THE DUST CYCLE: SINKS AND SOURCES, CAUSE AND EFFECT. Philip B. James
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Dust is ubiquitous on Mars; large portions of the Martian surface are covered with a veneer of the material, and the atmosphere contains significant amounts of dust as a dispersed aerosol. Dust participates in significant atmospheric phenomena that span an extremely wide range of spatial scales: dust devils, dust plumes, local dust storms, regional dust storms, and planet-encircling and global events. Both atmospheric and surface phenomena are highly variable on both seasonal and interannual time scales. In fact the term "dust cycle" is misleading because dust phenomena are certainly not periodic on an annual scale; and it is not even obvious that they are periodic at all, because of limitations on the continuity and resolution of observations. A review of Martian dust phenomena based mainly upon Viking studies was published following the Fourth Mars Conference by the University of Arizona Press [1]. This review will concentrate on developments since that article was written.

Martin and Zurek [2] compiled and classified earth based and spacecraft dust storm observations that were made before 1990. They somewhat arbitrarily defined a regional dust storm to be one with long dimension greater than 2000 km and classified a "planet-encircling storm" to be one that spread to encompass all longitudes. The first such planet-encircling storm to be unambiguously identified occurred in 1956. Since that time several of these dramatic events have been seen in imaging or inferred from other data. Regional storms occur preferentially in the "classic dust storm season" from roughly $L_S = 200°$ to $300°$, although some have been observed outside of this period [3]. However, no planet-encircling storm has been verified outside of that season, although this could be due to the much better resolution available during perihelic oppositions.

The development of regional storms into planet-encircling storms was observed in 1973 in Planetary Patrol images [4] and in 1977 by Viking orbiters [5]. Mars Global Surveyor (MGS) monitored a regional storm in the Noachis region of Mars that did not expand into a planet-encircling event during its first aerobraking phase in 1997 [6,7] (Figure 1). This storm started roughly at $L_S = 225°$, at its maximum extent extended from -25° to -65° latitude and from 320° to 15° longitude, and had measured IR opacities in excess of unity. It was accompanied by elevated planetary opacities but faded to essentially pre storm conditions by $L_S = 235°$. The Thermal Emission Spectrometer (TES) observed a second regional storm in the region to the north and northwest of Aryre during summer, $L_S = 309°$, a period when the Mars Orbiter Camera (MOC) could not view the Southern Hemisphere [8].

Figure 1: Noachis dust storm and associated activity near the edge of the seasonal south polar cap.

The difficulty in building statistics of regional and planet-encircling storms rests with the sporadic nature of the ground-based observations. Even Hubble Space Telescope (HST) is subject to a solar pointing constraint that prevented observing a "classic dust storm season" during the 1990's. Clancy has pioneered the use of microwave observations of optically thick lines of CO in the Martian atmosphere to determine the vertical profiles of temperature averaged over mid latitudes. These vertical temperature profiles, which are related to the amount of dust in the atmosphere, revealed that the Martian atmosphere in the season near aphelion in the 1990's was cold, dust free, and cloudy [9], consistent with HST observations of an equatorial condensate cloud belt. The results of the microwave technique and TES observations in 1997 are nearly identical, thereby in some sense calibrating the former by in situ data [10]. Clancy's data since 1988 reveal significant differences in the timing of and atmospheric heating produced by large dust storms around perihelion. His observations suggest that one or more regional storms such as the Noachis storm seen by MGS occurs during at least most perihelic seasons. However, they only develop into planet-encircling events in about half of these years. His data from 1994-96 resemble those from the Noachis storm, while the larger temperature peaks observed in 1992-1994 are similar to 1977 Viking data. The absence of observations of a regional dust storm in the well-observed, perihelic 1986 opposition suggests that the "classic dust storm seasons" in some years lack even a regional storm.

Simulations with global circulation models have resulted in significant progress in understanding the meteorological effects of dust in the Martian atmosphere [11,12]. The zonal mean circulation in the season near perihelion, already intrinsically stronger than its aphelion counterpart because of the stronger insolation, intensifies as the amount of dust in the atmosphere increases. Of particular interest are the very strong cross equatorial Hadley circulation, which may transport dust between hemispheres in the largest storms, intense thermal tides, and a near surface westerly jet at about -30°, all of which contribute to large surface stresses in this region. The frequent local dust storms seen in that latitude region between the two major 1977 planet-encircling storms are evidence for the high surface stresses [13]. The disparity of the strengths of the circulation near perihelion versus aphelion probably explains the fact that no expansion of a regional storm in northern summer to become planet-encircling has been documented.

Viking data suggested that most local dust storms occurred in only a few regions on Mars [14]. At least some of these regions are still important sources. For example, local storms were common along the edge of the receding south polar cap during Viking, and MGS also observed extensive local dust activity in this region. Local storm activity near the South Cap intensified and expanded prior to the Noachis storm [6,7,8], suggesting that the regional event was triggered by the local activity. But subsequent observations have expanded the domain of local dust storm activity. HST for the first time observed similar dust storms near the edge of the receding north polar cap during 1996-97 [15] and recorded a significant dust storm in Valles Marineris [16]. Several local storms were observed by MOC in Amazonis, not previously known as a frequent location of storms, and in Chryse, which was known previously as a dust storm locale [17] (Figure 2).

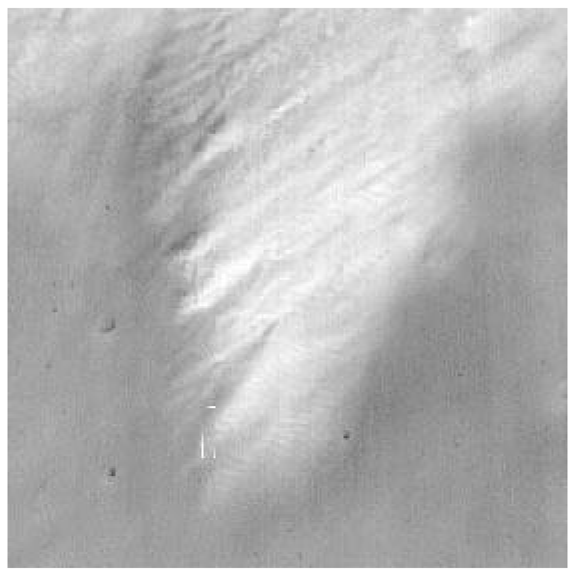

Figure 2: MOC image of local dust storm observed in Chryse Planitia.

There has been less quantitative progress in understanding the meteorology of local storm generation, that depends on local circulation patterns, than on the effects of global circulation on the development of the global scale storms. Higher resolution simulations with the Ames Mars General Circulation Model suggest that the combination of very strong zonal circulation and fronts associated with transient eddies moving across the seasonal cap could readily lift dust exposed during the sublimation of CO_2 [15]. Ryan et al. [18] also invoked baroclinic waves to explain the storms observed in Chryse during southern summer on the basis of Viking Lander observations. However, katabatic winds induced by the polar topography could also be important in producing cap edge storms, and slope induced winds have been inferred to be a factor in the occurrence of local storms in other regions of the planet. However, there has not been enough mesoscale modeling of such local wind systems, largely because of the lack of detailed topography.

Some images of local dust storms from Viking and from MGS suggest that these storms developed from groups of smaller scale dust plumes that have been formed by locally intense wind systems and have consolidated into the familiar turbulent, lobate structures that resemble terrestrial haboobs. Isolated plumes were also occasionally seen in Viking images. The role of dust devils in the development of larger scale dust activity is less clear. Dust devils were recognized in high resolution Viking images in Amazonis [19], and their signature was seen at the Chryse location of Viking Lander 1 [20]. Subsequently dust devils were observed at the Pathfinder landing site in Ares Valles both through their meteorological signature and in imaging [21]. These small-scale dust phenomena appear to be fairly common and probably play an important role in maintaining the background opacity of the atmosphere.

The dynamic nature of dust processes and their global influence are revealed by observation of changes in the distribution of dark and light albedo features on Mars. Earth based astronomers have recorded such changes for many years in features such as Solis Lacus and Nepenthes [22]. Spacecraft observations in the 1970's of specific changes in Syrtis Major, Solis Lacus, and other features established the relationship of these variations to excavation, transport, and deposition of bright dust during and following global storms [23]. Some regions that were dark and presumably free of dust when observed by Viking, such as Cerberus, are now bright and covered by dust deposited during the intervening twenty years [24,25], but the circumstances of these changes are unknown.

These observations indicate variability in the locations of sources and sinks of dust that is co-equal to the local meteorology in determining the occurrence of dust storms. For example, frequent local dust storms were observed in the northwestern portion of Valles Marineris in the year following the 1977 global storms but not in the preceding or following years [26]. This suggests that the deposition and depletion of the dust source in the region was the controlling factor. Of particular interest is the possibility that the layered terrain in the North Polar Region is a major sink for dust from global dust storms [27]; this dust, when exposed during seasonal cap sublimation, may become a source for the local storms near the cap edges [15].

The physical nature, scattering properties, and composition of the dust particles have been the subject of several significant studies during the 1990's. These were based on IRTM emission phase functions [28], infrared data from the Phobos Mission [29], a reanalysis of Viking lander images [30], a reanalysis of Mariner 9 IRIS spectra of the 1971 global storm [31], and Pathfinder dust observations [32]. There is generally good agreement between these various analyses. This is actually somewhat surprising in view of the different conditions and locations that are involved and suggests that the dust scattered around Mars in various reservoirs is relatively well mixed and homogeneous.

There are still major unanswered questions concerning dust processes on Mars. The instruments currently orbiting Mars on MGS, MOC, TES, and Mars Laser Altimeter (MOLA), as well as those currently in route on Mars Climate Orbiter (MCO), Pressure Modulated Infrared Radiometer (PMIRR) and Mars Color Imager (MARCI) should obtain data which can answer many of these. A few examples include:

1. The ability of MGS and MCO to observe the entire planet every day guarantees that the advent of regional storms will be observed. Such data will establish the necessary and sufficient conditions for evolution of local storms into a regional storm or for expansion of a regional storm to planet-encircling status, if this occurs.
2. The complete record of the distributions in time and space of local dust storms that will

be obtained for almost two Martian years will at least partially address major gaps in our knowledge of these events.

3. Detailed topographical data provided by MOLA and by MOC stereo imaging will provide data needed to model local storms. Coupled with the fine tuning of MGCM's made possible especially by the infrared experiments, this should make it possible to fully understand the origin and evolution of local dust storms.
4. Identification of sources and sinks of dust will be facilitated by imaging with wide-angle MOC and MARCI cameras. TES observations and MOC narrow angle images will reveal the nature of these surfaces and their temporal changes.
5. The simultaneous study of dust processes over wavelengths ranging from ultraviolet to infrared by MGS and MCO will greatly improve the understanding of the physical properties of the dust and differences between dust components in different regions. Also, the instruments on these spacecraft should answer questions concerning the local dynamics of dust clouds such as the importance of convection and possible associations with water ice condensation.

Despite these various advances, longer term observations using either permanent Mars observatories or continuous earth based monitoring in microwave and other bands will probably still be necessary to establish whether the "dust cycle" is, in fact, repetitive on some scale.

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