The dust storms of Mars

Richard McKim

The text of the 1995 Presidential Address, delivered on 1995 October 18 at 23 Savile Row, London W1

Mars may be dead in the biological sense, but it is nonetheless a dynamic and fascinating world. Telescopic observers have long followed the variations in the dark areas and the polar caps, and recorded the changing white clouds and the more mysterious yellow clouds, which sometimes conceal the outlines of the dark markings for months on end. This is a review of these yellow clouds, which we now know to be dust storms. It describes their location, development, composition and seasonal occurrence, their influence on the climate of the Red Planet, and demonstrates that they are the sole cause of long-term changes in the dark markings. Members of the Association have contributed significantly to our developing understanding of these phenomena, and it is to be expected that future BAA observations will be important to help resolve ongoing questions.

Introduction

One day, when humanity has its first outpost on the Red Planet, the subject of this Presidential Address may be of more than academic interest. To understand and possibly to anticipate large dust storms could be extremely important to future colonists. In this Address, I will try to explain what we know about the nature of the martian surface, and the dust storms that sometimes blow up, and what contribution the members of the Association have made to their understanding. As we cannot predict their location or onset except in very general terms, their detection remains a fertile area for the amateur astronomer. This will remain so, even with the latest probes such as *Mars Global Surveyor* and *Mars Pathfinder*. It is the observation of transient events that makes planetary observing so exciting, giving the amateur a distinct role to play. Many of the dust storms observed from Earth have been discovered by amateurs. No two storms are exactly alike, and I imagine discovering one gives an observer almost the same degree of satisfaction (though not the same degree of immortality!) as discovering a comet.

The Red Planet in brief

To begin with Mars itself. Mars is small, 6794km across at the equator, and rotates in 24.623 hours (sidereal). On average 1.52 AU from the Sun in an orbit more eccentric than the Earth's, and with an axial inclination of 23° 59′, the planet has a thin dry atmosphere (with a surface pressure of about 7mm of mercury) consisting mostly of carbon dioxide, and a surface temperature ranging from about –133°C to +23°C. To the naked eye, Mars has a strong red colour. Indeed, he was the God of War in ancient times. His surface is mostly reddish, marked with bright white areas at the poles, and a complex pattern of dark areas.

The polar caps wax and wane with the seasons. The southern cap is composed almost entirely of dry ice, and sublimes in the low pressure, well below the triple point of CO_2. It evaporates almost completely in the summer. The northern cap has a seasonal CO_2 overcoat, but a core of water ice persists throughout the northern summer. As the cap releases volatiles, atmospheric activity increases, with the so-called white clouds (like terrestrial ice-crystal cirrus) forming in low-lying areas at dawn and dusk, and over higher ground (such as the giant volcanoes) in the martian afternoon. Both caps regrow under winter fogs of water ice, called the polar hoods.

The dark markings on the surface observed telescopically from Earth (and once thought to be seas) actually bear little relationship to the geography of the highly cratered martian surface revealed by *Mariner* and *Viking*. But Hellas and Argyre, bright regions often filled with cloud or dust, turn out to be depressed basins formed by ancient asteroidal impacts. The bright red areas are vast deserts. As with the polar regions, the distribution of dark markings is quite different for the two hemispheres. To the north, the scant dark areas form a belt around latitude 50°, which is augmented by the dark Mare Acidalium at longitude 30°. Most dark areas are clustered to the south, in a broad belt stretching from latitude 40°S down to the equator. The reported green or blue tints are mostly illusory effects of subjective colour contrast with the red deserts, but the maria are on average less red than the deserts, ranging from reddish to blue-grey. The large dark areas consist of sand dunes and sand sheets, especially in the northern belt, trapped in crater floors and depressions. In other places the dark materials correspond to exposed bedrock, or coarse debris derived therefrom. The outlines of the dark areas are constantly being modified, being either covered or uncovered by martian winds and airborne dust, finally explaining the variations in their shape and intensity recorded by patient Earth-based telescopic studies of four centuries.

The spacecraft also discovered a vast canyon system along the martian equator, ancient dried-up riverbeds, and great extinct volcanoes and lava flows. The southern hemisphere is mostly ancient cratered highlands, somewhat like the lunar highlands but with a different crater size distribution, whilst the northern hemisphere is comparatively young.

Signs of past volcanism are evident in the great Tharsis bulge, with its volcanoes Ascraeus, Pavonis and Arsia Mons. Further west Olympus Mons rises to the dizzying height of some 25km above the surface, on a shield base over 520km wide. Volcanic rocks are estimated to cover

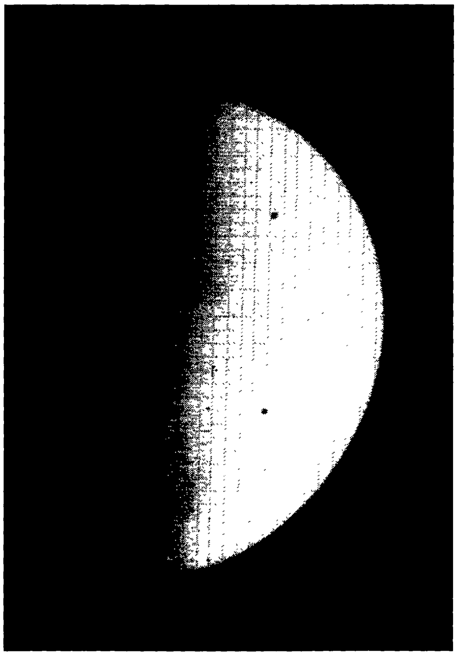


Figure 1. *Mariner 9* image of a featureless disk, 1971 November 11, JPL image P-12673. *(Courtesy NASA)*

60% of the planet's surface. There is much frozen water – permafrost – beneath the surface, but its exact disposition is presently unknown.

Viking told us that the surface is sterile, and somewhat oxidising chemically owing to its ultraviolet irradiation. But what might we find beneath? Our knowledge of the interior remains conjectural due to the failure of one of the *Viking* seismometers, but density measurements imply that any compact central core must be small.

Introducing the dust storms

As I have said, these are among the most interesting phenomena Mars offers to the telescopic observer. Mapping of the surface by *Mariner 9* in 1971 was delayed by several months owing to the greatest storm of the century, which was completely global. That storm had previously been predicted in general terms by telescopic observers (Figure 1). The terms 'dust storms' and 'yellow clouds' are synonymous. Dust storms can certainly look yellow, but sometimes they are more white than yellow, due to the presence of ice crystals.

Although the more common white clouds were detected by some early observers, there is little evidence of obscurations until the 1870s, when observations were made by G. V. Schiaparelli. It has been stated that H. Flaugergues recorded yellow clouds in the early 1800s, but I do not believe this was so. In looking over the observer's work, none of his sketches over several consecutive apparitions published in Camille Flammarion's famous work *La Planète Mars* (volume 1) show any recognisable features, so one must conclude that he simply did not see the planet well. Most of the oddities of the early drawings are due to personal idiosyncrasies and/or the limitations of the telescopes of the day.

So let us now look at some examples of actual dust storms, taken from the history of our own Mars Section, which goes back to 1892. Early telescopic observers sometimes detected these phenomena by what they *couldn't* see. That is, some familiar marking was missing or distorted. I will start by describing a few of the earliest BAA observations.

In 1892 we find that on September 23, Alice Everett, at Greenwich, found the lower part of the Syrtis Major cut by a broad bright band at about 10°N. This marking used to be known as the Kaiser Sea, and so in the terminology of her day Miss Everett stated: 'Bottom of Kaiser cut off flat'. There seem to have been no other observations that day: it must have been a short-lived event. During the next apparition, there was a period in October when the Mare Cimmerium was largely invisible, a very striking change. In 1907 Mare Cimmerium was again invaded by yellow cloud, as observed by L. A. Eddie of Grahamstown, Cape Colony, South Africa, on July 30. Major Eddie found the bright cloud had a deep golden hue, and the Mare Cimmerium was veiled throughout August. In 1909, a perihelic opposition, pre-September observations showed the markings were nearly invisible, and the disk a golden yellow. Here then was an undeniable link between the presence of yellow clouds and obscuration of the surface, a connection immediately recognised by E. M. Antoniadi, Director of the Section at that time. He wrote: 'A yellow appearance coincides with a lesser intensity of the dark areas and a lesser visibility of the details... As Mars receives more heat from the Sun at perihelion than at aphelion, in the ratio of 1.5 to 1, the movements in his atmosphere must be more pronounced in the former case than in the latter; and

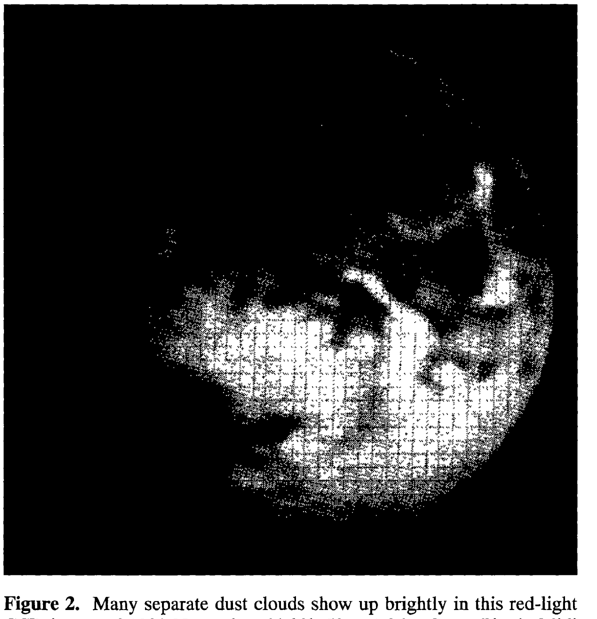


Figure 2. Many separate dust clouds show up brightly in this red-light CCD image of 1990 November 6d 02h 50m, 1.06m Cass., Pic du Midi Observatory, ω = 38°, *J. Lecacheux and F. Colas.* The complex storm covers Coprates, Eos, Solis Lacus, Thaumasia–Bosporus Gemmatus, Nilokeras–Tempe and Chryse. (All illustrations from the Mars Section records unless otherwise credited.)

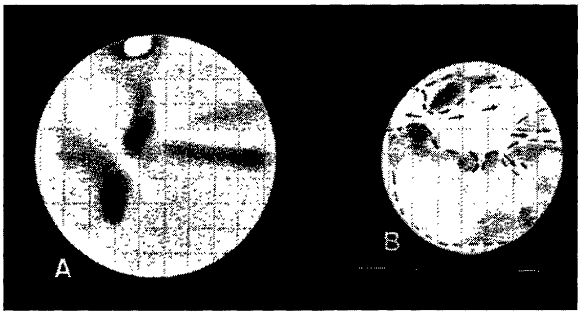


Figure 3. Development of the 1971 encircling storm:
A. Bright streak emanating from Hellas, September 21d 20h 30m, ω = 327°, 300mm refl., ×318, *A. W. Heath.*
B. The storm spreading around Mars, September 28d 03h 20m, ω = 11°, 600mm OG ×830, yellow filter, *C. F. Capen.*

the planet appears to be more yellow in perihelic than in aphelic apparitions'. Antoniadi further suggested dust as the cause, which turned out to be correct.

In the next apparition of 1911 there were again widespread obscurations in the southern hemisphere. Since that time, the presence of globally obscuring clouds like those of 1909 has come to be recognised as a rarity. Our Mars Section observed great storms in 1924, 1956, 1971 and 1973. Accounts of the latter three will be found in our *Journal*, but the 1924 work was never written up. In fact the 1924 event was first spotted by Rev. T. E. R. Phillips at Headley Observatory, Epsom, on December 10. It began as a bright streak emanating from W. Hellas and crossing Hellespontus into Noachis. When his next clear night came, on December 20, the disk was blank in perfect seeing, with the dust storm already hiding the surface details. The storm had abated by the following March.

Classifying the storms

Lowell Observatory astronomer Dr Leonard Martin has proposed a classification system which I have adopted:

a) Local dust storms: these are the smallest type, where the long axis of the affected area is less than 2000km. These are the most common.
b) Regional storms: where the long axis exceeds 2000km, but the storm does not encircle the planet.
c) Planet-encircling storms: rarest of all, and defined in terms of encirclement of Mars in the east-west sense. A subcategory of such storms would be those that achieve truly global coverage.

Let us have an example of each one.

a) In 1986 Japanese observers found a small bright yellow cloud covering the N. end of the Phasis streak on August 3. It was not present on neighbouring dates, and was just a local event.
b) In 1990 a small bright cloud appeared over Chryse–Xanthe on November 2, partly covering Aurorae Sinus. The storm expanded greatly the next day, dust soon invading Thaumasia and points north and south. The storm was unusual in that more than one secondary focus of activity appeared, after which the dust began to dissipate. This regional event lasted little more than a week (Figure 2).
c) On 1971 September 21, Alan Heath found a bright streak cutting across Iapigia into Aeria from Hellas. An outbreak of dust from Hellas was independently discovered photographically from South Africa the following night. This marked the onset of the great storm of that year, in which dust spread from Hellas into Noachis and subsequently encircled the entire planet. It was the greatest storm in history. Apart from the initial 'core' in Hellas, there was a secondary core in the Argyre–E. Thaumasia region (Figure 3).

Phenomena associated with storms

It would be appropriate at this point to mention some of the phenomena associated with dust storms. Obscuration, movement and expansion we have already seen. When first visible, storms are bright and sharp-edged. This sharpness is lost with the passage of time as the dust spreads out. In colour slides by W. S. Finsen of the early days of the 1956 encircling storm we see something else: a transient darkening of the Mare Australe adjacent to the path of the great yellow cloud (Figure 4). Affected regions often revert to their previous appearance once the dust has settled, but semi-permanent albedo changes can result from storm activity. The phenomenon has been known for a long time, and in 1894 Amenthes showed just such a darkening when Mare Cimmerium was veiled by dust, which from other evidence suggests the storm began in Libya/Isidis Regio. We now know this darkening must arise from the excava-

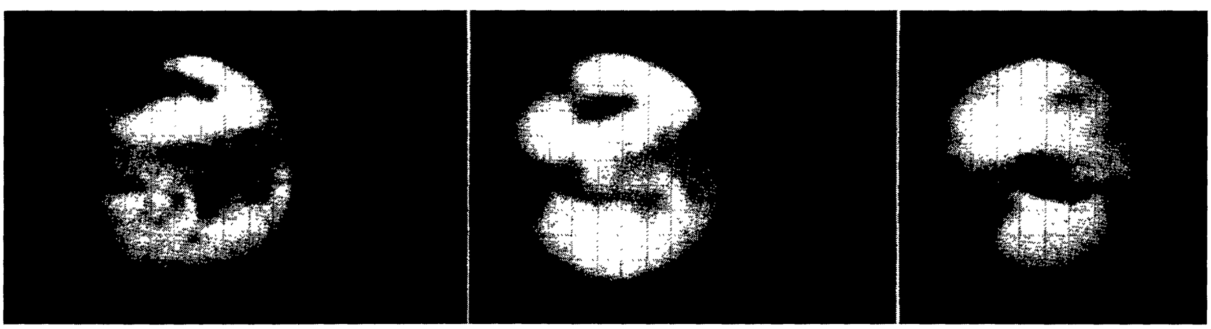


Figure 4. Images of the evolution of the 1956 encircling storm, 673mm OG (diaphragmed to 336mm), Union Observatory Johannesburg, red filter, *W. S. Finsen.* Left: August 30d 22h 05m, ω = 6°; centre: September 1d 21h 28m, ω = 339°; right: September 5d 22h 37m, ω = 321°. Note the unusual darkness of the Mare Australe in the region of Depressiones Hellesponticae in the first two; in the third, eastern Pandorae Fretum is starting to darken.

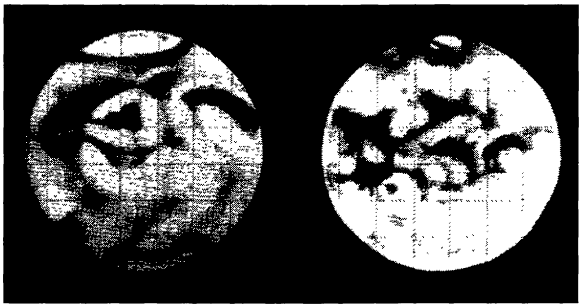


Figure 5. The Solis Lacus region in 1971 and 1973, showing the great development of the Claritas–Daedalia desert in 1973. Left: 1971 July 1d 02h 50m, ω = 87°, 260mm refl., *J. Dragesco*; right: 1973 October 9d, ω = 76°, 600mm OG, ×1000, *C. F. Capen.*

Figure 6. White clouds in association with yellow ones during the 1956 encircling storm, 300mm refl., *C. F. Capen*. Left: September 7d 08h 00m, ω = 92°; right: September 10d 07h 00m, ω = 36°. From *Sky & Telesc.*, **41**(2), 119 (1971).

tion of darker underlying terrain adjacent to the storm front, whereby the martian winds strip away a thin veneer of light dusty surface material. Depending on viewing geometry the darkening of the surface may be visible from Earth during the storm. Earl C. Slipher was aware of this phenomenon, and in his famous Mars book he gave a list of what he called 'Ephemeral Dark Spots' which we may take to be indicators of minor storms. Some investigators have suggested that the darkenings could be due to cloud shadows. I think this is generally impossible, as well as unnecessary, as does Prof. Audouin Dollfus of Meudon Observatory, but perhaps in just one instance of a double yellow cloud over Hellas seen on the terminator by Antoniadi in 1924 October a shadow really may have been involved.

In fact, it is obvious that dust movement must be responsible for explaining *all* albedo changes, ephemeral or permanent, large or small. The darkening of Pandorae Fretum is one good example, a phenomenon once thought to be seasonal. It is seasonal in the sense that a dust storm in nearby Hellas–Noachis will occur only near perihelion, but if the storm does not occur, or is insufficiently vigorous, the feature does not change. Thus in 1988 we find it darker after a regional storm in Hellas–Noachis, but in 1939 it was never dark because there was no obliging dust storm. Storms commencing in Hellas–Noachis cause Pandorae Fretum to darken as dust is removed adjacent to the northern edge of the storm. Storms beginning in Isidis Regio–Libya cause temporary darkenings in the Amenthes–Nepenthes region, as we can see in some unpublished drawings from 1926 by T. E. R. Phillips, whilst storms in Chryse–Xanthe can cause Ganges to darken. Finally, storms over Thaumasia can change the size and shape of Solis Lacus. A storm in that region caused an enormous desert area (Claritas–Daedalia) to darken in 1973, and I want to show you a 'before' and 'after' picture here, too (Figure 5).

Another phenomenon sometimes associated with dust storms is the presence of white clouds around their edges, as though the dust acts as a seed for the crystallisation of volatiles. These drawings by Capen (Figure 6) were made in 1956 during the great storm of that year, and clearly show white clouds in association with the yellow ones. Sometimes, the whole of a dust storm can look white rather than yellow, and one is tempted to suggest that the colour depends on how much water vapour there is in the atmosphere above the developing storm. If a lot of water vapour is present, and gets forced upwards by the convecting storm, it may crystallise above it, and will effectively mask the underlying yellowness. Thus Slipher referred to a dust storm over Margaritifer Sinus in 1922 as a 'great white cloud'.

For this reason we now need to look at how we can be sure whether a martian cloud is a dust storm or not.

Observing dust storms

A dust storm rotates with the planet, and will obscure any dark markings in its path. Some storms initially look white, not yellow, as I have just said. It turns out that the storms are bright in red light, whereas ordinary white clouds are not visible at these longer wavelengths. Dust storms are bright in yellow light too, but red is more discriminating. Dust storms sometimes show up bright in blue light too, which indicates the presence of water vapour. Colour imaging will be more useful than monochrome in this respect, but considerations of grain dictate that the most useful images by amateurs have been black and white ones through red, blue and green filters. Professionals have also taken infrared images of the planet from Earth, in which the dust is well differentiated from white cloud. Of course, it is equally possible to use colour filters visually, and CCDs also come to the rescue: during the 1990 November dust storm it transpired that yellow clouds showed up quite brightly on CCD images (see Figure 2). CCDs are especially receptive to longer wavelengths, making them ideal for recording dust storms. On a practical point about storm mapping, morning or evening cloud can significantly interfere with the perception of storm boundaries, so dust storms should preferably be imaged as close to the central meridian as possible.

Leaving aside pure imaging work, in 1924 Bernard Lyot at Meudon was making his first polarimetric observations, and discovered that the degree of polarisation of the sunlight reflected from the martian surface was modified by the dust from the great storm that started in December of that year. You can see from his graph that the planet's polarisation curve was abnormal until 1925 March, until which time yellow clouds veiled its surface (see de Vaucouleurs, 1954). In later years in the hands of Dollfus, J. H. Focas of Athens Observatory and Shiro Ebisawa of Japan, polarisation

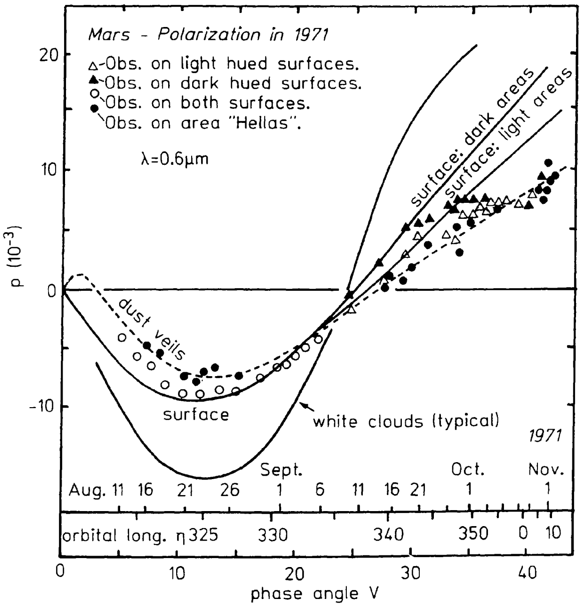


Figure 7. Curves of the degree of polarisation (in units of 10^{-3}) versus phase angle for the martian surface and for the bright white clouds. The dotted curve shows the polarisation behaviour of a typical opaque dust cloud. Between 1971 August and December the Hellas basin (dots) had the polarisation produced by dust clouds. From Dollfus *et al.* (1984).

mapping was to become a major technique for both detecting and understanding dust storms. Except at certain phase angles the characteristic polarisation curves of the bare ground, white clouds and yellow clouds depart sufficiently from each other to make the observations diagnostically useful. Figure 7 is an explanatory graph by Dollfus which shows that at most phase angles yellow clouds will tend to reduce the degree of polarisation observed. The polarimetric behaviour allows the scattering properties of the aerosols to be determined, and the particle size estimated. The technique needs much observational skill, but from 1988 onwards it has been possible to make the measurements automatically. I refer you to a paper by Dollfus (1990) about video polarimetry for details.

What about *Viking*? Apart from their imaging capability, the Orbiters detected dust by noting any significant difference in brightness temperatures in the 6–8μm and 8–10μm bands of the Infrared Thermal Mapper (IRTM) (see Hunt, 1979). Dust absorbs strongly at 8–10μm, but not at 6–8μm. The Landers were able to monitor the opacity of the atmosphere by imaging the Sun.

Having said all that, the Mark One Eyeball remains the amateur's preferred dust-storm detecting instrument. The amateur who is thoroughly familiar with the normal appearance of the planet is most likely to spot any new storm.

What is the dust in the storms made of?

So what is martian dust? Do not confuse it with what you might find when dusting your home! A lot of household dust is in fact dead skin mixed with pulverised quartz sand. For Mars we are talking about the purely inorganic, most finely-divided weathering products of the surface rocks. Terrestrial weathering can arise from both chemical and physical action. On Mars, with its diurnal extremes of temperature, frost fracturing is expected to be the current dominant process in which rocks are broken down into fines. The Red Planet, with its extensive desert areas, exhibits strong signs of weathering, and the fine sand and dust are widespread. The first *Viking* Lander images of Utopia and Chryse showed remarkably vesicular boulders strewn across open plains (Figure 8).

From laboratory modelling of infrared spectra, martian dust seems to consist of a mixture of basalt and clay materials like montmorillonite with at least 60% silicon dioxide

Figure 8. *Viking 1* landing site, showing boulders and dust-drifts. 'Big Joe' boulder (left) is about 2 metres across. Small horizontal markings on some drifts indicate that dust was deposited there some time ago, and is now being eroded away. JPL image 11B097. *(Courtesy NASA)*

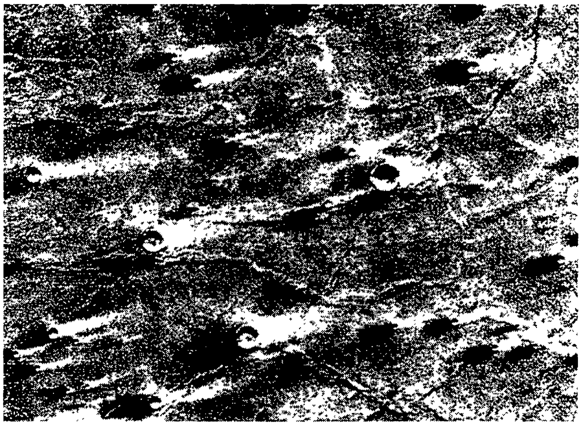


Figure 9. Showing bright and dark streaks in Hesperia Planum. The dark streaks represent erosion, the bright streaks dust fallout. *Viking* Orbiter image 553S54. *(Courtesy NASA)*

(SiO_2), together with about 1% iron (III) (or ferric) oxide, the latter giving it the red colour: I sometimes worry about corrosion on my car, but here we have an entire planet literally covered with rust! The desert colour in some areas is a much more intense red, due to a higher percentage of Fe_2O_3. The mineralogical state of the ferric oxide is not yet known, but reflectance spectra suggest that it is not the same as common iron ore on Earth, haematite (see Soderblom, 1992, for details). By measuring the settling time for the great 1971 storm observed by *Mariner 9* from orbit, it appears the particles are 1–10 micron in size or less, with a mean of about 2μm. Polarimetric data confirm this.

We know that much of Mars is desert, and radar measurements indicate that the surface deposits may be deeper in some places than in others. Recent investigations with the Very Large Array at a wavelength of 3.5cm have revealed a region to the west of Tharsis, centred on the equator and encompassing parts of the deserts of Memnonia and Amazonis between longitudes 125 and 168°, over 2000km in east-west extent, that displayed no detectable radar echo! This anomaly has been interpreted by Muhleman and coworkers as a vast deposit of dust and ash (with density less than 0.5g/cm^3 and free of rocks greater than 1cm in size) several metres deep. Being downwind from the Tharsis volcanoes it may be considered as a massive aeolian deposit.

Spacecraft images show us dark and bright streaks on the martian surface (Figure 9). The dark ones are usually exposed bedrock and the bright ones represent fallout from the dust storms. Thus wind directions can be inferred, and compared with those deduced from telescopic records. Such data can be put together to produce a global climatic model.

We now consider three leading questions about dust storms: Where, When and How? Let us take them in that order.

Where do the storms begin?

Several 'emergence sites' correspond to depressed regions of the surface, and large basins associated with Hellas, Argyre, Chryse and Isidis Regio spring to mind as candidates. Few substantial basins exist in the N. hemisphere. The following basins are among the largest listed by Cattermole:

Name	*lat., long. (°)*	*diameter (km)*
Hellas Planitia	–43, 291	2000
Isidis Planitia	+16, 272	1900
Argyre Planitia	–50, 42	1200
Chryse Planitia	+24, 45	800

Other sites like Thaumasia centred around the dark marking Solis Lacus, or Tempe, near lat. 40° north, are less obvious (but nonetheless important) locations. Storms are known to start in many places.

Let me explain something about nomenclature. In general I shall use the old telescopic nomenclature, favouring Ebisawa's chart as the widely reproduced 1957 IAU one is not detailed enough. But because the modern system names places according to the geological nature, the new names tend to refer to wider or even slightly different areas than the historical ones. For the basin sites Chryse Planitia is in fact in NW Xanthe on the Ebisawa map.

Now let us visit some of the major sites in turn, as they appear on the latest maps by the US Geological Survey (Figure 10). All altitudes are relative to a mean level with surface pressure of 6.1 millibars.

a) Hellas (Hellas Planitia): The entire basin lies at least 2000m below the mean datum, but it is deeper near the centre, and near the NW corner it reaches to 5000m (5km!) in depth. It is this NW corner that has been the emergence site of several encircling storms. Neighbouring Noachis (Noachis Terra) is a plateau by comparison, mostly 4000–5000m high. Primarily, storms tend to expand westward across Hellespontus into Noachis (*e.g.*, the encircling events of 1924, 1956, 1971), but they can also spread across Iapigia and into Aeria. Hellas is the most active of all sites, but its storms can only become planet-encircling at certain martian seasons (Figure 10A).

b) Isidis Regio/Libya (Isidis Planitia): This is another basin, some 2000m deep. Storms often commenced here between 1894 (or earlier) and 1958. In every instance, the dust has propagated to the south-east, invading Hesperia and Mare Cimmerium, and sometimes reaching as far E. as Electris and Phaethontis (Figure 10B).

c) Argyre (I) (Argyre Planitia): This is a much less active site than either of the last two. Although it is a basin, it has an altitude of 1000m above the mean, a few km below the surrounding high ground. In some instances it has generated significant storms such as one in 1977 mapped by *Viking*, but on several other occasions dust merely seems to have become trapped in this basin from outbreaks in Hellas–Noachis to the east, or in Thaumasia to the west (Figure 10C).

d) Chryse/Xanthe: Classically a 'desert' area bordering the Mare Acidalium, encompassing an impact basin to the NW, Chryse Planitia. The basin edges Mare Acidalium, and is about 2000m deep. Xanthe Terra on modern maps slopes upwards to the south, to about 3000m, into the

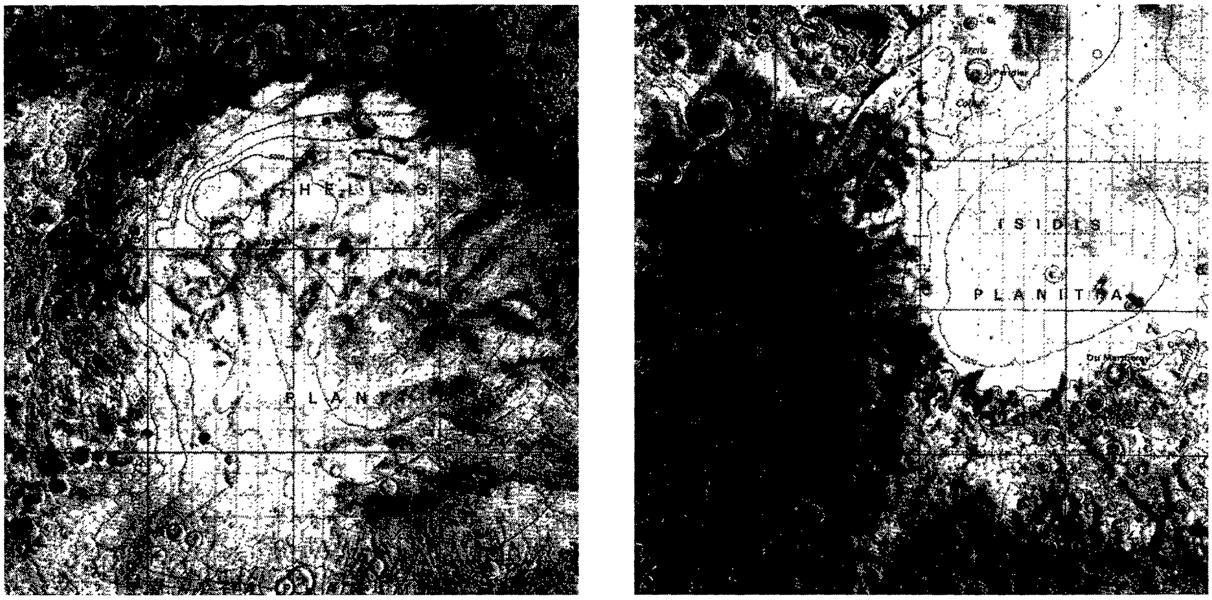


Figure 10. Extracts from USGS 1:15,000,000 scale Topographic Maps of the Eastern and Western Regions of Mars, Map I-2160, by kind permission of the US Geological Survey.
A. *(left, above)* Hellas Planitia; **B.** *(right, above)* Isidis Regio; **C.** *(below)* Argyre Planitia and Solis Planum, etc.; **D.** *(page 192)* Chryse Planitia and Tempe Terra, etc. North is uppermost.

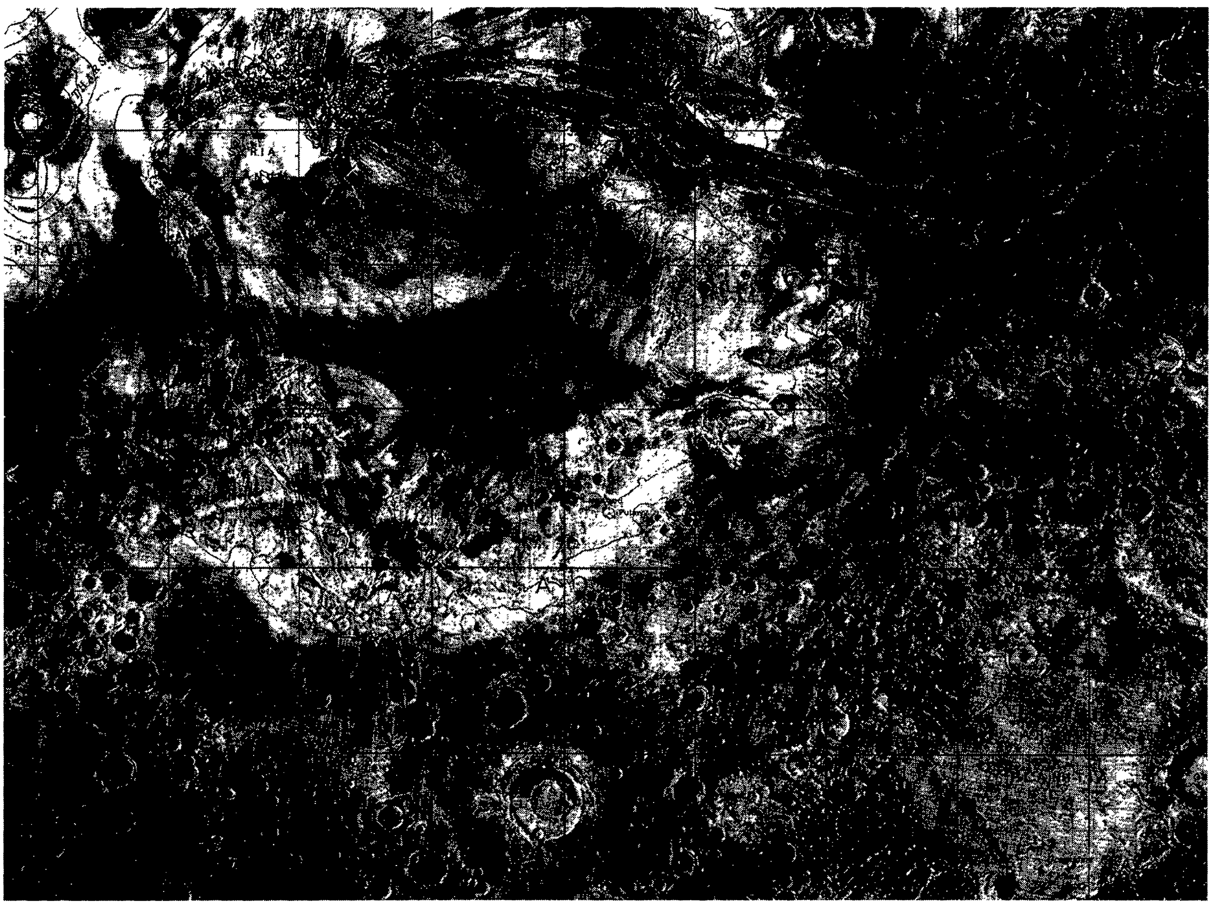


Figure 10D. Chryse Planitia and Tempe Terra, etc. *(see page 191)*. + marks the Viking 1 landing site.

chaotic terrain intercut by valleys, and which is associated with the NE end of Valles Marineris. Chryse Planitia has been associated with storm activity in the *Viking* years, while Xanthe Terra (classical SW Chryse) is interesting in that it initiated two, probably three, regional storms in 1990 at intervals of one terrestrial month. The initiation source for the best-observed event (1990 November) was near –12°, 47°, and therefore possibly associated with Capri Chasma. It continues to remain dust-active (Figure 10D).

The remaining sites are not involved with basins:

e) Thaumasia/ Solis Lacus (Sinai Planum, Syria Planum, Solis Planum): This is high plateau country, mostly 6000–8000m high, bounded to the north by the complex Valles Marineris. It is a very important site, for the 1973 encircling storm, at least one of the 1977 encircling storms, and the second large regional storm of 1988 began here. The 1973 initial cloud seemed to coincide with the centre of Solis Lacus. Other storms have begun to the E. of Solis Lacus (1984 June), or to the north or west, in the Thaumasia desert. The area can also be a source of secondary activity, as in 1990 November (Figure 10C).

f) Tempe (Tempe Terra): From mean datum level near Mare Acidalium, Tempe slopes upwards towards Alba Patera to the west. It was first positively identified as a site in 1952, and again in 1978, with activity spreading to nearby Arcadia and Chryse. Activity recurred in 1982. Tempe is the most northerly site that has generated a significant number of telescopic storms, this time during the *northern* hemisphere spring and summer (Figure 10D).

g) Elysium (Elysium Mons): This region is mostly above 1000m high, with the ground reaching 5000m high on the lower slopes of the Elysium Mons and Albor Tholus volcanoes. Telescopic data have indicated local or regional storms here in 1982 and 1993, but they have never been satisfactorily followed owing to the absence of good reference albedo points. Earlier polarimetric data also identify the site as a possible source.

From the standard map of the planet (Figure 11) it will be noticed that all these regions except Elysium fall between longitudes 260° westward through 0° to 120°. The longitude band from 120° to 260° is much more rarely storm producing, and even then involves but local events. In addition to these sites, *Viking* discovered a number of local storms along the edge of the spring S. polar cap, during its recession phase.

When do the storms begin?

First we need to define the martian seasons, for if we record that a storm started on 1956 August 19 it is relatively meaningless until we relate it to the martian calendar. The Section has adopted a system by Parker and Capen which corresponds with the terrestrial calendar, with twelve seasons divided equally into the martian year of 687 days or 669 sols.

But better still we refer to the areocentric longitude at which a phenomenon happened. This quality, abbreviated to L_s, is defined to be the planetocentric longitude of the Sun, measured along the orbital plane from its ascending node on the martian equator. Defined in this way the martian seasons are as follows:

L_s (°)	*Season*	
	N. hemisphere	*S. hemisphere*
0	Vernal equinox	Autumnal equinox
90	Summer solstice	Winter solstice
180	Autumnal equinox	Vernal equinox
270	Winter solstice	Summer solstice

The seasons are of unequal duration. Perihelion takes place at 250°, aphelion at 70°. (In the older Mars reports of the

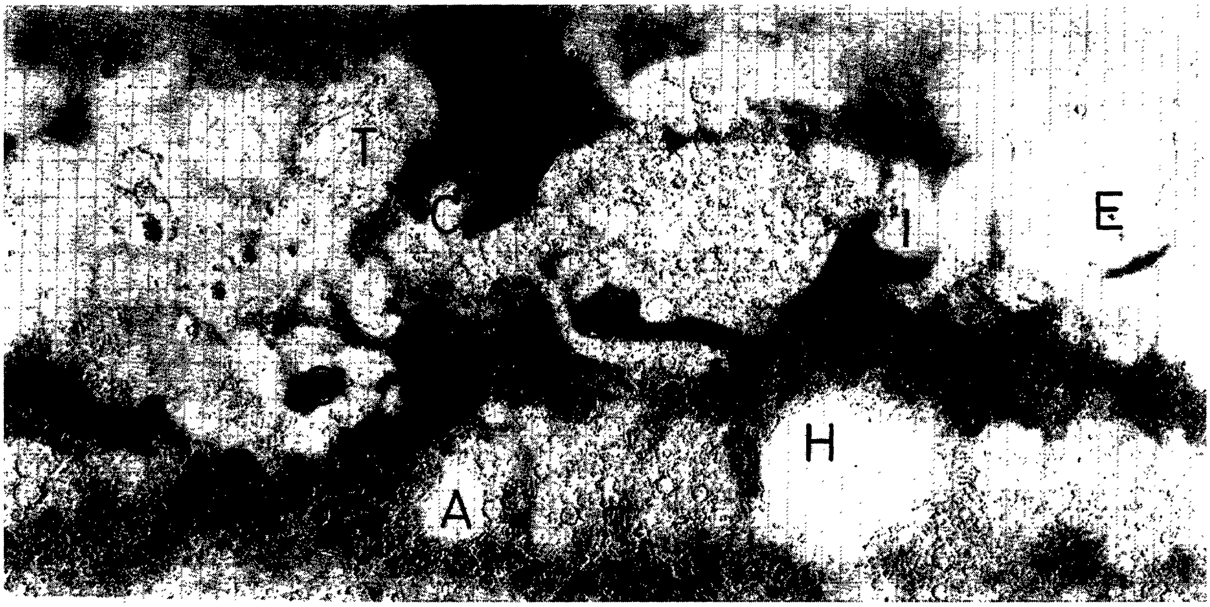


Figure 11. Albedo-topographic map with principal telescopic dust storm sites marked (H= Hellas; I= Isidis; A= Argyre; S= Solis Planum; T= Tempe; E= Elysium). North is up for comparison with Figure 12. *(Copyright Lowell Observatory)*

Association you will come across a term called the 'heliocentric longitude', the ecliptic longitude of Mars seen from the centre of the Sun. The heliocentric longitude can be obtained from L_s by adding 85°.) (Figure 12).

We know that the S. hemisphere summer is shorter and hotter than the northern one. At such times of the year, martian winds will be at their strongest, their dust-raising potential at a maximum. It is no surprise therefore, to learn that most storms occur (a) in the S. hemisphere, and (b) in the S. spring and summer seasons. Although it would appear local storms can occur at any time, planet-encircling storms can only develop over a restricted range of areocentric longitudes, between 204° and 312°. The following encircling storms are known. In 1977 Mars was near solar conjunction and the two successive events of that year were recorded only by *Viking*, but orbital restrictions meant that the precise start of each storm was missed, and the exact point of origin of the second could not be fixed.

Terrestrial date	L_s(°)	*Point of origin*	*Remarks*
1924 December 10	312	NW Hellas	First storm observed by polarimetry
1956 August 19	249	NW Hellas/Noachis	First storm to be really extensively photographed
1971 September 21	260	NW Hellas/Noachis	Greatest storm ever observed
1973 October 13	300	Thaumasia/Solis L.	
1977 February 15±	204±	Thaumasia/Solis L.	*Viking* data
1977 May 27±	268±	Southern mid-latitudes	do.

Another substantial storm was indicated by the one remaining Lander (VL1) in October 1982, near L_s= 208°, just before contact with Earth was finally lost. The 1909 storm was also planet-encircling but its date of origin is not known. We will look at the detailed seasonal frequency of dust storms later.

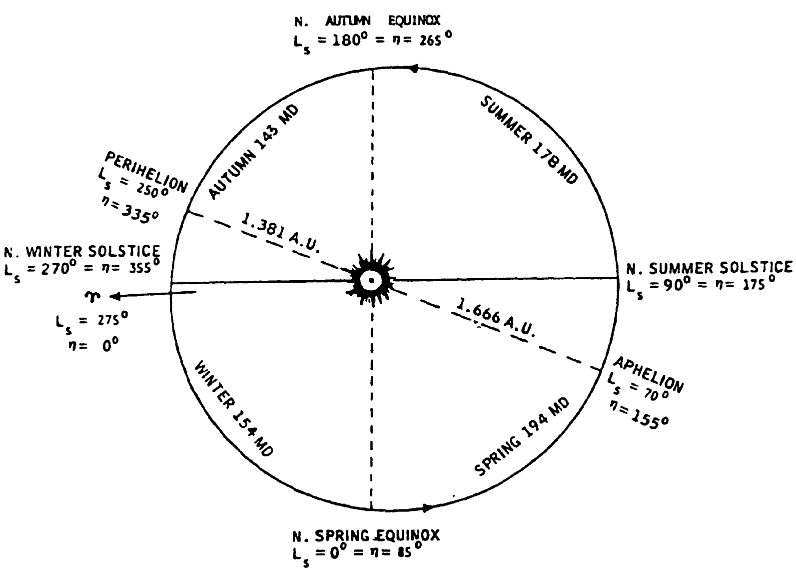


Figure 12. To illustrate the use of the planetocentric (areocentric) longitude L_s. The old system of heliocentric longitude, η, is also shown. From Parker and Capen (1980).

How do the storms begin and end?

We shall now try to understand the mechanisms by which storms may begin and grow. This is still conjectural, so I will refer those interested in the detail to reviews by Greeley *et al.*, Kahn *et al.*, and Zurek *et al.*, and just give some generalities here. A network of martian groundstations will be needed to fully understand its atmospheric processes.

In principle, one would think it easy

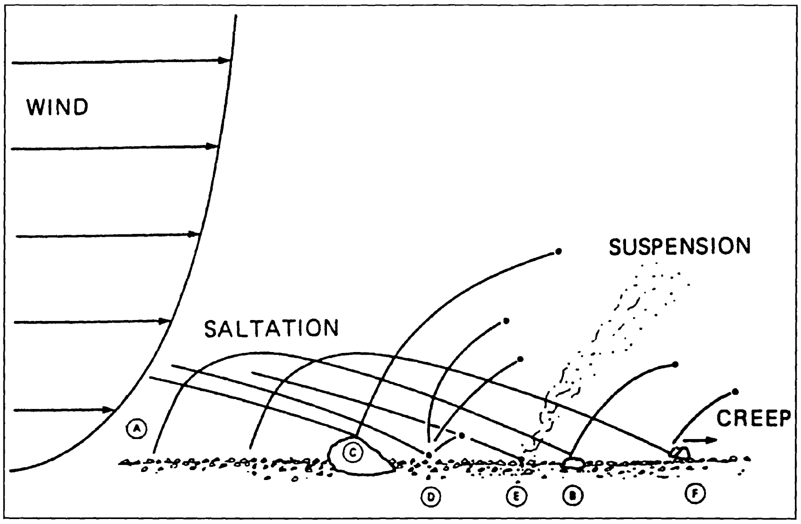
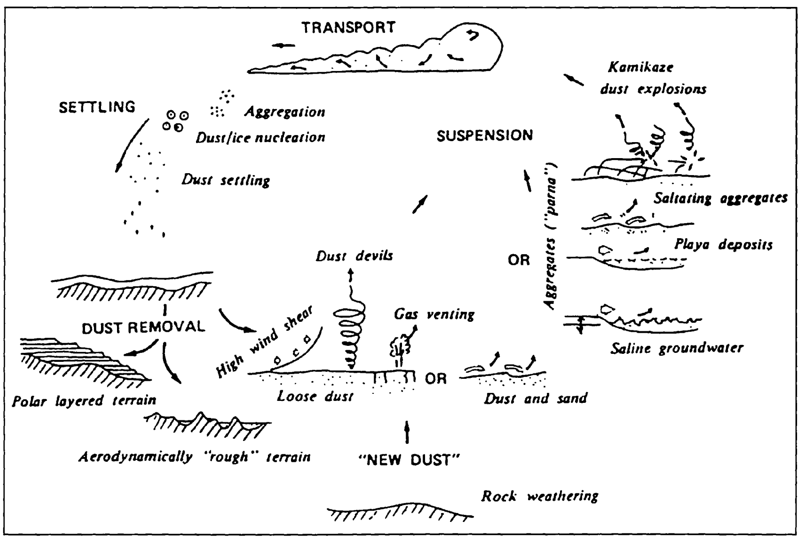


Figure 13. Above: explaining saltation and creep. Surface shear stress exerted by wind causes grain (A) to lift off the surface; at (B) it bounces back into flight. Grain at (C) hits large rock, possibly causes some erosion, and rebounds into saltation trajectory. Grain at (D) triggers other grains into saltation. Grain at (E) sprays fine particles (too fine to be moved by wind alone) into suspension. Grain at (F) pushes larger grain downwind a short distance by impact creep. **Below:** the martian aeolian cycle. Both reproduced from Keiffer *et al.* (eds.), *op. cit.*, p.735 and p.764 respectively, by kind permission of Professor R. Greeley. (p.735 originally published in Greeley R. & Iversen J. D., *Wind as a Geological Process on Earth, Mars, Venus and Titan*, Cambridge University Press, 1985; p.764 originally published in Greeley R., in Lee S. (ed.), *MECA Workshop on Dust on Mars II*, LPI Tech. Rept. 86-09, 1986, pp 29–31).



to account for the dust storms. But although there is plenty of dust and quite rapid near-surface winds, the surface shear stress exerted by winds in the rarefied atmosphere is too low to directly loft the micron-sized particles we know to be suspended in the yellow clouds. In fact, most dust-sized particles are probably thrown into suspension by saltation, a process also important in terrestrial dust storms which involves downwind propagation in a series of bouncing steps, tending to dislodge still more surface particles of different sizes (Figure 13). On Mars, according to Greeley *et al.*, the particle size most easily moved by winds is in the 'fine sand' category, about 100μm across. These particles move by saltation, in leaps of about 1 metre long and 10–20cm high. Collisions with larger grains up to 1cm across can push them slowly along the surface in 'creep', and, most importantly, dislodge small grains less than 20μm in size and throw them into suspension. Once aloft, the relatively light martian winds are quite adequate to hold the micron-size particles in suspension. It turns out that the 100μm particles can just be moved by near-surface winds of about 25 metres/second, which corresponds to the strongest (but infrequent) gusts reported by the Landers. F. A. Gifford, a meteorologist who made an important study of yellow clouds, gave the essential modern picture as long ago as 1964 when he wrote of 'wind-driven sand-grains moving by saltation within a few metres of the martian surface, accompanied by an overlying dust cloud, of much smaller particles, extending, perhaps, to many thousands of metres.' This process is hardly a small-scale one, for the Russian investigators working on the *Mars 2* and *Mars 3* missions estimated that the 1971 global storm had thrown a thousand million tonnes of material into the martian skies.

Other processes also contribute towards raising dust. Of these, we know for sure that 'dust devil' activity occurs, involving local cyclonic winds resulting from atmospheric instabilities. It doesn't require such high winds, and is probably important in maintaining the observed level of background haze or opacity. *Viking* imaged a number of these dust devils, appearing as 1–3km high spiralling clouds. But as the breadth in no instance exceeded 1km, they must only account for the smallest local events.

Amongst other possibilities listed by Greeley *et al.*, I particularly liked a suggestion due to McCauley and Sagan *et al.*, in which certain saltating surface grains could be pulverised into fine grains by the so-called 'kamikaze' effect as they collide with one an-other and with the surface rocks (Figure 13). Aggregated particles are especially susceptible to the latter effect, leading to 'kamikaze dust explosions'. A process known as 'dust fountaining', resulting from CO_2 desorption, may also operate.

Let us consider storm development further. In southern summer, a large temperature gradient exists between the freshly exposed surroundings of the shrunken S. polar cap, and the cap remnant itself. The evaporation of the cap also generates large pressure gradients in the atmosphere, and atmospheric tides will have maximum dust-raising potential, especially in places where the Sun is overhead. If these global effects are sufficiently enhanced in certain regions by local effects, dust-raising, by one of the mechanisms I have outlined, may occur.

Let us now assume that a small amount of dust has been lofted, either by saltation or by dust devil activity. The suspended particles absorb in the infrared, leading to heating of the nascent storm, and thermal gradients thereby set up result in faster, ever more dust-laden winds, which in turn raise more dust by positive feedback. In this way a storm can expand rapidly on a timescale of hours. *Viking* data demonstrate that the storms exhibit a convectiveness that peaks in early martian afternoon, as would be expected from solar heating, and activity may be subject to diurnal effects of contraction and regeneration over the same locale.

Though modified by the effects of local topography, dust clouds tend to expand chiefly in an east-west sense, over a certain longitude range, before spreading to other latitudes. Probably several conditions must be satisfied if a storm is to become global or encircling, not least of which it must begin within about 60° in L_s of perihelion. I would suggest that in such instances, a great deal of dust must be raised very quickly.

Let us look at regional circumstances that will supplement the global winds. Kahn *et al.* have written: 'Regional winds may arise from a variety of effects, including slopes and strong horizontal surface temperature variation (as at polar-cap edges and areas of large albedo or thermal inertia contrast). The local effect of global winds (*e.g.* the seasonal mass flow, Hadley-type circulations and atmospheric tides) may be important additive factors for initiating dust motion, but may be even more critical to the expansion of local storms to larger scales.' Earlier, we noticed how some deep, dusty basins could act as storm centres. Hellas, the largest and deepest, has a significantly higher atmospheric pressure on its floor. In southern summer the Sun can come within 5–10° of the zenith over the deepest, NW part, leading to the maximum possible insolation. These facts explain why Hellas is such a prolific storm site. What about Tempe? Here in the N. hemisphere we have much less favourable conditions of insolation, and so the presence of the large neighbouring dark area of Mare Acidalium is expected to be crucial. As we can see from the *Viking* thermal inertia map (Figure 14), the Mare has a much higher thermal inertia than Tempe, and this thermal inertia contrast will act in enhancing regional winds and lead to dust-raising given the appropriate forcing seasonal conditions. As Chryse Planitia is also adjacent to the same large dark area I suspect the same dust-raising mechanism could contribute there.

What causes a storm to die out? It is most unlikely that a storm should abate simply because of the exhaustion of the dust supply at the source: witness the consecutive major storms of 1977 which probably arose in the same area. Therefore there must be a simple physical explanation for storm decay, based upon the effect suspended dust has upon the thermal structure of the atmosphere. As a storm increases in area, the very temperature contrasts within the dust cloud that led to its growth decrease, causing regional windspeeds to drop, inducing storm abatement and a gradual settling of the dust. Thus through this speculative process of negative feedback, all storms effectively possess a built-in obsolescence. Much less is known about the decay of storms than about their initial growth; it has been suggested that dust may settle faster if the grains become significantly coated with H_2O or CO_2 ices. The time for the martian air to clear will depend proportionately upon the quantity of dust raised initially.

During a storm, the dust opacity factor can reach as high as *ca.* 9.0. Before a fresh storm can start over the same site, there has to be a finite timelapse before the atmosphere becomes clear enough for a new thermal gradient to build up. If conditions then dictate, another storm may arise. Pollack *et al.*, cited by Zurek *et al.*, have suggested that when the opacity factor falls below 1.2, dust-raising might again proceed. In 1993 I noticed that the time lag between similar phenomena in two successive apparitions was about the same: 5–6 terrestrial months. Here are the figures:

Site	*Initiation date (T.D.)*	$L_s(°)$	*Interval* (L_s°)
Hellas	1986 May 28	178	100
Hellas	1986 November 8	278	
Hellas	1988 June 3	207	107
Thaumasia/ Solis Lacus	1988 November 23	314	

The nearly constant time delay between these regional storms therefore may represent the time for the dust opacity

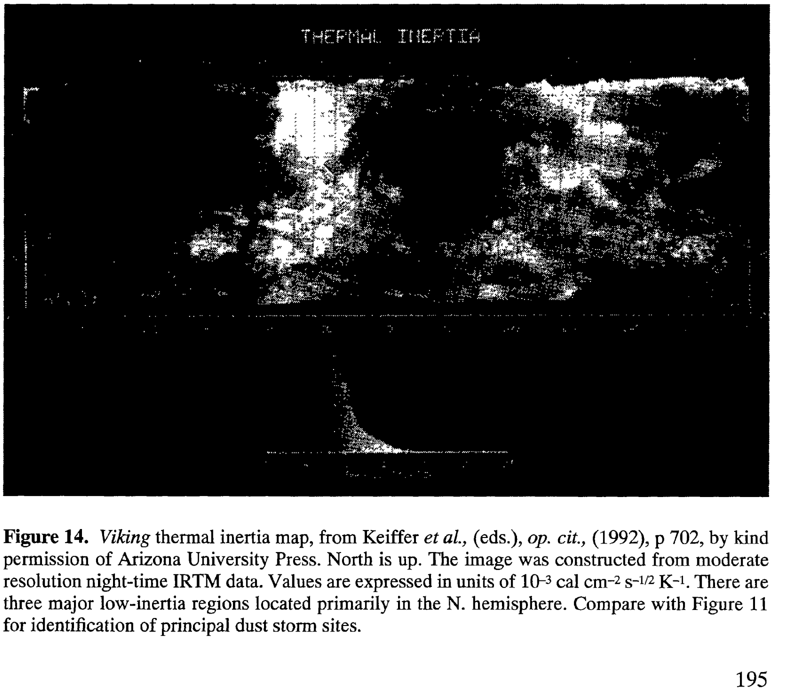


Figure 14. *Viking* thermal inertia map, from Keiffer *et al.*, (eds.), *op. cit.*, (1992), p 702, by kind permission of Arizona University Press. North is up. The image was constructed from moderate resolution night-time IRTM data. Values are expressed in units of 10^{-3} cal cm^{-2} s$^{-1/2}$ K^{-1}. There are three major low-inertia regions located primarily in the N. hemisphere. Compare with Figure 11 for identification of principal dust storm sites.

factor to fall to the threshold below which dust-raising might again commence.

In the visible waveband the optical depth of the 'clear' martian atmosphere during the *Viking* years was found to be about 0.3–0.5. This slight residual opacity results from sunlight scattered by tiny amounts of suspended dust rather than by the molecules of the rarefied atmosphere, and explains the pinkness of the planet's sky. It seems that Mars may have been dustier than usual in the late 1970s. We can all recall the dark blue skies portrayed by the early space artists: perhaps at some time in martian history, they were appropriate!

It is pertinent to ask how dust is returned to an initiation site. Clearly some dust from a storm will settle upon the site from which it came, but much will settle elsewhere. One has to assume that in the long-term, dust will be received as outfall from other active sites, as local weathering could not adequately resupply an active site on a short timescale. We shall see some consequences of this redistribution later.

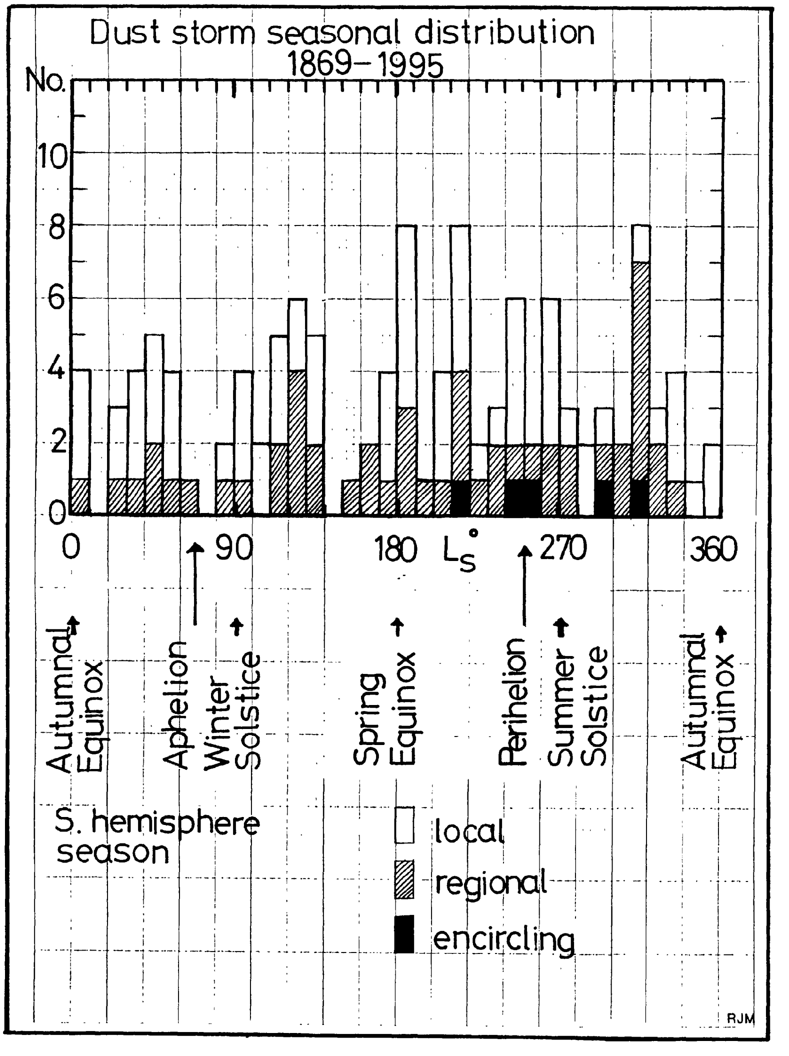


Figure 16. Preliminary BAA histogram of yellow cloud seasonal frequency for the epoch 1869–1995. Data are binned in 10° intervals in L_s. *R. J. McKim.*

Velocities and heights

I have already remarked that wind velocities will be critical in studying meteorology. How are they determined? Wind velocities have been deduced from terrestrial observations, and improved upon by the Landers. The velocities of clouds deduced from Earth-based observations may be misleading; we can only measure the overall rate at which a storm propagates, not necessarily the velocity of the dust within it, nor the martian wind velocity driving it, which will certainly be higher. Typical (*Viking* Lander) windspeeds are of the order of 7m/sec, or 25km/hr, with gusts to 25m/sec or 90km/hr. These winds show strong diurnal variability. From the patterns of bright and dark streaks Zurek *et al.* note that 'the major features include winter mid-latitude westerlies, particularly in the northern hemisphere; low-latitude wind systems controlled by topography; a seasonally reversing cross-equatorial circulation; and some evidence for outflow winds from the receding south polar cap during spring.'

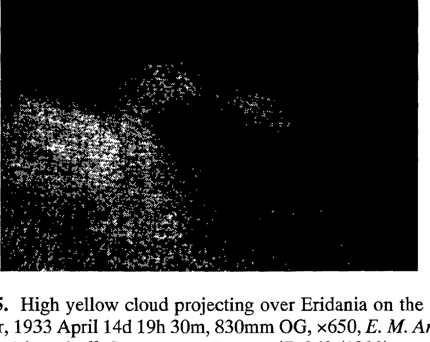


Figure 15. High yellow cloud projecting over Eridania on the morning terminator, 1933 April 14d 19h 30m, 830mm OG, ×650, *E. M. Antoniadi.* Reproduced from *Bull. Soc. Astron. France*, **47**, 360 (1933).

How high can the dust get into the martian atmosphere? In the case of the 1971 global storm, the most energetic ever recorded, dust was detected at altitudes up to 70km. This is atypical, and 10–30km is more usual. Historically, heights were estimated (or, more accurately, overestimated!) by measuring the degree of protrusion of the clouds at the morning or evening terminator: the higher the cloud, the more the feature projected beyond the geometric terminator on account of its top being sunlit. Thus Antoniadi obtained a height of 56km for an especially long dark yellow cloud detected above Zephyria in April 1933 (Figure 15). Storms imaged by *Viking* that showed ground shadows could be measured by simple trigonometry, the viewing geometry being known.

Dust storm statistics

It is important to say that we need better statistics from our Earth-based work, in order to extend the observational record. Only a handful of perihelic oppositions have gone by since we were first able to photograph dust storms. One cannot do statistics without data! I shall include only Earth-based work in the figures I shall present here, because *Viking* data would seriously bias them towards one narrow epoch. In 1977 alone, the mission logged 35 storms, including two encircling ones! But the whole mission lasted only six years.

A number of investigators have catalogued the storms. But some have included features which are clearly white clouds, and others have catalogued the same storm twice at two different times of its development, or excluded some of the visual work. One modern author (A. E. Smith, in his book *Mars: The Next Step*) has even confused the well-known 'W' cloud with a dust storm: in fact it represents coalescing white clouds over the martian volcanoes. In his *Handbook of the Physical Properties of the Planet Mars*, Michaux lists the earliest modern catalogue, the work of Gifford. My own investigations, begun in 1980, and centred upon published and unpublished BAA work have shown that much material in the foreign periodicals and books has been left out. A final difficulty in discussing the BAA data is that between 1922 and 1954 hardly any of the Mars Section work was analysed or published. Our archives contain much information not recorded elsewhere, particularly for epochs where planetary observing by professionals was at a low ebb. I have re-examined all the published and unpublished Mars observations (some 22,000 in 49 apparitions), and consulted every other archival and published source I could. The data here will come from these sources combined, and I hope to publish a final catalogue at a later date.

We return to the questions: *where* and *when*? On a Lowell Observatory chart, L. J. Martin identified features prone to obscuration in a relative way, which highlighted the pre-eminence of Hellas. To illustrate graphically *when* storms occur I have prepared a histogram from the draft BAA storm catalogue (Figure 16). The data have been 'binned' into 10° intervals in L_s. The encircling storms are strictly limited to southern spring and summer, but regional and local events can apparently occur any time. The next diagram, due to Peterfreund (1985), and reproduced by Kahn *et al.*, shows how storm latitudes exhibit a measurable seasonal trend (Figure 17). It also shows clearly that the S. hemisphere not only predominates over the N. hemisphere in the southern summer, but that it does so *throughout* the martian year. I had reached this conclusion and had compiled a very similar BAA graph before I first saw this figure reproduced in print a few years ago.

Modern observations reveal more of the minor storms than our predecessors witnessed. Looking down a chronological list can give the misleading impression that Mars is getting more and more dusty. Although it is quite plausible that the opacity of the atmosphere does vary on a timescale of decades – witness the somewhat opaque martian air at the time of Viking, as I mentioned earlier, compared with the relative clarity perceived by the Russian *Phobos* mission in 1989 and by the HST in 1995 – there can be little doubt that the wider team of modern observers is more adept at catching minor storms. For the period 1901–1931 the BAA made some 2,800 observations; during 1933–1963 there were 4,200 observations, but for 1965–1995 there were 15,000, allowing much better observational coverage. Also it is important to have observers spread around the globe, which was not the case in the earlier periods.

Notwithstanding the above, I have broken the data down into three convenient 'bins' of 32 years. The Earth and Mars go through a series of aphelic and perihelic oppositions every 15 or 17 years, after which they return to the same relative positions, and during which observers sample the same set of martian seasons through the succeeding series of approaches. The values of L_s after 15 or 17 years do not agree closely, but if we go for an interval of 15+17 = 32 years, the agreement is good enough, as can be seen:

Opposition year	*L_s(°) at opposition*
1995	58
1963	50
1931	42
1899	35
Average	46 (range ±12°)

Thus all seasons will be sampled pretty equally within each of the 32-year periods. I have chosen to define the epoch 1901–1995 as the 96-year period, in order to use all the latest data from the last opposition as follows: 1901–1931, 1933–1963 and 1965–1995. But in order not to waste data from the first few years of the BAA Mars Section, I have added the epoch 1869–1899, and searched all the extant pre–BAA records too. In fact the only pre–1892 event of significance is a regional storm at the perihelic (and epoch-making) approach of 1877.

When one breaks down the data into these periods, a

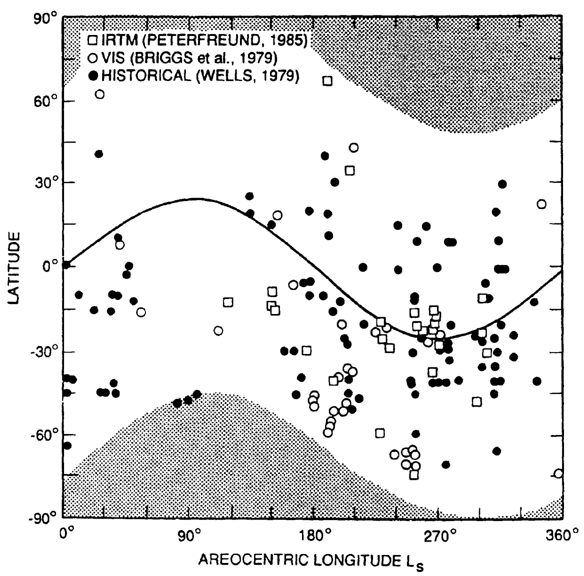


Figure 17. Dust storm latitudes as a function of L_s. The solid curve represents the subsolar latitude. From Keiffer *et al.*, (eds.), *op. cit.*, (1992), p 1038. (Originally published in Peterfreund A. R., *Contemporary Aeolian Processes on Mars: Local Dust Storms*, PhD thesis, Arizona State Univ., 1985.)

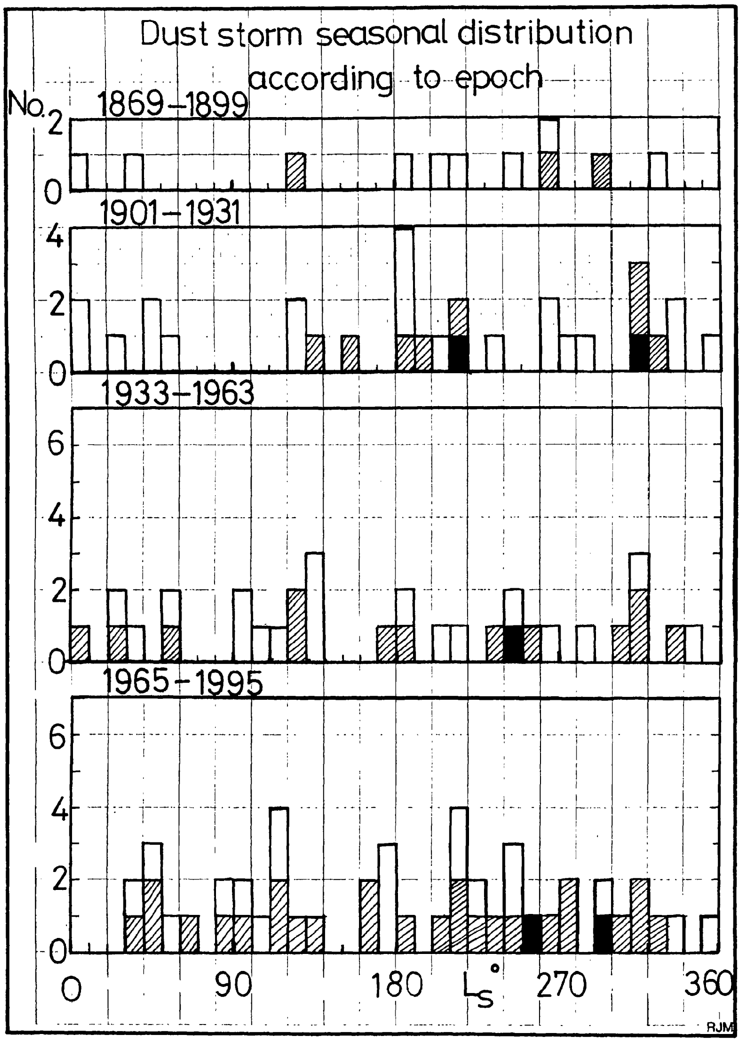


Figure 18. Preliminary BAA histogram of yellow cloud seasonal frequency for the four separate epochs described in the text. Compare with Figure 16. *R. J. McKim.*

somewhat different picture emerges (Figure 18). The great storms still show the same preference for southern spring and summer, without one such event in the first epoch. But the regional and local storms are quite diverse in their behaviour. You can see that there was not even a local storm in the 0–30° bins in the 4th epoch, despite the most intensive observational patrol, although such events are recorded in the histograms for the first three epochs. *Viking* data are also of interest: for the first martian year the probes recorded many storms. In the second and third years there was much less activity.

We can make the same analysis with the locations of storms, although I shall omit the 'first epoch' on the grounds of inadequate data. I have selected seven initiation sites from the many possible. Notice that there are more storms observed in Hellas today then previously, but this is true of the sites generally. Therefore any site where the trend reverses must be both unexpected and significant. We have such a case: Isidis Regio/Libya, or Isidis Planitia. Earlier a favoured site, no such telescopic event has occurred there since 1958.

We are forced to the conclusion that favourable sites may become unfavourable over a few decades, and vice-versa. Chryse appears as a more favourable site, whilst Isidis Regio/Libya drops out. I have been careful to emphasise that this is not a case of observational selection, but is a real phenomenon. Ebisawa and Dollfus note that the Hellas source predominated during 1941–1971. Of course, other sites also appear and disappear on an irregular basis. This cyclical variation has important observational consequences.

Dust storms and cyclical changes in the dark markings

The conclusion we have reached about the cyclical variability of dust storm sites should not be so surprising when we recall the fact the dark areas of Mars also vary in a cyclical manner. The excavation of darker underlying ground by martian wind activity causes the occasional darkening of Pandorae Fretum (as described earlier), of Hellespontus, Mare Serpentis, Nepenthes and the changes in size and shape of Solis Lacus, etc. Not since the mid-1960s has Nepenthes, bordering Libya–Isidis Regio, nor Moeris Lacus nearby, been at all prominent. Telescopically, Isidis Planitia has not been significantly active as a dust storm centre since 1958. We may have missed a few local storms, but it is unlikely that anything larger has happened. The connection is at once clear: in the past the frequent removal of dust from Nepenthes by activity in Isidis Planitia kept it dark. Nowadays Nepenthes and Isidis Planitia would appear to act as dust sinks. Figure 19 shows some modern observations compared with earlier views. It has been calculated that deposition of just 10^{-4} gm/cm^2 of dust on the average dark area should increase its albedo (that is, its brightness) by several tens of percent, even though the depth of the deposit is only a few tenths of a micron.

Hellas has been active a lot in recent years, and the dark regions of Mare Serpentis and Pandorae Fretum have remained fairly conspicuous. As we see in Figure 20, Hellas has been subject to both seasonal and secular variations in the past. Note the few very odd years where it has even appeared dark, clearly denuded of bright dusty deposits. Elsewhere, occasional activity in the Solis Lacus/Thaumasia region since 1973 has given us a larger-than-average Solis Lacus and continual albedo changes in the Claritas–Daedalia region nearby. Conversely, Cerberus, characteristically a dark marking which borders Elysium, is presently faint, fainter than it has been for many decades. This appears to be another example of a region where net dust deposition is currently going on. Kahn *et al.* have also described how dust fallout may be seasonally removed from

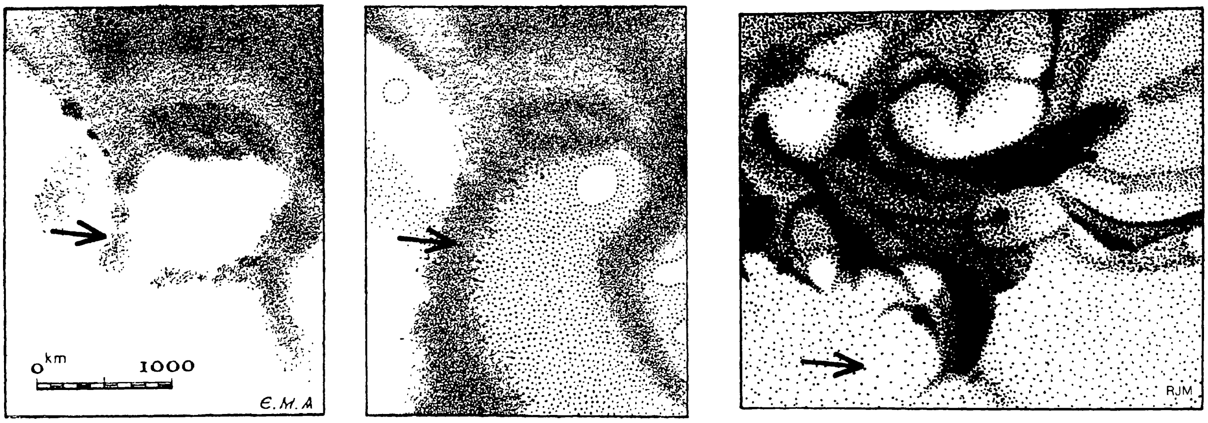


Figure 19. The Syrtis Major–Moeris Lacus–Nepenthes region, drawn with the 830mm OG at Meudon Observatory. Left: 1909, *E. M. Antoniadi*; centre, 1911, *E. M. Antoniadi;* right: 1988, *R. J. McKim.* Note the great width and darkness of Nepenthes (arrowed) in 1911, contrasting with its invisibility in 1909 and 1988.

Syrtis Major Planitia and deposited in the neighbouring Arabia desert.

There are some observational problems: for obvious reasons, we cannot directly observe which desert areas accumulate dust, so we must see what happens to the albedo features and make deductions. There are also many apparitions when the southern spring and summer seasons cannot be viewed at all from Earth due to distance or solar conjunction. But we can still get a general idea of the storms that occurred in particular areas by seeing how the dark markings have varied in the interval since the last apparition.

If an active site loses more dust than it receives as fall-out from storms elsewhere, it must ultimately lose its ability to produce significant storms. If a region is a net accumulator of dust, a new site may be born. It does seem to me that the telescopic Chryse–Xanthe region is currently ascendant, Hellas may be declining, and Isidis Regio/Libya is dormant. I would predict that in the next few apparitions we shall see Isidis Regio/Libya active again, and that the sweeping curve of Nepenthes will reappear, joining the E. side of Syrtis Major to Nodus Alcyonius (or Thoth, if you prefer the IAU chart, though at present neither Ebisawa nor the IAU chart are at all near the mark in this area). But whether it will be in one or ten apparitions' time I cannot say: and nor can anyone else. I am hedging my bets, for as we all know to our cost, predictions have a nasty habit of being overtaken by facts!

Dust storms and climatic change

There is no doubt that the martian climate has changed greatly in the last few thousand million years. The 'early, wet Mars' hypothesis is popular, but the desiccation of the red planet requires only the kinetic theory and the passage of time to explain it. We have seen that dust storms can alter the climate of Mars considerably from one year to the next: we can have years with one, two or no encircling storms. It is very likely that dust deposition in the polar regions will affect future cap recession by increasing the amount of solar radiation absorbed by the surface frost, thus accelerating evaporation. In this way, dust provides a kind of 'memory' of the degree of opacity during the time at which the cap was being deposited. Small interannual variations in both caps have been recorded by ground-based observations. More dust deposition would be expected in the NPC than the SPC, because atmospheric dust-loading in the southern winter is low, although BAA work suggests that it is the southern cap that is the more variable. Our data for 1986 showed the SPC recession was in advance of that for 1988. And as we saw from the regional dust storm dates for both apparitions, the 1986 storms were seasonally about 30° in L_s in advance of events in 1988. The timing of the rise in atmospheric pressure by the evaporating cap would therefore seem to be a very critical factor in anticipating the onset of storms.

If these short-term effects are detectable, then so must be the long-term ones. We know that the polar areas consist of regions of complex layered terrain, modelled by long alternating epochs of warm and cold climatic conditions. If the foci of dust storms have detectably varied in the recent

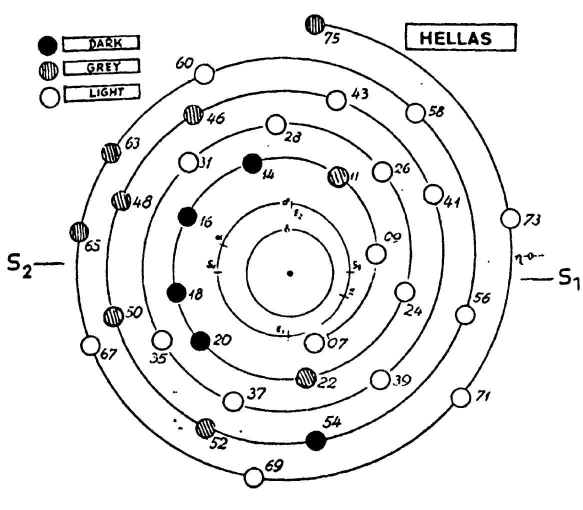


Figure 20. The brightness of Hellas at opposition, 1907–1975, plotted so as to illustrate both seasonal and long-term changes. From Dollfus and de Mottoni (1982).

past, they must have altered completely on a geological timescale. Hunt writes: 'Over a period of 50,000 years, the perihelion subsolar latitude of Mars will vary between ±25°. Consequently, the dark areas of Mars may then also migrate around the planet within the same period. At past epochs, the perihelion dust storms may have originated in the Chryse basin, which would then have been stripped of the brighter deposits.' Indeed, N. hemisphere regions such as Tharsis, Arabia and Elysium might also become favoured sites in the future, or may have once been, in the past. We see that Mars will long remain a dynamic world.

Conclusion

I would like to conclude this Address with a few final remarks. I have tried to show the contribution of members of the Association to the development of our knowledge about the martian dust storms. I have explained the importance of these storms, their interrelationship with the dark markings, their seasonal character and their long-term variations. The dust storms are important for climatic reasons, and they are intimately bound up with the variations in the polar regions. Future explorers will have to contend with them. In the meantime, professional astronomers have asked amateurs to help them in their observational programmes. To me there seems to be no doubt that whatever the latest Mars probes do in the next few years, the amateur still has a role to play, and if he or she chooses to observe with a small reflector and the Mark One Eyeball such work will be even more valuable if the observer spots and reports a dust storm before the high-tech friend with a CCD and computer. Remember that many of the basic observations that went into the statistics presented here have come from the visual work of amateurs using comparatively small telescopes.

I will risk one more prediction, a pretty safe one this time: as long as Mars shines in the night sky, there will always be amateur astronomers like you and me, out in our back gardens observing him.

Address: 5 Ashton Road, Oundle, Peterborough PE8 4BY

Selected bibliography

Antoniadi E. M., *La Planète Mars*, Hermann & Co., 1930. (A classic work, with much interesting detail about dust storms.)

BAA Mars reports in the *Memoirs* for 1892–1920 and 1941, and in the *Journal* for many later years. The 1986, 1988, 1990 and 1993 apparition reports by the present writer appeared in the *Journal*, **99**, 215 (1989), **101**, 264 (1991), **102**, 248 (1992) and **105**, 117 (1995), respectively.

Capen C. F., 'Martian Yellow Clouds – Past and Future', *Sky & Telesc.*, **41**, 117 (1971)

Cattermole P. J., *Mars: The Story of the Red Planet*, Chapman & Hall, 1992. (An excellent general book, especially for martian geology.)

Dollfus A., & de Mottoni G., 'Surface Marking Variations of Selected Areas of Mars', *Astron. Astrophys.*, **116**, 323 (1982)

Dollfus A., Ebisawa S., & Bowell E., 'Polarimetric analysis of the Martian dust storms and clouds in 1971', *Astron. Astrophys.*, **131**, 123 (1984)

Dollfus A., *C. R. Acad. Sci. Paris*, **311**, II, 1185 (1990). (A description of the technique of video polarimetry.)

Dragesco J. (transl. McKim, R. J.), *High Resolution Astrophotography*, Cambridge University Press, 1995. (A detailed practical description of how to secure the best planetary images.)

Ebisawa S., 'Analytical Study on the Secular and Seasonal Modifications of Martian Soil', *Contr. Kwasan & Hida Obs., Univ. of Kyoto*, No. 210, 1973

Flammarion C., *La Planète Mars et ses conditions d'habitabilité*, Gauthier–Villars, 1892 (volume 1) and 1909 (volume 2)

Gifford F. A., 'A study of Martian yellow clouds that display movement', *Monthly Weather Rev.*, **92**, 435 (1964). (An early catalogue, with meteorological interpretations.)

Greeley R., Lancaster N., Lee S., & Thomas P., 'Martian aeolian processes, sediments and features', in Keiffer H. H. *et al.*, (eds.), *op. cit.*, pp 730–766

Hunt G. E., 'Some aspects of martian dust storms observed during the *Viking* mission', in Moore P. (ed.), *1980 Yearbook of Astronomy*, Sidgwick & Jackson, 1979

Kahn R. A., Martin T. Z., Zurek R. W., & Lee S. W., 'The martian dust cycle', in Keiffer H. H., *et al.* (eds.), *op. cit.*, pp 1017–1053

Keiffer H. H., Jakosky B. M., Snyder C. W., & Matthews M. S. (eds.), *Mars*, Arizona University Press, 1992. (Encyclopaedic summary of our knowledge of the red planet up to the present day.)

McKim R. J., 'Historique des tempêtes martiennes', *Bull. Soc. Astron. France*, **107**, 312 (1993). (A preliminary summary of the BAA dust storm catalogue work, given as a talk to the French Astronomical Society.)

Martin L. J., '1973 Dust Storm on Mars: Maps from Hourly Photographs', *Icarus*, **29**, 363 (1976)

Martin L. J. & Zurek R. W., *J. Geophys. Research*, **98**, no. E2, 3321–3246 & 3247–3259 (1993). (A catalogue of dust storms displaying motion, with detailed discussion and analysis.)

Michaux C. M., *Handbook of the Physical Properties of the Planet Mars*, NASA SP–3030, Washington, DC, 1967. (An early compilation, as the title implies.)

Moore P. A., *Guide to Mars*, Lutterworth, 1977. (Especially good for the history of telescopic observation.)

Muhleman D. O. *et al.*, 'Radar Images of Mars', *Science*, **253**, 1508 (1991)

Parker D. C. & Capen C. F., 'Martian Date: Its significance and methods for its determination', *J. Assoc. Lunar Planet. Obs.*, **28**, 210 (1980)

Slipher E. C., 'The Photographic Story of Mars', *Sky Publishing*, 1962

Soderblom L. A., 'The composition and mineralogy of the martian surface from spectroscopic observations...', in Keiffer H. H. *et al.* (eds.), *op. cit.*, pp.557–593

de Vaucouleurs G., *Physics of the Planet Mars*, Faber & Faber, 1954. (Another classic work, with good historical details about yellow cloud motions.)

Viking Orbiter imaging team, *Viking Orbiter Views of Mars*, NASA SP-441, Washington, DC, 1980. (One of several such reference books.)

Zurek R. W. *et al.*, 'Dynamics of the atmosphere of Mars', in Keiffer H. H. *et al.* (eds.), *op. cit.*, pp 835–933