for habitability purposes. Therefore, our calculations will resolve trends, rhythms and aberrations in φ (Figs. 2-4).

Because of the long interval between low- φ /high- φ transitions, different (equally likely) Mars evolution tracks can experience high φ at very different levels of L_{\odot} (Fig. 2b). L_{\odot} is a key control on climate (Kasting et al. 1993, Pierrehumbert 2010, Forget et al. 2013). Given L_{\odot} 's 7%-per-Gyr rise, it is therefore quite surprising that liquid water availability has *decreased* overall since 3.5 Gya (Carr & Head 2010), and this is usually interpreted as the result of a fall in *P*. High *P* ($P \approx P_{CO2}$) contributes to top-down climate



Fig. 3. Our proposal in the context of (a small subset of) published Mars climate evolution models, showing that the proposed work extends a long-standing community-wide effort towards spatially explicit, orbitally resolved climate evolution models.

driven melting by suppressing evaporative cooling and reducing Outgoing Longwave Radiation (Ingersoll 1970, Hecht 2002). P's decline is caused by atmospheric escape to space, potentially supplemented (when circumneutral surface liquid water is available) by carbonate formation. Carbonate formation can be either a negative feedback (Walker et al. 1981) or a positive feedback (Kite et al. 2011b) on surface liquid water availability. L_{\odot} , P and φ have coupled effects. The longer the period of global desert, the greater the increase of L_{\odot} between potentially wet intervals. Higher insolation is more favorable for surface liquid water when high φ returns. However, long low- φ periods also allow more time for CO₂ to escape to space. Importantly, warming of snow/ice driven by φ change and assisted by CO₂ forcing can trigger positive feedbacks - involving water vapor or water ice clouds - and prime the system for modest additional net warming by SO₂ (e.g. Mischna et al. 2013, Halevy & Head 2014). High obliquity is a necessary, but not sufficient, condition for climate-driven surface liquid water on late Hesperian and Amazonian Mars (Mischna et al. 2013, Kite et al. 2013). For example, there is no evidence for widespread low-latitude surface melting ~ 5 Mya which was the last time φ exceeded 40°. In summary, φ variations are expected to drive global-desert episodes – time gaps in the geologic record of surface liquid water (Kite et al. 2013) – and this is consistent with the absence of deep weathering and deep erosion on post-Noachian terrains (Fig. 2). Global-desert periods would be a challenge to life.

Orbital forcing of snowmelt predicts intermittency *during* a melt episode (Toon et al. 1980), in that it is globally dry most of the time, and dry in most places even during a wet year. This is supported by the sedimentary record: seasonal intermittency is suggested by paleolake hydrology (Irwin et al. 2014); and unweathered minerals in soil and ancient outcrops of olivine indicate some places never saw much water (Hoefen et al. 2003, Goetz et al. 2005). Ice-covered lakes

buffer seasonally variable melting (McKay et al. 1985). If runoff occurs for some fraction of an orbital cycle, then wet soil must occur for a greater fraction of that orbital cycle (and a wider range of locations). Orbital pacing of liquid-water availability for sediment inducation is suggested by rhythms in deposition (Metz et al. 2009, Lewis & Aharonson 2014). Moreover, not every obliquity peak will correspond to runoff, in part because eccentricity and the longitude of perihelion modulate liquid water availability during a high- φ episode (Kite et al. 2013).

2.3.3. *Preliminary work:* Coupling climate model output and obliquity change enables simulation of post-Noachian liquid water intermittency.

Given that the importance of Mars obliquity variations to Mars climate has been noted for 30 years (Jakosky & Carr 1985, Jakosky et al. 1995, Haberle et al. 2003), it is perhaps surprising that there is no publicly available ensemble of multi-Gyr Mars obliquity simulations (Laskar et al. 2004 provide data for 0.25 Gyr; Chambers et al. 2005 provide data for 1.0 Gyr). Therefore, to build a representative sample of the chaotic obliquity variations, we generated 18 orbital histories for Mars (Touma & Wisdom 1993, Laskar et al. 1993, Head et al. 2003, Forget et al. 2006, Fassett et al. 2014) using the mercury6 N-body code (Chambers 1999) to integrate the solar system for 3.5 Gyr. We then applied an obliquity code (10 randomly chosen spin-axis orientations per mercury6 simulation). The results show a remarkably wide spread of equally plausible orbital forcings (Fig. 2).

To assess the likely consequences of these disparate orbital forcings, we used the spin-orbit output (obliquity, eccentricity, and longitude of perihelion as functions of time) to drive a simple snowpack energy balance model (Kite et al. 2013), which was in turn coupled to an atmospheric evolution model. The energy balance model assumes that warm-season snow was only present in cold traps (locations that minimize annual-average sublimation rate) (Wordsworth et al. 2014, Kite et al. 2013). It calculates snow temperatures taking into account sensible and latent heat exchange with the atmospheric surface layer, Rayleigh scattering, greenhouse warming, time-of-day, and season, and the solid-state greenhouse effect. The atmospheric evolution model uses an initial P of 100 mbar ($P \approx P_{CO2}$) for the example output shown in Fig. 4. If P(t) had not decreased over the last 3.5 Gyr then habitability would have increased over time, the opposite of what is observed (Knoll et al. 2008). CO₂ is currently escaping from Mars at >1 mbar/Gyr. Our escape-to-space parameterization imposed molar CO₂ loss as $\frac{1}{2}$ the centennial-average $\Sigma(O^+)$ loss inferred by Lundin et al. (2013), scaled to the higher UV flux of the young Sun. Self-consistently calculating P loss also requires considering carbonate formation, because modest amounts of liquid water, P > 0.006 bar, and cold temperatures are sufficient physical conditions for rapid carbonate formation (Nezat et al. 2001, Foley et al. 2006, Stephens 1995). Carbonate formation requires low melt rates and runoff requires high melt rates, so evidence for climate-driven runoff (Williams et al. 2013) implies physical conditions suitable for carbonate formation over a much wider range of locations and times. Carbonate formation must have occurred on Mars to explain the carbonate dispersed in the soil (e.g. Boynton et al. 2009), and the (1-4) wt % abundances reported (e.g. Boynton et al. 2009, Leshin et al. 2013) equate to ~1 mbar CO₂ drawdown per 10^5 km³ dust/silt/sand. Because $\gg 10^6$ km³ dust/silt/sand was cycled through the weathering-prone diurnal skin depth since 3.5 Ga (§2.4.4) (Bradlev et al. 2002, Byrne & Murray 2002, Bridges & Muhs 2012, Zuber et al. 2007), there is a potential for liquid water availability to feed back on P (as on Earth) (Walker et al.



Fig. 4. Intermittency of liquid water (peak day-integral melt, blue) predicted by using our obliquity tracks (red) to drive a simple energy balance model of snowmelt. Three different, equally likely tracks are shown. Black lines show atmospheric pressure. Bottom right: Intermittency of surface liquid water (blue) is much greater than intermittency of high-obliquity (gray). Though the specifics of the tracks differ greatly, the three tracks show common intermittency-spectrum characteristics.

1981, Manning et al. 2006, Kite et al. 2011b). Although a potentially significant feedback on climate, the amounts of carbonate formed in our models are two orders of magnitude smaller than in pre-Mars Exploration Program models of Mars climate evolution (e.g. Pollack et al. 1987), and this relatively modest carbonate inventory is consistent with isotopic constraints (§2.4.4) and with the paucity of bedrock carbonate (e.g. Niles et al. 2013). To produce the example output shown in Fig. 4, we assumed carbonate formation within parts of the planet experiencing seasonal melting was limited by the supply of weatherable sand, silt and dust ($\rho = 2000 \text{ kg/m}^3$) at a deposition rate of ~30 µm/yr (Christensen 1985, Lewis et al. 2008, Lewis & Aharonson 2014), giving 3 g/m²/yr of CO₂ consumed. This assumes that 10% of the input is converted to MgCO₃, high values that are subsequently diluted by mixing with never-weathered materials from outside the spatially-restricted melt zones.

The results show a wide range of possible histories (Fig. 4). >10⁸-yr long global-desert intervals are common, due to long periods of low φ . The longest continuous run of wet years (each wet

year has a dry season) is ~60 Kyr. In this model, some Mars-like planets are habitable at the present day. ~2 Gya crater-retention ages obtained for alluvial fans¹ can be understood in terms of higher L_{\odot} at later times favoring surface liquid water. Intriguingly, the reasonable expectation of $\gg 100$ comparably-wet intervals (given 10⁵ yr quasiperiodic forcing) is flatly contradicted by the results, which show a few very wet "spikes" due to rectification at the melting-point and buffering of *P* by carbonate formation (Fig. 4).

These results motivate us to extend our forward modeling framework to investigate obliquity's role in the greater detail allowed by a GCM.

2.4 Technical Approach and Methodology.

To simulate surface liquid water intermittency through the Late Hesperian and Amazonian requires $\sim 10^2$ dynamical integrations of the



orbits of the planets (to marginalize over strongly varying orbital forcing), 3.5 Ga-long runs (for comparison with the geologic record), and 1 hour time resolution (to capture peak melting around noon). Two features of the problem greatly reduce the computational burden and enable the proposed science. (1) Seasonal melting/freezing timescales are decoupled from the >>yr timescales needed to change φ , L_{\odot} , or P, and surface ice distribution and atmospheric collapse/reinflation responds quickly to changes in φ (Hudson & Aharonson 2008, Soto et al. 2014). Therefore, we run a grid of climate simulations with fixed { φ , L_{\odot} , P}, building a look-uptable for incorporation into a model of climate evolution. (2) Snow and ice tends to pile up where sublimation is minimized, and (at any one time) liquid water is volumetrically minor compared to the ice reservoir (Wordsworth et al. 2014, Mischna et al. 2003, Kite et al. 2013). Therefore, we can run the GCMs without interactive melt handling, and allocate melt flexibly in postprocessing.

2.4.1. Compute an ensemble of 3.5 Gyr-long obliquity trajectories for Mars.

The goal of our *N*-body runs is to obtain a statistically representative ensemble of post-Noachian Mars spin-orbital histories. Initial positions are generated by perturbing the position of Mars in its orbit, by ~100m (in a random direction) relative to JPL Horizons ephemeris for 1/1/2000. Initially close trajectories diverge within <100 Ma. We omit the gravitational effects of planetesimals because the Kuiper belt and asteroid belt lost most of their mass before 3.5 Gya (Levison et al. 2011). Our preliminary work used a Newtonian integrator. We propose to run with post-Newtonian corrections for 96 solar system integrations using the HNBody code and Burlisch-Stoer integrator (Rauch & Hamilton 2002), with a 1.2 day timestep, for 3.5 Gyr each. With this correction, >98% of runs will remain stable over 3.5 Gyr (Laskar & Gastineau 2009).

¹ ~2 Gya from applying the latest corrections (from re-counts of Apollo/Luna radiogenic calibration sites; Robbins 2014) to the crater counts of Grant & Wilson (2011). Count area (= $1.2 \times 10^4 \text{ km}^2$) exceeds the Warner et al. (2015) recommended minimum count area.

For each of the *N*-body calculations, we will calculate obliquity using the code of Armstrong et al. (2004), obtained from https://sites.google.com/site/wsuvpl/software. We neglect hypothetical climate-obliquity feedbacks because lithospheric deflection beneath ice loads on Mars is small (Phillips et al. 2008, Bills 1999). A spread of obliquity evolution tracks

will be generated for each *N*-body calculation by randomly seeding the initial spin pole orientations from the distribution of Laskar et al. (2004) for 3.5 Gya while holding spin rate constant. Histories will only be accepted if they match Mars' present day obliquity within 5°. This will be repeated until 6 acceptable obliquity threads have been found for each *N*-body simulation, giving >500 spin-orbit trajectories.

2.4.2. Use MarsWRF and energy balance models to predict snow/ice pile-up locations and melting.

The goal of our Mars Weather Research and Forecasting (MarsWRF) Global Climate Model (GCM) runs is to simulate surface liquid water



availability given an imposed spin/orbit state, solar luminosity, and atmospheric pressure. We will do this by using MarsWRF to calculate radiative fluxes and near-surface air temperatures. A simple energy balance model will then calculate melt rates (usually zero) at the cold trap locations found using MarsWRF. On present-day Mars, equatorial surface temperatures regularly exceed 273K – yet no melting occurs, because of (1) cold-trapping of H₂O_(i) near the poles and (2) evaporative cooling at P = 6 mbar. To track cold-trapping and evaporative cooling requires a model of snowpack temperatures, which set snowpack stability (snow and ice accumulates in locations that minimize snow sublimation; Wordsworth 2014, Mischna et al. 2003, Kite et al. 2013). Earlier, we used our energy-balance model to find melt distribution for a range of orbital conditions and atmospheric pressures (Kite et al. 2013a), and our 3D model to investigate melt-prone climates under a narrow range of orbital conditions while considering SO₂ and H₂O feedbacks (Mischna et al. 2013). Major strengths of MarsWRF for our purposes include self-consistent treatment of both lateral heat transport and the effect of topography on planetary waves. Example MarsWRF output is shown in Fig. 5.

<u>GCM runs.</u> The paleo-climate look-up table consists of 5 eccentricities {0, 0.045, 0.09, 0.12, 0.015}, 5 obliquities {0°, 25°, 35°, 45°, 70°}, 9 longitudes of perihelion (0°-315°, 45° intervals), 6 atmospheric pressures (12, 25, 50, 100, 250, 500 mbar), and 5 solar luminosities (76% to 100% present solar luminosity in steps of 6%). (P < 1 bar is probable for post-Noachian Mars; Kite et al. 2014a, Lammer et al. 2013, Richardson & Mischna 2005). From previous exhaustive work with the simple energy balance model we have determined that this choice of grid will give efficient coverage of melt-prone conditions. Each entry in the table is populated with spatially resolved GCM output.

MarsWRF is a Marsspecific implementation of the PlanetWRF GCM (Richardson et al., 2007) which in turn is derived from the terrestrial WRF model (Skamarock and Klemp, 2008). MarsWRF solves the primitive equations using an Arakawa-C grid. The horizontal resolution of the model is set to $5^{\circ} \times 5^{\circ}$, and the vertical grid follows a modified- σ (terrainfollowing) coordinate with 40 vertical layers in the range 0-80 km.



Fig. 6. Example of our melt model calculations showing surface liquid water areas (green) for { $\varphi = 50^{\circ}$, e = 0.145, $L_p = 0^{\circ}$, P = 49 mbar, $\Delta T = 5$ K} using our simple energy balance model (Kite et al. 2013a). Blue-shaded areas correspond to cold traps – likely locations of warmseason snow. Red-shaded areas are hot enough for melting at some point during the year, if snow were present. Where the blue and red zones intersect, melt occurs (solid green shading). Thick black line corresponds to the boundary of recently-resurfaced terrain, which is masked out. Ga = Gale; Gu = Gusev; MP = Meridiani Planum. Background contours are topography: interval 1.5 km, minimum -5 km, maximum +10 km.

Periodic boundary conditions in the horizontal dimensions are employed, and an absorbing ("sponge") upper boundary condition is used. Surface albedo and thermal inertia are matched to Mars Global Surveyor Thermal Emission Spectrometer (MGS-TES) observations (Christensen et al. 2001, Putzig et al. 2005). Radiative transfer is handled using a correlated-*k* method and includes CO₂, cloud aerosol, and H₂O_(v) effects. A basic water cycle is present in MarsWRF, allowing for the formation of radiatively active atmospheric water clouds (liquid or ice), including particle sedimentation, transport and radiative scattering. From this, we can evaluate the influence of cloud cover on radiative fluxes. Atmospheric collapse is not expected to affect melt-prone climates because for *P*<1 bar collapse only occurs at $\varphi < 40^{\circ}$ (Soto 2014, Forget et al. 2013) (Fig. 1). If atmospheric collapse is detected after 4 years, we stop the simulation and assign melt rate in all pixels to zero. Topography is approximated as constant; the changes needed to affect planetary waves (Hollingsworth et al. 1996) exceed post-3.5 Gyr topographic change (e.g. Kite et al. 2009). Sensitivity tests shall include 1 run with uniform spatially-averaged surface material properties (albedo / thermal inertia), and 7 runs at 2°x 2° spatial resolution (one per *P* value, at melt-optimal conditions).

From experience gained during prior work by the Co-I (Mischna et al. 2013), each run will take \sim 1 day per (multi-core) node. We set the number of runs, and the number of parameters to vary, based on this prior experience.

<u>Energy balance model runs</u>: Snow melt is calculated in postprocessing using a simple energy balance model (Kite et al. 2013) that is driven by the radiative fluxes, local pressures, and near-surface air temperatures obtained from the GCM. Evaporative cooling is calculated in the melt model assuming a constant humidity of 50%. (In effect, we assume that snowpack is patchily

distributed so that snow latent heat fluxes do not feed back strongly on planetary boundary layer energetics). We will employ the parameterizations of Dundas & Byrne (2010) for surface layer fluxes. Major strengths of the energy balance model for this melt estimation calculation are the solid-state greenhouse effect and the high vertical resolution in the subsurface (Kite et al. 2013). We will calculate melt rates at 1° resolution by downsampling MarsWRF results to local elevation/local pressure employing elevation-regression coefficients that we will obtain using the output from a small number of high-resolution MarsWRF runs.

In calculating melting, we select a snowpack thermal inertia of 300 m² K⁻¹ s^{-1/2}, and a dustcontaminated albedo of 0.3, parameter selections that are similar to (and thus aid comparison with) previous melting models for the Late Hesperian / Amazonian (Costard et al. 2002, Morgan et al. 2010, Williams et al. 2009), as well as the low albedos of present-day seasonal snow (Vincendon et al. 2010, Keresturi et al. 2011). Dust contamination is expected for snow at high obliquity (Haberle et al. 2003, Madeleine et al. 2014). We shall report the sensitivity of our melt calculations to the higher (dust-free) albedo of 0.4 used by Richardson & Wilson (2002) as well as to higher (ice-like) thermal inertia of 1000 m² K⁻¹ s^{-1/2}. Water is not allowed to drain and refreezes in place.

The most important control parameters for melt calculations are f_{snow} and ΔT . ΔT corresponds to a freezing-point depression. It can also be interpreted as due to salinity, unmodeled additional greenhouse warming (for example, due to H₂), or subgridscale melt-favoring fluctuations in material properties and surface orientation. We will consider $\Delta T = \{0K, 2K, 5K, 10K\}$. The fraction of planet surface area that is occupied by warm-season snow, f_{snow} , may be as large as 50% (Kadish et al. 2010) or as small as 1%. We treat f_{snow} as a free parameter and consider f_{snow} = $\{0.5\%, 1\%, 2\%, 5\%, 10\%, 20\%, 50\%\}$. An alternative approach is to trust the GCM predictions of f_{snow} . While this is a reasonable choice for the late Amazonian where – albeit with extensive tuning of the dust cycle – GCMs can match data (Madeleine et al. 2009, Madeleine et al. 2014), the large variance in GCM snow accumulation predictions for high φ , and the uncertain H₂O_(v) content of high- φ higher-*P* atmospheres (Richardson & Mischna 2006) lead us to select an approach that is agnostic with respect to poorly constrained details (Urata & Toon 2013) of cloud microphysics.

2.4.3. Calculate climate evolution including surface liquid water intermittency.

Surface liquid water availability is strongly controlled by P, which has fallen over time (Hecht 2002, Lammer et al. 2013, Kite et al. 2014a). The time evolution of Mars' volatile carbon inventory (P) is a balance between atmospheric escape to space (F_{esc}), carbonate formation (R), and volcanic resupply (V):

$$\mathrm{d}P/\mathrm{dt} = V - F_{esc} - R(1)$$

We will model initial (3.5 Gya) atmospheric pressures of 50 mbar, 100 mbar, and 250 mbar. We neglect *V* in the carbon balance because the volume of Late Hesperian and Amazonian volcanism is probably insufficient to release enough CO₂ to drive large scale warming (Kite et al. 2009, Stanley et al. 2014). We also neglect polar storage of CO₂ (Phillips et al. 2011) because this CO₂ is released at $\varphi > 40^{\circ}$.

For F_{esc} , we will use parameterizations based on published Mars Express data and simulations, at least initially. (It is easy to update our model with MAVEN constraints as appropriate, because the dP/dt code is computationally inexpensive.) We will consider four cases, spanning the range 0-100 mbar atmospheric escape over 3.5 Gyr: (1) $F_{esc} = 0$ (control); (2) medium case following Lundin et al.'s (2013) regression of low-energy $\Sigma(O^+ + CO_2^+)$ loss against the 10.7 cm solar activity index; (3) high case using the pickup ion sputtering calculations of Leblanc & Johnson (2002); (4) low case assuming CO₂ escapes solely as CO₂⁺ ions using ASPERA-3 measurements (Barabash et al. 2007). In each case, the escape flux will be scaled to the active young Sun using the <1200Å fluxes of young solar analogs (Ribas et al. 2005). This is broadly consistent with the model of Gröller et al. (2014).

For carbonate weathering (R), we shall model five scenarios that span the range from kinetic limitation to supply limitation. In all cases, we shall set initial CO_2 concentration in meltwater using Henry's Law and shall not allow more carbonate to form than the stoichiometric equivalent of that dissolved CO₂. In each scenario, the physical picture is that freezeout of diurnal or seasonal melt zones leads to carbonate supersaturation and precipitation, as is observed in polar climates on Earth (e.g. Dijkmans et al. 1986, Vogt & Corte 1996). (1) R = 0 (control); (2) kinetically limited: using rate constants measured using Mars-chamber experiments (Stephens 1995) and the specific durations of $T_{surf} \ge 273.15$ K in snow zones predicted by the model; (3) supply-limited, assuming a gross deposition rate of 30 µm/yr (Lewis & Aharonson 2014, Christensen 1986) for weatherable, atmospherically transported material ($\rho = 2000 \text{ kg/m}^3$) that is 10% converted to carbonate if and only if liquid water is available at that location in that year (Fig. 4); (4) diffusive weathering front at each spatial location, no atmospheric transport. In this scenario, each location is assigned a weathering front that deepens as (total wet years)^{1/2}. Thus, persistently wet locations are more weathered, but weather more slowly, than infrequently wet locations. The uniform diffusivity is 10^{-13} m² s⁻¹, which is chosen by terrestrial analogy (e.g. Anand & Paine 2002); (5) supply-limited, assuming that weathered soil is quickly remixed into a finite reservoir of initially weatherable, atmospherically transported material. The volume of the initially-weatherable silicate reservoir is set using geologic data (e.g., Table 1).

Present-day location of	Volume (km ³)	Ref.	CO ₂ equiv.
post-Noachian surface			(mbar) @ 4
materials			wt% MgCO3
upper Medusae Fossae	1.9×10^{6}	Watters et al., 2007	~20
Formation.			
Silicates in Planum	6×10^{5}	Zuber et al. 2007, Li et al.	~4
Australe and lower		2012, Byrne & Murray	
Planum Boreum.		2002	
Duststone, dust drifts,	$>10^{6}$	Bridges & Muhs, 2012,	~10
dust in midlatitude		Schon et al. 2009, Fassett	
mantling deposits.		et al. 2014	

Table 1. At least 3×10^6 km³ silicates have undergone atmospheric transport during the Late Hesperian and Amazonian, corresponding to at least 30 mbar potential CO₂ draw-down. We will update and extend this inventory as part of the proposed work, taking account of additional reservoirs (e.g., the global soil reservoir).

If merited by our analysis of the results using these five specific scenarios for carbonate formation, then we shall investigate more sophisticated carbonate-formation approaches with detailed tracking of water/rock ratios, initial mineralogy, and final mineralogy (e.g. Melwani Daswani et al., accepted).

2.4.4. Select trajectories matching geologic constraints.

For each of our >500 orbital evolution tracks, we now have $(4 \times 7) \times (3 \times 4 \times 5) = 1,680$ climate evolution scenarios bracketing the main uncertainties in Mars climate evolution, giving $\approx 800,000$ forward models in total. The goal of our final step is to compare the results to data and then to analyze the intermittency of habitability for the successful models. If none of these forward models (or only high ΔT models) fit data, that would **falsify our underlying hypothesis**, which is that obliquity forcing may account for the intermittency of habitability on a mostly dry post-Noachian Mars.



Figure 7. *Left:* Rhythmite of the upper Gale mound, a possible carbonate reservoir (2km across, HiRISE PSP_009927_1750). *Center:* Soil carbonate content, where measured, is 1-4 wt% (Phoenix image, view is ~1m across in nearfield). *Right:* Peak runoff at some Late Hesperian / Amazonian sites >2 mm/day (Lyot is shown here; HiRISE ESP_016339_2295; ~4.5 km across).

The geologic record requires post-Noachian runoff production of >2 mm/day for >7 × 10³ yr (intermittent) at Eberswalde, and runoff columns of >3.2 km, >3.6 km, >6 km at Harris, Saheki and Gale craters respectively (Irwin et al. 2014, Williams et al. 2011, Morgan et al. 2014, Palucis et al. 2014). We (very conservatively) equate melt to runoff when excluding too-dry climate evolution scenarios. However, the persistence of juvenile chemical sediments and olivine outcrops indicates that melt-permitting conditions weren't sustained for >3.3 × 10⁸ yr at sites with hydrated silica (Tosca & Knoll 2009), for >3 × 10⁷ yr at olivine outcrops, nor for >10⁵ yr after jarosite formation at Meridiani (Elwood-Madden et al. 2009, Ehlmann & Edwards 2014). We consider these hard constraints. Additional indicators include the frequency of pedestal craters (suggesting >6 × 10⁸ yr at φ > 25°), the geographic distribution of supraglacial runoff channels showing nonzero peak runoff (Fassett et al. 2010), and low average erosion rates (Golombek et al. 2014). We can also discount histories that predict P > 12 mbar today (Phillips et al. 2011) or that predict P < 3 mbar today. Orbital integrations #9 and #1 in Fig. 4 can be rejected for this reason, but #6 is acceptable.

Isotopic data do not currently constrain the relative importance of carbonate formation and escape to space since 3.5 Gya. Mars air today is richer in ¹³C than was the air in equilibrium with

carbonates in ALH84001 at 3.9 Gya (Webster et al. 2013), which requires a contribution by escape to space to atmospheric escape since 3.9 Gya. However, escape to space may have proceeded at a high rate before 3.5 Gya and a lower rate after 3.5 Gya. Although our modeling's success is not contingent on stratigraphic logging of δ^{13} C versus elevation by MSL at Mt. Sharp, it is easy to include MSL isotopic constraints as they become available to further "thin out" our set of acceptable forward models. From successful runs we will compute maps of cumulative liquid water column, peak runoff, and years with some melting, and intermittency. We will use the spatial distribution of runoff (e.g. Fassett et al. 2010) to reject climate histories that yield a distribution of late-stage runoff incompatible with observations.

Finally, negative feedback involving the rate of carbonate formation and the intensity of greenhouse forcing by CO_2 is thought to underpin long-term habitability on Earth (Walker et al. 1981). This negative feedback is fundamental to our understanding of long-term climate stability around Sun-like stars (Kasting et al. 1993, Kopparapu et al. 2013). However, on cold planets with a large day-night surface temperature contrast, such as Mars, a reduction in atmospheric pressure may cause an increase in liquid water availability leading to an irreversible weathering-mediated drawdown to 6 mbar – a positive feedback (Kahn et al. 1985, Richardson & Mischna 2005, Kite et al. 2011b). We will test this hypothesis, taking account of the possibility of patchy and/or thin snow cover.

2.4.5. Assumptions and caveats

It is worth emphasizing the assumptions driving the design of our modeling approach. We ask "Given that top-down melting occurred, what is its intermittency spectrum?" and not "What are the detailed mechanisms responsible for $\Delta T > 0$?" Our modeling approach assigns a potentially prominent role to carbonate formation on post-Noachian Mars, which is reasonable because carbonates of unknown age are present in the Martian soil, large volumes of potentiallyweatherable materials were available (Table 1), surface liquid water was present in the post-Noachian, and when small amounts of CO₂-charged liquid water are in contact with weatherable materials, carbonates can form (Stephens 1995, Boynton et al. 2009). We neglect the possibility of gas-solid carbonation and of ultraviolet decomposition of carbonates because currentlyavailable data provide little support for these as rapid processes (e.g., Quinn et al. 2006). We neglect SO₂ inhibition of carbonate precipitation because volcanoes were not active all the time (Halevy & Head 2014). We assume that high obliquity is needed to drive ice and snow to low latitude (Mischna et al. 2013). This assumption is valid when atmospheric P < 1 bar, as likely for the post-Noachian (Kite et al. 2014a, Lammer et al. 2013). High obliquity is not required for low-latitude snow/ice in the immediate aftermath of a catastrophic groundwater outburst or an impact, when transient localized precipitation is predicted to occur for any φ (Kite et al. 2011a, 2011c). However, the wide spatial distribution of post-Noachian runoff evidence (not clustered around outflow channels or young impacts), together with the $>10^3$ yr timescales inferred for runoff (Irwin et al. 2014), both suggest an important contribution from synoptic precipitation to runoff (Grant & Wilson 2012).

2.5. Perceived Impact of the Proposed Work.

Our ensemble of orbital histories will be made publicly available by ftp at geosci.uchicago.edu/~kite and could assist investigations of (for example): (1) the rate of H loss from Mars space, which is sensitive to tropospheric water vapor abundance (Clark

et al. 2014), which in turn is affected by obliquity (e.g. Richardson & Wilson 2002); and (2) cyclostratigraphy, which relates orbital forcing to stratigraphy, and is an important technique for analyzing the sedimentary record of Mars (Putzig et al. 2009, Hinnov 2013, Fueten et al. 2014, Lewis et al. 2008). Abrupt transitions in obliquity may correspond to breaks in the sedimentary record (Kite et al., 2014b).

Quantification of the intermittency of liquid water availability during the late Hesperian and Amazonian (as a function of the uncertain history of atmospheric pressure) may benefit the study of Mars sedimentary geology and geomorphology. Our spatially-resolved approach is a strength here because it is a step on the path towards detailed comparison to spatially variable geologic data. The need for such a model will only increase as the multi-Gyr-integrated geologic record imaged by HiRISE, CTX and CRISM is distilled into constraints on intermittent habitability (e.g. Palucis et al. 2014, Morgan et al. 2014, Irwin et al. 2014). The statistical properties of our simulations have parameter-independent characteristics (e.g., Fig. 2), and these may help understanding of lake hydrology (Howard 2007, Irwin et al. 2014).

The future integration of MAVEN data into Mars climate science could benefit from the kind of integrated climate-evolution model that we propose. Although our proposed work builds on (and is a continuation of) long-standing community-wide efforts (Fig. 3), no existing model can relate an atmospheric-escape history as boundary condition to a prediction for intermittent habitability.

The duration of dry spells on timescales from the day-night cycle up to 3.5 Gyr – which we will calculate – defines a challenge to life's persistence (Johnson et al. 2011). If the surface was indeed sterilized by UV and galactic cosmic radiation during long global-desert intervals, subsequent occupation of intermittently available surface niches would have required inoculation of the surface oasis from subsurface refugia on a faster timescale than further climate change (renewing the desert). This balance of timescales determines how (if) life could have persisted to present-day Special Regions (such as Recurring Slope Lineae; McEwen et al. 2014). The preservation of any organic matter deposited in an intermittently wet environment is affected by wet/dry cycles, which are unfavorable for organic-matter preservation because they allow oxidation (Summons et al. 2011). Slow net burial rates associated with intermittent sediment transport allow more time for radiolytic processing or aeolian abrasion of organic-matter hosting sediments (Sadler & Jerolmack 2007, Pavlov et al. 2012, Farley et al. 2014).

2.6. Relevance of the Proposed Work.

Our proposed work is within the scope of the Habitable Worlds call, specifically "the presence of water" and "the astrobiological potential of past environments on or in the Martian surface or subsurface." Our proposed work directly addresses Objective I.C of the MEPAG goals document (MEPAG 2012), "Determine how the long-term evolution of Mars affected the physical [...] environment critical to habitability [...]", and it is also relevant to Objectives II.B and II.C. Because our simulations of liquid water availability over time are spatially explicit, we can highlight locales that are more likely to have sustained life from the past into the present (candidate "special regions"). Independently, we can identify rank locales in terms of their relative exposure to liquid water, with implications for future landing site selection (e.g., Mars 2020).

2.7. Work Plan.

	Activities/milestones.	Products.
Year 1.	 Recalculate the Mars spin-orbit integrations including the effects of general relativity. Begin construction of the MarsWRF look-up table. Update and extend geologic inventory of weatherable materials. Train Postdoctoral Researcher on MarsWRF analysis. Calculate climate evolution trajectories. 	 ✓ LPSC presentation on: Statistics of low-obliquity "desert" intervals since 3.5 Gya on Mars. ✓ Short GRL-length manuscript on: Statistics of Mars insolation from an ensemble of orbital simulations.
Year 2.	 Complete assembly of the MarsWRF look-up table. Calculate climate evolution trajectories for a range of assumptions about carbonate formation and escape to space. Begin comparison to geologic data. 	 ✓ LPSC presentation on: Forward modeling of intermittency of late bursts of Martian habitability. ✓ Detailed manuscript on: Ensemble approach to intermittency of late bursts of Martian habitability, using a climate evolution model.
Year 3.	 Complete parameter sweeps using the climate evolution model. Analyze the results and determine the intermittency of surface liquid water. Update geologic constraints, adding SAM δ¹³C and MAVEN data if appropriate, to narrow the range of acceptable climate-evolution trajectories. 	 ✓ LPSC presentation on: Effect of calculated dry intervals on Mars surface for microbial survival and organic-matter preservation. ✓ Short manuscript on confronting model with geologic constraints.

2.8. Personnel and Qualifications. (For FTE information, see §6, Budget Justification). PI Edwin Kite is an assistant professor at the University of Chicago (UChicago). As PI, he will participate in all aspects of the proposed work and oversee its implementation. Co-I Michael Mischna is a group supervisor at the Jet Propulsion Laboratory. He will have primary responsibility for running the MarsWRF model, and will also contribute to analysis of the MarsWRF output and to paper-writing. Postdoctoral researcher Mohit Melwani Daswani will carry out the majority of the geologic analysis, the carbonate formation modeling, and the comparison of model output to data, at UChicago. He will contribute to analyzing the MarsWRF simulations. Kite, Mischna, and Melwani Daswani will all participate in interpretation of results. David Mayer is a full-time Planetary GIS/Data Specialist in Kite's group at UChicago. He will support the geologic analysis and the comparison of model output to data.

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- Zuber, M.T., et al., 2007, Density of Mars' South Polar Layered Deposits, Science, 317, 1718-.

4. Biographical Sketches.

Edwin S. Kite (Principal Investigator).

Appointments:

University of Chicago (Assistant Professor), Department of the Geophysical Sciences, 2015 – Princeton University (Harry Hess Postdoctoral Fellow), 2014. Caltech (O.K. Earl Prize Postdoc), Geological and Planetary Sciences Division, 2012-2014.

Professional preparation:

B.A. Cambridge University (Natural Sciences Tripos – Geological Sciences), 2007 M.Sci. Cambridge University (Natural Sciences Tripos – Geological Sciences), 2007 Ph.D. University of California Berkeley (Earth and Planetary Science), 2011

Mars papers from the past 42 months:

Kite, E.S., Howard, A., & Lucas, A., 2014, "Resolving the era of river-forming climates on Mars using stratigraphic logs of river-deposit dimensions," *in review*. [**Intermittency constraint**]

Kite, E.S., Howard, A., Lucas, A., Armstrong, J., Aharonson, O., & Lamb, M., "Stratigraphy of Aeolis Dorsa, Mars: sequencing the great river deposits," *in revision.* [**Intermittency constraint**]

Kite, E.S., Williams, J.-P., Lucas, A., & Aharonson, O., 2014, "Paleopressure of Mars' atmosphere from small ancient craters," *Nature Geoscience*, 7, 335-339. [**pCO*₂ upper limit*]

Kite, E.S., Lewis, K.W., Lamb, M.P., Newman, C.E., & Richardson, M.I., 2013, "Growth and form of the mound in Gale Crater, Mars: Slope-wind enhanced erosion and transport," *Geology*, 41, 543-546. ("Highlight of the AGU Meeting" in *Science*, 338, 1522).

Kite, E.S., Halevy, I., Kahre, M.A., Manga, M., & Wolff, M., 2013, "Seasonal melting and the formation of sedimentary rocks on Mars," *Icarus*, 223, 181-210. [**ISEE-Mars climate model**]

Kite, E.S., Lucas, A., & C.I. Fassett, "Pacing Early Mars river activity: Embedded craters in the Aeolis Dorsa region imply river activity spanned ≥(1-20) Myr," *Icarus*, 225, 850-855. [**Intermittency constraint**]

Manga, M., Patel, A., Dufek, J., & **Kite, E.S**., 2012. "Wet surface and dense atmosphere on early Mars inferred from the bomb sag at Home Plate, Mars," *Geophys. Res. Lett.*, doi:10.1029/2011GL050192.

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Kite, E.S., Rafkin, S.C.R., Michaels, T.I., Dietrich, W.E., & Manga, M., 2011. "Chaos terrain, storms, and past climate on Mars," *J. Geophys. Res. Planets*, 116, E10002, 26 pp., doi:10.1029/2010JE003792 ("Research Highlight" in *Nature Geoscience*, 4, 580).

Mangold, N., **Kite, E.S.,** Kleinhans, M., Newsom, H.E., Ansan, V., Hauber, E., Kraal, E., Quantin-Nataf, C. & K. Tanaka, 2012, "The origin and timing of fluvial activity at Eberswalde Crater, Mars," *Icarus*, 220, 530-551.

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Additional papers on Mars or planetary habitability:

Kite, E.S., & A.M. Rubin, Sustained eruptions on Enceladus explained by turbulent dissipation in tiger stripes, *in preparation*.

Šrámek, O., McDonough, W., **Kite, E.S.**, Lekic, V., Zhong, S.T., & Dye, W.F., Geophysical and geochemical constraints on geoneutrino fluxes from Earth's mantle, *Earth Planet. Sci. Lett.*, doi:10.1016/j.epsl.2012.11.001. ("Research Highlight" at Nature).

Kite, E.S., Gaidos, E. & M. Manga, 2011. "Climate instability on tidally locked exoplanets," *Astrophys. J.*, 743, 41, 12 pp. [**This instability may apply to post-Noachian Mars**]

Rappaport, S., Levine, A., Chiang, E., El Mellah, I., Jenkin, J., Kalomeni, B., **Kite, E.S.**, Kotson, M., Nelson, L., Rousseau-Nepton, & Tran, K., 2012, "Possible disintegrating short-period Super-Mercury orbiting KIC 12557548," *Astrophys. J.*, 752, 1.

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Kite, E.S., Matsuyama, I., Manga, M., Perron, J.T., & Mitrovica, J.X., 2009, "True polar wander driven by late-stage volcanism and the distribution of paleopolar deposits on Mars," *Earth Planet. Sci. Lett*, 280, 254-267.

Kalas, P., Graham, J. R., Chiang, E., Fitzgerald, M. P., Clampin, M., **Kite, E. S.**, Stapelfeldt, K., Marois, C., & Krist, J., 2008. "Optical Images of a Planet 25 Light Years from Earth," *Science*, 322, 1345-1348 ("Breakthrough of the Year #2" at Science; AAAS Newcomb Cleveland Prize).

Kite, E.S., & R.C.A. Hindmarsh, 2007. "Did ice streams shape the largest channels on Mars?", *Geophys. Res. Lett.*, 34, L19202.

Field geology experience:

Central India (Proterozoic paleobiology). Greece, SE Spain, England, Scotland, California, Hawaii (fieldwork, mapping courses). NW Spain (independent mapping project, 6 weeks). Utah (Graduate Student Instructor for Professor W. Alvarez).

(*Page 2 of 2*)

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EMPLOYMENT

Jet Propulsion Laboratory (2004-present)

- Group Supervisor, Earth and Planetary Atmospheres, 2010-present
- EDL/Atmosphere Scientist & Participating Scientist, Mars Science Laboratory (2011-present)
- EDL/Atmosphere Scientist, Phoenix Lander (2007-2008); InSight Lander (2012present); Mars 2020 (2013-present)
- Member of the Technical Staff, 2004-present

EDUCATION

University of California, Los Angeles (1999-2004)

- Geophysics and Space Physics, M.S. June 2002, Ph.D. July 2004
- The Pennsylvania State University (1997-1999)
 - Meteorology, M.S. May 1999

Cornell University (1993-1997)

• Atmospheric Science, B.S. (Honors), May 1997

RELEVANT PUBLICATIONS

- Soto, A., M.A. **Mischna**, T. Schneider, C. Lee and M. Richardson, Martian atmospheric collapse: Idealized GCM studies, *Icarus*, in press, available online, doi:10.1016/j.icarus.2014.11.028.
- **Mischna**, M.A., V. Baker, R. Milliken, M. Richardson and C. Lee, Effects of obliquity and water vapor/trace gas greenhouses in the early martian climate, *J. Geophys. Res.*, 118, doi:10.1002/jgre.20054, 560-576, 2013.
- **Mischna**, M.A., C. Lee and M. Richardson, Development of a fast, accurate radiative transfer model for the martian atmosphere, past and present, *J. Geophys. Res.*, 117, E10009, doi:10.1029/2012JE004110, 2012.
- **Mischna**, M.A., M. Allen, M.I. Richardson, C.E. Newman and A.D. Toigo, Atmospheric modeling of Mars methane surface releases, Planet. Space Sci., 59, 227-237, 2011.
- Johnson, S.S., A.A. Pavlov and M.A. **Mischna**, The fate of SO₂ in the ancient martian atmosphere: Implications for transient greenhouse warming, *JGR*. doi:10.1029/2008JE003313, 2009.
- **Mischna,** M.A., S. Lee, M. Allen and R.J. Terrile, Use of evolutionary computation for isolating surface emissions from orbit, *IEEE Aerospace Conf. Proc.*, #1524, 2009.
- Johnson, S.S., M.A. **Mischna**, M.T. Zuber and T.L Grove, Sulfur-induced greenhouse warming on early Mars, *JGR*, doi:10.1029/2007JE002962, 2008.
- **Mischna,** M.A. and M.I. Richardson, A reanalysis of water abundances in the martian atmosphere at high obliquity, *GRL*, **32** L03201, doi:10.1029/2004GL021865, 2005.
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- **Mischna**, M.A., J.F. Kasting, A. Pavlov and R. Freedman, Influence of carbon dioxide clouds on early martian climate. *Icarus*, **145**, 546-554, 2000.

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Education

2011-pres: Ph.D. Student in Planetary Science, The Open University. Thesis title: Aqueous alteration on early Mars. Advisers: Monica M. Grady, Susanne P. Schwenzer and Ian P. Wright.

2009–2011: M.Sc. (Erasmus Mundus European Commission initiative) Geo-information Science and Earth Observation for Environmental Modelling and Management, at the consortium of the University of Southampton, Lund University, University of Warsaw and ITC -University of Twente (host institution). Thesis title: Mineral spectra extraction and analysis of the surface mineralogy of Mars with hyperspectral remote sensing. Advisers: Frank J. A. van Ruitenbeek and Wim H. Bakker. Website: http://www.gem-msc.org/

2003-2009: B.Sc. Geology, Autonomous University of Barcelona. Erasmus exchange year in Switzerland (2007-2008) at the Universities of Fribourg, Neuchâtel and Bern (host institution).

Publications

Melwani Daswani, M., Morlok, A., Wolters, S. D., and Grady, M. M. (in prep. for Icarus) Mid-infrared reflectance spectroscopy of calcium aluminium-rich inclusions: A tool to detect primitive asteroids?

Melwani Daswani, M., Schwenzer, S. P., Reed, M. H., Wright, I. P., and Grady, M. M. Fluids on early Mars: New insights from an old meteorite. Geochim. Cosmochim. Acta (accepted).

Gross, J., Filiberto, J., Herd, C. D. K., Melwani Daswani, M., Schwenzer, S. P., and Treiman, A. H. (2013). Petrography, mineral chemistry, and crystallization history of olivine-phyric shergottite NWA 6234: A new melt composition. Meteorit. Planet. Sci., 48(5): 854-871.

Melwani Daswani, M. (2011). Mineral spectra extraction and analysis of the surface mineralogy of Mars with hyperspectral remote sensing. (M.Sc. thesis.) ITC, University of Twente, Enschede, the Netherlands, 62 p.

Experience with analytical instruments

Cameca SX 100 Electron Microprobe Analyser (regular user).

FEI Quanta 200 3D Scanning Electron Microscope (regular user).

Finesse - custom built multi-element (C, N, and noble gases) high sensitivity static isotope mass spectrometer (occasional user).

UV-VIS petrographic miscroscope (regular user).

Raman spectrometer for geological samples (occasional user).

Experience with research related software

Geochemical modelling: CHIM-XPT (regular user), FrezChem (regular user), Geochemist's Workbench (occasional user), MELTS (occasional user).

Remote sensing and GIS: ENVI (regular user), ArcGIS (regular user), IDRISI (occasional user), ILWIS (occasional user), GRASS (occasional user), gvSIG (occasional user).

Remote sensing (Mars-specific): SOFT and Alpha (ESA's OMEGA datacube calibration; regular user), PyENVI (geometric, noise, thermal and other corrections for CRISM and OMEGA; regular user).