INVESTIGATION OF THE BAGNOLD DUNES BY THE CURIOSITY ROVER: PLANS FOR THE FIRST STUDY OF AN ACTIVE DUNE FIELD ON ANOTHER PLANET

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Introduction: For much of Mars' history the dominant geomorphic processes have been due to wind, with resultant effects on landscape modification through burial, exhumation, and abrasion. Initial orbital studies showed that bedforms ranging in scale from enigmatic "transverse aeolian ridges" (TARs) to dunes were common on the surface, although the level of activity could not be gauged due to limitations in image resolution and temporal observation baselines. Hints of dune dynamics from the Mars Orbiter Camera [1-3] and Mars Exploration Rover (MER) surface observations [4-6] were confirmed with increasingly sophisticated data and studies using the High Resolution Imaging Science Experiment (HiRISE) [7-10]. These results showed that many dark dunes and ripples on the planet were active, with displacements and sand fluxes comparable to those on Earth [10]. Surface investigations from the MERs and later the Mars Science Laboratory (MSL) Curiosity rover have investigated, in situ, ripples, sand shadows, and megaripples/TARs, but an active dune field on Mars (or any planetary body besides Earth) has never been studied up close despite the fact that sandstones make up a significant component of the Martian stratigraphic record [11,12]

Of the seven sites so far visited by landed spacecraft, the MSL traverse region in Gale Crater is the only location where large, active dunes are accessible for in situ investigation. HiRISE time series images show that this dune field is in an active state of migration, with dune migration rates of 0.4 m per Earth year [13]. Although not a primary goal of the MSL mission, the planned traverse path passes through the informally-named Bagnold Dunes, offering a unique opportunity, for the first time, to investigate an extraterrestrial active dune field. Here we describe plans for the campaign, which is expected to provide important information on Martian sedimentary processes, dune mineralogy/chemistry, aeolian transport rates, sandstone genesis/stratigraphy, and possibly even habitability.

The MSL payload is well suited for studying active dunes. The rover mast cameras, Navcam [14], Mastcam [15], and the ChemCam remote microimager (RMI) [16,17] provide images of varying coverage and spatial scale. The Mars Hand Lens Imager (MAHLI), located on the rover arm, can achieve a pixel scale of 14.5 μm at a working distance of 22 mm [18]. The Rover Environmental Monitoring Station (REMS) measures wind speed and direction, pressure, relative humidity (RH), air temperature, ground temperature, and ultraviolet radiation, with 1 Hz sampling for ~5 min every hour and extended hour-long observations typically several times per sol [19]. ChemCam LIBS (laser-induced breakdown spectroscopy) remotely measures major and many minor elements within a spot size less than 0.5 mm [16,20]. The Alpha Particle X-ray Spectrometer (APXS) provides in situ elemental abundance for $Z \geq 11$ (Na) in a ~1.7 cm diameter spot size [21]. The Dynamic Albedo of Neutrons (DAN) instrument detects hydrogen beneath the surface to depths of ~60 cm [22]. The rover Sample Acquisition, Processing, and Handling (SA/SPaH) system uses a scoop and rotary-percussion drill to acquire soil and rock samples, which can be sieved to size fractions of <150 μm and < 1 mm [23]. The samples can then be delivered to the CheMin [24] and Sample Analysis at Mars (SAM) [25] instruments for detailed mineralogical and elemental/isotopic measurements, respectively. In addition, the rover wheels can "scuff" soils and sand, revealing sub-surface structure in the exposed walls.

Science Goals and Objectives: The MSL Bagnold dune campaign addresses four broad science goals: 1) Understanding current Martian dune processes and rates, including differences between dunes and other bedforms, 2) deciphering dune processes, rates, and geochemical pathways in the past (e.g., consider Bagnold as an unaltered Mt. Sharp [Aeolus Mons] sandstone protolith), 3) determining dune material provenance, and 4) assessing the dunes as traps for interplanetary dust particles (IDPs) and water. These goals are met by achieving the following objectives:

1. *Determine dune mineralogy and chemistry* (ChemCam, APXS, CheMin, SAM) (Goals 1, 2, 3, 4) a. Measure mineralogy and chemistry as a function of location on the dunes and dune ripples, both on the surface and in the interior. b. Relate mineralogy/chemistry to dune dynamics, infrared spectral and photometric properties, and development of sedimentary structures.

2. *Determine grain size and sorting as a function of mineralogy, and contributions of atmospheric dust* (ChemCam, MAHLI, AXS, CheMin, SAM) (G1,2,3) a. See how grain chemical, mineralogical, and physical properties vary as a function of location on dunes and

dune ripples, both on the surface and in the interior. b. Relate the level of activity to grain properties and dust content. c. Relate to spectral/photometric properties which can then serve as a calibration for remotely sensed data elsewhere on Mars

3. *Determine modern aeolian transport rates* (Mastcam, ChemCam RMI, REMS) (G1, 2) a. Measure movement of dune slip faces and ripples at a range of spatial scales and temporal baselines, with simultaneous wind measurements. b. Measure size of dune ripples to calibrate contributions to sand flux. c. Measure saltation fluid and impact threshold speeds and provide better estimates of reptation and saltation fluxes on Mars.

4. *Determine dune stratification and structure* (G1,2) (Mastcam, ChemCam RMI, MAHLI) a. Measure size, shape, and volumes of wind ripple, grain fall, grain flow, and interdune deposits. b. Look at stratification and structure within dune and dune ripple scuffs.

5. *Determine if dunes trap IDPs and sequester water* (G4) (DAN, REMS HS, SAM) a. Use DAN to measure hydrogen and thereby infer the presence of water at depth, and SAM to measure H_2O and other volatiles released in sampled materials. b. Have REMS measure surface and atmospheric temperature, pressure, and relative humidity with extended hours at night to determine if there are changes in the local water volume mixing ratio over dunes. c. Use SAM to search for the presence of organic matter, either within mafic grains [e.g., 26] or as IDPs by characterizing the amount and type of reduced carbon as well as its mineral/chemical associations.

Planned Campaign: The exact path that MSL will take to approach and then sample the Bagnold Dunes has not yet been decided, although notional traverses have been proposed. The dunes that could be investigated are barchan-barchanoid to longitudinal in morphology. The distance over which the rover may drive on the dunes is also uncertain; short drives along the stoss or near the lateral edges may be possible but there is risk of getting stuck in the sand.

With these caveats in mind, the overall plan is to investigate at least two dune locations, each being distinct in the level of aeolian activity as determined from HiRISE data and infrared spectral properties determined from CRISM. Prior to reaching the dunes, MSL will image the same locations at similar times of day to document any changes. As the rover closes in, increasingly finer scale changes, such as ripple migration at shorter temporal baselines, are expected. During the approach, the plan is to “calibrate” REMS wind speed measurements by orienting the rover in 120° increments for a full sol each to sample the wind field with the one working wind sensor.

Each dune stop is expected to last at least 6-7 sols, with the following planned activities (described in very generalized form here, without contingencies, and with recognition that early measurements may inform upon and change subsequent plans and rover operational constraints and consumables must be considered):

Sols 0-1: 1) Approach dune, 2) Mastcam and ChemCam remote sensing, 3) MAHLI goniometer and Mastcam multiple time of day sequences for photometric characterization, 4) short drive on to dune with DAN in active mode to detect possible sub-surface hydrogen, 5) scuff edge of dune, with Mastcam imaging

Sols 2-4: 1) Scoop and deliver <150 µm fraction to SAM, 2) Mastcam and ChemCam remote sensing of scuff, 3) MAHLI and APXS on dune surface and scuff, 4) SAM EGA/TLS/GCMS analysis, 4) deliver sample to CheMin, 5) Dump sieved and sieved-rejected materials, followed by remote sensing of piles, 6) CheMin overnight analysis, 7) MAHLI and APXS on dump piles, 8) CheMin overnight and SAM preconditioning.

Sols 5-6: 1) Scoop and process < 1mm portion and deliver to SAM (there may be a possibility of segregating to a 150 µm – 1 mm size, but this must be tested), 2) SAM EGA/TLS/GCMS, 3) Dump sieved and sieved-rejected materials, followed by remote sensing of piles, 4) CheMin overnight.

Sol 7+: Drive to next dune location

Expected Outcome: At the conclusion of the Bagnold Dune campaign we will have investigated, in situ and for the first time, an active dune field on Mars. We expect to significantly expand our understanding of current and past aeolian processes, sand provenance, and other questions that, until now, have been addressed solely from remote orbital observations, models, or partial analogs. This campaign should result in significant advancements in Martian and aeolian science.

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