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Non-active dunes in the Acheron Fossae region of Mars between the Viking and Mars Global Surveyor eras

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Abstract. Comparison of a high resolution Viking image (422B10; 8 m/pixel) with a Mars Orbiter Camera image (SP2-502/06; 5.6 m/pixel) of dunes in the Acheron Fossae region of Mars (38°N, 135°W) reveals that the dunes moved <1 pixel during a span of almost 21 Earth years. Very shallow illumination in the MOC image indicates the dunes are <1.5 m high. The images indicate that any movement of these Martian dunes is <0.4 m/yr, a rate that is less than the documented movement of comparable dunes on Earth by a factor of up to 200. The Acheron Fossae dunes occur within a region of low thermal inertia, indicating that the dunes may be stabilized by a pervasive dust cover. Alternatively, the saltation threshold was not exceeded significantly at this location in more than 20 years.

Introduction

Dunes were first recognized on Mars in Mariner 9 images [*McCauley et al.*, 1972; *Cutts and Smith*, 1973]. Large dune fields surrounding the north polar region were clearly revealed both in Mariner 9 [*Cutts et al.*, 1973] and Viking images [*Cutts et al.*, 1976; *Tsoar et al.*, 1979], and numerous intracrater dune fields occur throughout the high latitudes of the southern hemisphere [*Thomas*, 1981; *Greeley et al.*, 1992]. Nominal Viking Orbiter resolution during the primary missions (~40 m/pixel) made identification of slip faces difficult except on the largest dunes, but different seasonal illuminations led to the interpretation that some of the north polar dunes may be active [*Tsoar et al.*, 1979]. Infrared measurements of low albedo dune patches, present mostly on the floors of impact craters throughout the highlands, documented the fine to coarse sand size of these materials [*Edgett and Christensen*, 1991, 1994].

The highest resolution Viking images (<10 m/pixel) were obtained during the Extended and Survey missions, when periapsis was lowered from 1500 km to ~300 km for both orbiters [*Snyder*, 1979]. The high resolution images revealed an abundance of small dunes scattered across diverse terrains; in particular, a dune field in the Acheron Fossae region (38.3°N, 134.9°W) illustrated that dunes visible at 8 m/pixel were invisible at 57 m/pixel resolution [*Zimbelman*, 1987]. The enhanced capabilities of the Mars Orbiter Camera (MOC) narrow angle camera on the Mars Global Surveyor (MGS) spacecraft have challenged many concepts derived from the Viking images; small dunes appear to be ubiquitous in MOC narrow angle images [*Malin et al.*, 1998], and isolated patches on frost-covered dunes in both northern and southern polar latitudes clearly revealed that saltation had occurred since the deposition of the frost [*Smith*, 1999]. A MOC image was targeted on the Acheron Fossae dune area during the Science Phasing Orbit portion of the MGS mission [*Albee et al.*, 1998], the images from which were recently released. The MOC image covers an area coincident with one of the highest resolution images obtained during the Viking missions. This situation represents a unique opportunity to assess the mobility of Martian dunes (at one location) over the nearly 21 Earth years that separate the Viking and MGS missions.

Procedure

The Viking image (frame 422B10, 8 m/pixel) was processed using ISIS software to provide radiometric calibration, blemish and reseau removal, and geometric rectification into a vertical view (Fig. 1a). The early morning MOC image (frame SP2-502/06, 5.6 m/pixel) was flipped along a vertical axis, to account for the mirrored condition of the data, and the brightness levels were inverted to portray illumination comparable to that of the mid-afternoon Viking image. The MOC image was referenced to the rectified Viking image using features in the highland knobs exposed around the dunes (Fig. 1b). The best registration occurred around a Y-shaped dune field (to the lower left of center in Fig. 1), where highland knobs on three sides of the dunes produced registration better than one pixel. A difference image of these dunes showed no systematic trends. The dune crest locations from the high fidelity MOC image were overlain onto the corresponding part of the Viking image (Fig. 2), which indicated that the dune locations are consistent between the two images to within one (Viking) pixel, or <8 m.

Results

The correspondence of dune locations indicates that the dunes have moved <8 m between Nov. 3, 1977, and Aug. 20, 1998; this represents an upper limit for the dune movement rate of <0.4 m/yr over the 20.7 Earth years between images. The very shallow illumination angle of the MOC image (85.4° from vertical) places tight constraints on the dune height. Shadow lengths of the dunes (identified on the original non-inverted MOC data) range from 11 to 17 m. Brightness values do not reach zero in the shadows; however, solar illumination only 4.6° from horizontal makes it likely these are true shadows that are partially illuminated by light scattered from particles in the atmosphere, a situation prevalent at the Mars Pathfinder (MPF) site [*Smith et al.*, 1997].

The low solar incidence angle and the shadow lengths indicate the dunes at Acheron Fossae are <1.5 m in height. This low height is not particularly surprising for dunes on Mars. The MPF Sojourner rover imaged barchan-like dunes only 10-15 cm high, ~1 m wide, with angle-of-repose slip faces and windward slopes <15° [*Greeley et al.*, 1999]. The MPF dunes have lower height-to-width ratios than similar sand accumulations on Earth,

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attributable to the higher wind speeds required for saltation [*Greeley et al.*, 1983] and to the flatter saltation trajectories on Mars caused by the higher wind speeds [*White*, 1979].

Individual dunes at Acheron Fossae range from circular patches ~45 m across to linear ridges (likely transverse dunes) 50 to 80 m wide and 200 to 340 m in length. Dune spacing is comparable to dune widths, ranging from 80 to 110 m. The overall dune dimensions, including the low height, are roughly comparable to stabilized transverse dunes in the eastern Mojave Desert [*Zimbelman et al.*, 1995]. A ripple pattern, perpendicular to the long axis of the dunes, is present along some of the margins between the dunes and the highlands (e.g., upper right in Fig. 1). The ripples have an average spacing of ~35 m, are ~11 m wide and ~80 m long; they are much smaller than the main dunes and possibly are more comparable to the MPF dunes.

Discussion

It should be emphasized that the Acheron Fossae results represent a single dune field on a planet with abundant dune deposits (see Introduction). Martian dunes result from a variety of wind regimes ranging from seasonal polar winds to variable winds associated with regional slopes (e.g., in the Tharsis area) and crater walls [*Greeley et al.*, 1992]. Global Circulation Models (GCMs) have proved useful in assessing the global distribution of sand on Mars [*Anderson et al.*, 1999], but dune orientations are generally less well correlated to the models than are wind streaks, likely due to the complex influence of topography on dunes [*Greeley et al.*, 1992]. While we are unlikely to constrain the global sand-driving capabilities of the Martian atmosphere here, it is still instructive to discuss the implications of the Acheron Fossae results for dune mobility at this particular location.

Dune mobility is a function of both the duration and intensity of wind above the saltation threshold and the size of the dune. *Bagnold* [1941, p. 214] quantified this relationship by assuming that if the dune is in an equilibrium form then it will move as a whole, conserving its shape, which results in the following simple expression:

$$c = q / (p\ h) \qquad (1)$$

where c is the rate of dune advance, q is the mass-transport rate (expressed as mass per unit lane width per second) of sand flow over the dune, p is a packing factor (or bulk density), and h is the dune height [*Cooke and Warren*, 1973, p. 276; *Greeley and Iversen*, 1982, p. 182]. Dune advance rate is directly proportional to the sand flow over the dune (which reflects wind conditions) and it is inversely proportional to the dune height, so smaller dunes will move faster than larger ones under similar conditions. *Greeley and Iversen* [1985, p. 182] point out that a dimensionless form of this expression, incorporating consideration of the wind friction speed over the surface, indicates that a dune on Mars will migrate ten times faster than a comparable dune on Earth (for equivalent wind speeds) because the threshold friction speed in the current rarefied Martian atmosphere is about ten times greater than the threshold friction speed on Earth.

Documented rates of dune movement on Earth are quite extensive for barchan dunes, primarily because individual discreet dunes can be monitored for periods of years to decades [e.g., *Finkel*, 1959; *Long and Sharp*, 1964; *Norris*, 1966; *Hastenrath*, 1967; *Embabi*, 1982]; these all show similar trends for dune advance rates [Fig. 5.29 of *Greeley and Iversen*, 1985]. Two published data sets for barchan dune movement, bracketing the range of measured rates, provide insight into the movement of small dunes (most relevant here given the small height of the Acheron Fossae dunes). Data for the movement of dunes (<4 m in height) located in southern Peru [*Finkel* , 1959] and in the

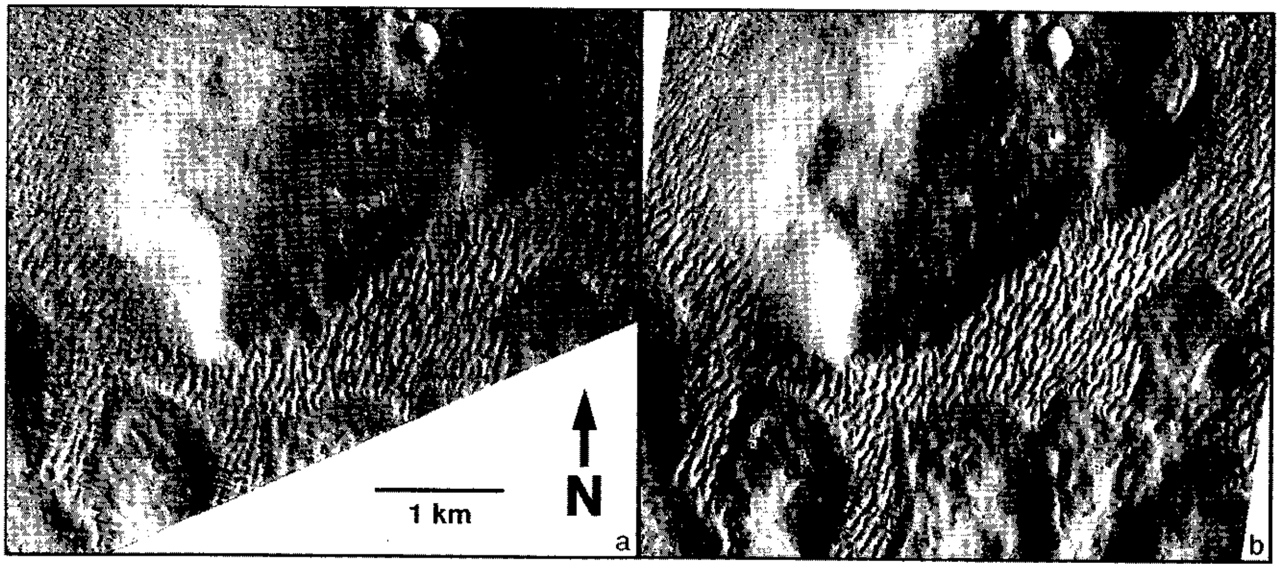

Figure 1. a) Portion of Viking image 422B10 showing dunes in the Acheron Fossae region of Mars. The image was radiometrically calibrated, had blemishes removed, and was geometrically rectified with north to the top (8 m/pixel, slant range 325 km, solar incidence angle 62.8°, local solar time 15.36 H, taken on Nov. 3, 1977, centered on 38.3°N, 134.9°W). b) Portion of MOC image SP2-502/06. The MOC image was referenced to the Viking image using only features in the highland knobs exposed around the dunes. The image was flipped left to right to account for the mirrored state of the data, and the brightness values were inverted to portray illumination conditions comparable to that in the Viking image (MOC image has 5.6 m/pixel, slant range 1500 km, solar incidence angle 85.4°, local solar time 6.21 H, taken on Aug. 20, 1998).

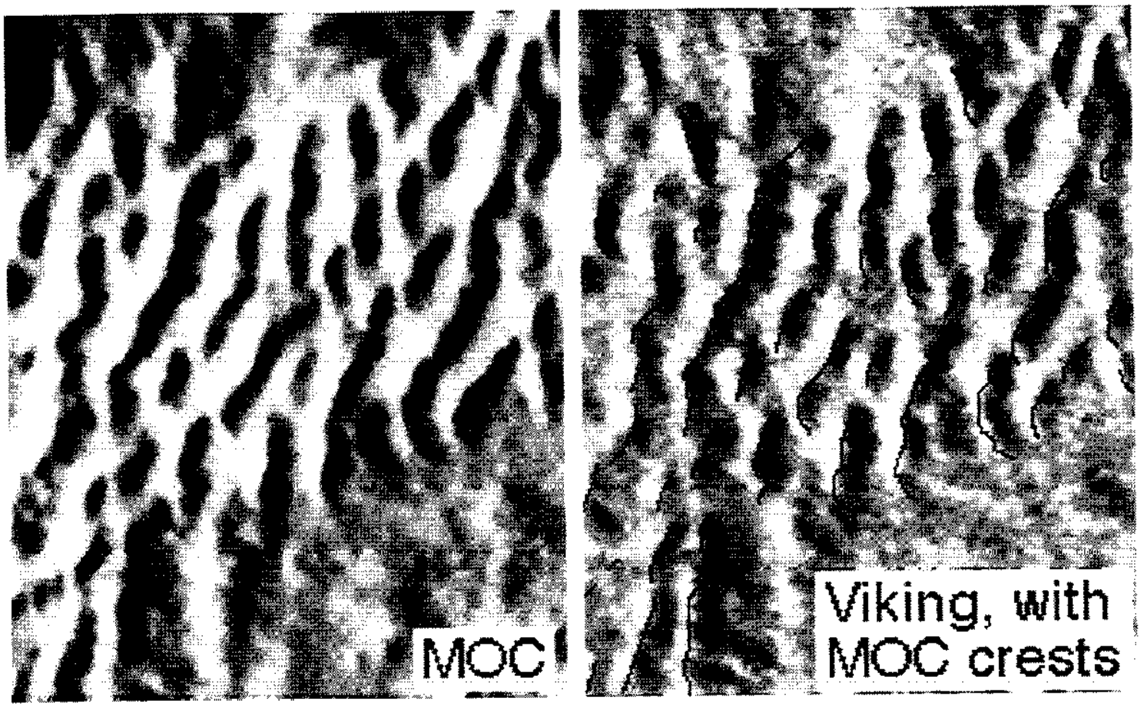

Figure 2. Comparison of Acheron Fossae dunes in MOC and Viking images. The area shown is ~800 m wide, and it is from the lower left of center in Figure 1, where the dunes are surrounded on three sides by highland knobs. a) Portion of referenced MOC image of dunes on the valley floor between highland knobs, b) Overlay of MOC dune crests (black lines) on corresponding part of Viking image. The lines mark the transition from light to dark along individual dunes in part a.

Kharga region of Egypt [*Embabi* , 1982] result in the following linear regression:

$$c_4 = 106.1 - 16.6\ h \qquad (2)$$

where c_4 is the dune movement rate (m/yr) for dunes <4 m high (with a correlation coefficient of -0.76). Equation 2 indicates that a dune 1.5 m high should move at a rate of 81 m/yr, while a dune 1.0 m high would move at a rate of 90 m/yr, for wind conditions representative of Peru and Egypt. The Martian dunes thus could move at a rate of >80 m/yr under sand flow conditions like those in Peru and Egypt; this rate is 200 times greater than the maximum rate inferred for the Acheron Fossae dunes. The thin Martian atmosphere could increase this difference to a factor of 2000.

Clearly Earth and Mars do not have equivalent wind regimes, so that Mars may not experience Earth-like sand-driving winds. The higher threshold friction speed on Mars likely corresponds to a greatly reduced amount of time during which the wind exceeds this speed. However, whenever the threshold speed is exceeded on Mars, dune migration should be very rapid. Assuming that the threshold friction speed was exceeded for some period of time during the interval between the two images, the Acheron Fossae dunes may not have moved because they were stabilized.

The Martian dunes certainly are not stabilized by vegetation, as are the similar-sized transverse dunes in the Mojave Desert [*Zimbelman et al.*, 1995], but other natural agents could stabilize the dunes. "Rock" abundance, determined from multiwavelength thermal infrared observations made by the Viking orbiters, are low in the Acheron Fossae area (<5%), similar to values throughout the surrounding region [*Christensen and Moore*, 1992]. It is difficult to explain the presence of rocks on the dunes in sufficient quantity to stabilize them. An alternative mechanism for stabilization comes from the observation that the Acheron Fossae dunes are within a large area of low thermal inertia [*Christensen and Moore*, 1992]. The dunes may be covered by a dust layer that effectively separates the wind from the dune materials, but which is thin enough to not be visible in the MOC image. Without the presence of saltating sand or abundant roughness elements (excluded by the low rock abundance), dust is extremely difficult to remobilize by the action of the wind alone [*Greeley et al.*, 1992]. A pervasive dust cover at Acheron Fossae is also consistent with the high albedo of the region [*Christensen and Moore*, 1992].

If the dunes are not stabilized, an alternative interpretation is that the threshold friction speed was not exceeded at this site during the 21 Earth years separating the Viking and MOC images. This situation seems unlikely for most aeolian settings on Earth but it is at least a viable possibility for Mars. Threshold friction speeds were only barely reached during 6 Earth years of monitoring at the Viking 1 landing site [*Greeley et al.*, 1982], and may not have been reached during 4 Earth years at the Viking 2 landing site, even during the height of global dust storms [*Ryan and Henry*, 1979]. More recently, the Mars Pathfinder site showed similar relatively low wind speed during three months of observations [*Schofield et al.*, 1997]. These lander observations are consistent with saltation modeling based on GCMs which conclude that the observed distribution of dunes on Mars compares favorably with wind stress threshold values a factor of two lower than the lowest theoretical dynamic threshold value, implying it is difficult to form the present sand distribution under current conditions [*Anderson et al.*, 1999]. It therefore remains a distinct possibility that the dunes at Acheron Fossae did not move simply because the local winds never blew strong enough to initiate saltation under current atmospheric conditions.

The wonderful MOC narrow angle images hold great potential for studying aeolian features on Mars. Researchers should watch for additional locations on Mars where dune mobility between the Viking and MGS eras can be assessed, particularly at any locations outside of the low thermal inertia regions.

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