The 2018 opposition of Mars & the global dust storm: Part I

Richard McKim

A report of the Mars Section. Director: R. J. McKim

The perihelic opposition that occurred on 2018 Jul 27 at areocentric longitude (*Ls*) 219° was monitored by 121 observers, yielding nearly 9,000 observations. Part I of this paper focuses upon the global dust storm that arose on 2018 May 30 in early southern spring, at *Ls* = 184°. The event was unprecedented in having commenced in the northern hemisphere, and the process of encirclement (over 25 days) was unusually slow. The expansion of the storm in both the northern and southern hemispheres was faster to the east than to the west. Its effects were still apparent in mid-August, and there were striking and long-lasting albedo changes including the reappearance of *Phasis*, the unprecedented distortion of the N. part of *Margaritifer Sinus – Oxia Palus*, and the intensification of *Indus* at SE *Mare Acidalium – Niliacus Lacus*. The global storm deposited dust upon the S. polar cap, accelerating its early recession, though the majority of the recession curve followed that of 2003 (a year without an encircling storm) extremely closely. Other global storm phenomena included terminator projections – due to suspended dust – up to some 80km in altitude, increased activity of the N. polar hood, and the presence of a bright morning limb cloud arc adjacent to the S. polar cap. Dust velocities of up to 118km h^{-1} were measured. In Part II, other local and regional dust storms are described, as well as white cloud activity and the behaviour of the polar regions.

Introduction

This paper, continuing from our 2016 report,[1] covers 2017 September to 2019 June (Martian Years (MY) 34 to 35).[2]

Mars was at opposition in Capricornus on 2018 Jul 27, at areocentric longitude (*Ls*) 219°: the first of the new perihelic approaches. The disc diameter was 24.2″, while at closest approach on Jul 31, it reached 24.3″. The declination (–25.5°) greatly favoured southern observers, but became favourable to northern ones late in 2018. The disc diameter was 6″ or more from 2018 mid-February till 2019 early February. The most seasonally comparable post-1890 oppositions were 1892, 1907, 1924, 1939, 1954, 1971, 1986 and 2003. The closest match was 1939 (*Ls* = 215°). Reports upon many of these are available online.[3]

Table 1. Physical details of the 2018 apparition

	Ls (°)	*Date*
Solar conjunction	39	2017 Jul 27
Aphelion	70	2017 Oct 5
N. summer solstice/ S. winter solstice	90	2017 Nov 20
N. autumn equinox/ S. spring equinox	180	2018 May 22
Opposition	219	2018 Jul 27
Perihelion	250	2018 Sep 14
N. winter solstice/ S. summer solstice	270	2018 Oct 16
N. spring equinox/ S. autumn equinox (MY 35 commences)	0	2019 Mar 23
Aphelion	70	2019 Aug 23
Solar conjunction	74	2019 Sep 2

At opposition the latitude of the sub-Earth point (D_e) was –11.1°. Until early 2018, early-March observation of the planet's northern hemisphere was favoured; after that, and up till 2019 mid-May, the southern hemisphere was tilted towards Earth. Seasonal data are given in Table 1.

D. A. Peach made extensive use of the remote Chilescope facility, with an observing trip to Barbados in the first half of May. The writer spent three weeks of August in the Czech Republic, taking the optics of a 254mm reflector. Other members have described observing trips or personal research.[4–6]

UK-based observers had serious issues due to the planet's low altitude, but D. L. Arditti and N. J. Haigh acquired useful images of the developing global dust storm, and post-opposition work by M. R. Lewis attained high resolution. Good seeing around opposition was rare, but if the air flow was laminar one could make out a lot of detail visually, while the usual image enhancement and stacking routines proved effective. The Director made 123 sketches between 2018 Jan 7 and 2019 Mar 28.

In Europe, C. E. Pellier experimented with spectroscopy. Further afield, C. Foster, P. Gorczynski, T. Kumamori, P. W. Maxson, E. Morales and K. Yunoki each secured more than 400 individual images (Foster over 700), while over 250 drawings came from M. Adachi in Japan. Apparition maps were submitted by P. G. Abel, Foster, R. Heffner and Peach.

8,981 observations (8,134 images and 847 drawings) were made by 121 observers in 28 different countries (Table 2). The first image was taken by R. Iwamasa on 2017 Sep 26 (*Ls* = 066°), the first drawing by Adachi on Nov 2, the final image by R. Hillebrecht on 2019 Jun 29 (*Ls* = 046°) and the final drawing by G. Adamoli on Jun 13. An interval 95% the length of a Martian year was covered, from N. late spring in MY 34 (which began on 2017 May 5) till N. mid-spring in MY 35.

The distribution per month (days observed/possible) was: 2017 Sep 2/30, Oct 11/31, Nov 26/30, Dec 30/31, 2018 Jan 31/31, Feb 27/28, Mar 31/31, Apr 29/30, May 30/31, Jun 30/30, Jul 31/31, Aug 31/31, Sep 30/30, Oct 31/31, Nov 30/30, Dec 31/31, 2019 Jan 30/31, Feb 26/28, Mar 26/31, Apr 20/30, May 18/31, and Jun 5/30.

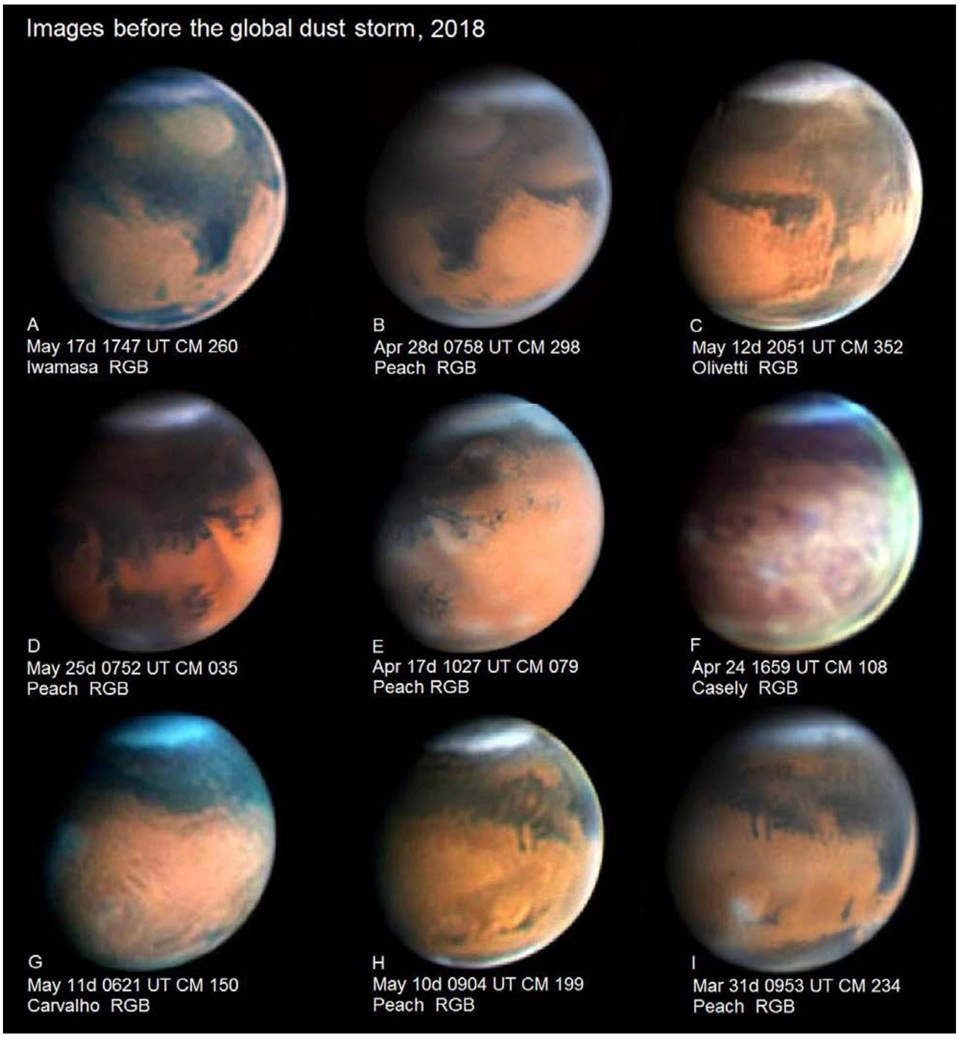

Figure 1. Images prior to the start of the global storm, by F. & G. Carvalho (ASI 290MM camera), A. Casely (ASI 290MM), R. Iwamasa (ASI 290MM), T. Olivetti (PG GS3 IMX252), and D. A. Peach (1m RCT, ASI 174MM (except (H): 355mm SCT, ASI 290MM)). *Top row:* Region I (longitudes 250–010°). *Middle row:* Region II (010–130°). *Bottom row:* Region III (130–250°). Images (B), (E) and (I) show the S. polar hood, and the rest the ground cap; (C) shows a dust storm at the N. edge of the SPC and *Argyre*. Orographic clouds are shown in (F), (G) and (I). *Note*: All figures in this paper have south uppermost.

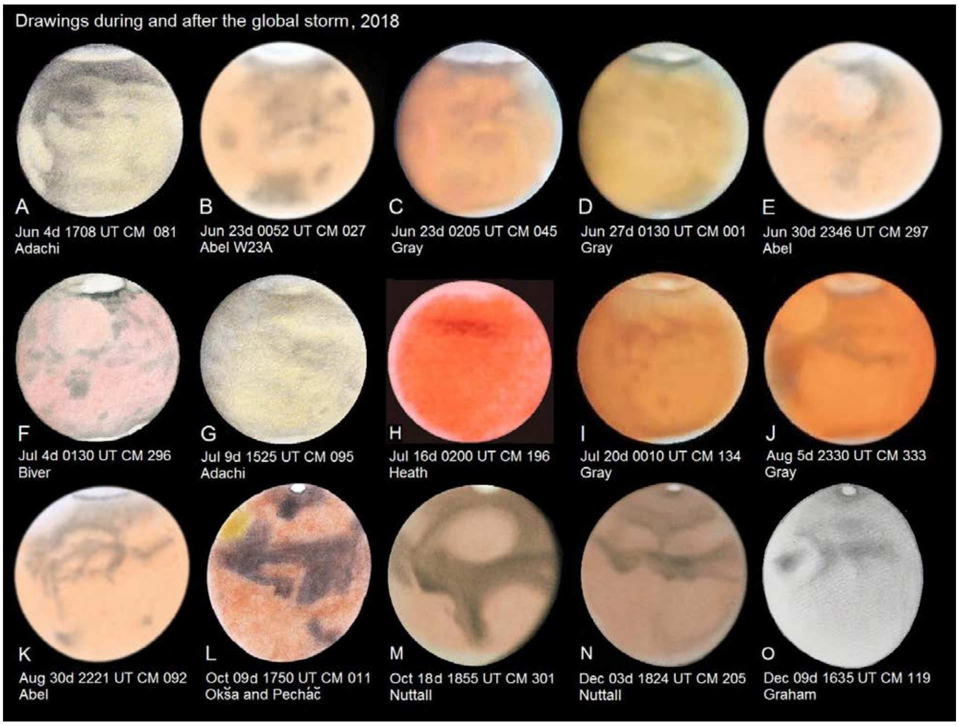

Figure 2. Drawings made during and after the 2018 global dust storm, by P. G. Abel (508mm DK Cass., ×154, ×230), M. Adachi (310mm refl., ×400), N. D. Biver (×538), D. L. Graham (×340, W21 filter), D. Gray (×365), A. W. Heath (×200), C. Nuttall (×333, int./W23A/W25), and G. Okša & J. Pecháč (×360).

The *ExoMars* spacecraft began imaging in 2018 April.[7] On 2018 Nov 26, long after opposition, the suite of spacecraft working upon Mars or in orbit around it was augmented by the arrival of NASA's *InSight* lander at SW *Elysium Planitia* at +4.5°, 224.1° (or telescopic SE *Aethiopis*).[8,13] It landed on smooth terrain and deployed its seismograph station and thermograph tool to take the planet's subsurface temperature. *Mars Reconnaissance Orbiter* (MRO) continued its daily meteorological monitoring.[9]

Observing tips were published by the Director in the *Journal*,[10] as well as in popular magazines.[11] Two interim reports appeared,[12,13] while a regular illustrated 'blog' was maintained at the new Section website. (The latter had recently been migrated from a previous web address and updated.[14]) The Director was interviewed for the monthly BBC *Sky at Night Magazine* podcast about using images for research.[15]

The ALPO Japan (JALPON) website has become the most widely supported for online archiving,[16] while the OAA Mars Section (Japan),[17] ALPO (USA),[18] SAF Mars Section,[19] and PVOL websites also archive online.[20] However, the writer is not aware of any organisation other than the BAA that has produced post-2007 apparition reports.

The observations

General

For nomenclature we use Ebisawa's telescopic map.[21] East and west are aerographic, where the planet's E. limb is the preceding (*p.*) one, and longitudes are in degrees west of the zero meridian.

In Part I we review the global dust storm of 2018 and its effect upon albedo features. Lesser dust storms, white clouds and the polar regions will be discussed in Part II. D_e and D_s (the latitude of the subsolar point) momentarily coincided in 2018 mid-July at –13°, but the global storm eliminated any chance of checking for the incidence of any specular 'flash' from the planet's surface.

Albedo features

With the small exceptions below, prior to the 2018 global storm the albedo features (Figure 1) precisely matched 2016.[1] Many changes were caused by the storm, and several proved remarkably persistent, existing even in 2021.[22,23]

Region I: long. 250–010°

Late in the 2016–'17 apparition,[1] a large Regional dust storm had caused a darkening of *Mare Serpentis* and *Pandorae Fretum*. These areas were still well marked upon the 2017 December images by Miles and Wesley, but *Pandorae* was already faint by 2018 Jan 20 (Kumamori), and its faintness persisted (see Olivetti's image of May 12 (Figure 1C)). However, *Mare Serpentis* (extending into and darkening E. *Noachis*) remained prominent up till the global storm (Figures 1B & C).

Region II: long. 010–130°

Baetis, which joins *Juventae Fons* to *Aurorae Sinus*, looked rather broad at low resolution, as it was in the last few apparitions. At high resolution a short dark streak paralleled its N. border to give the impression of a short, double 'canal' (Figures 1D & E). The little projections to the north of *Aurorae Sinus* and along the S. border of *Chryse* were again very conspicuous (Figures 1C–E). Already at the previous opposition, *Oxia Palus* had exhibited a long drawn-out N. tip, while the thin *Indus* 'canal' running NW from the western side of *Oxia Palus* reached S. *Mare Acidalium / Niliacus Lacus* (Figure 1C–D): these features would change substantially as a result of the global storm.

Ganges was again broad, but the sharper W. border compared to 2016 gave it more prominence. Its tone was uniform, with no sign of the darker edges that it sometimes exhibits (Figures 1D & E).

Region III: long. 130–250°

As in several oppositions up to 2016, a bright yellow patch (pink to some eyes) of dust fallout remained visible in the NW of *Elysium*, adjacent to the *Aetheria* secular dark feature. This surprisingly enduring feature (Figures 1G & H) could still be traced, though slightly faded, and it persisted until covered by the global storm.

The Martian atmosphere

The 2018 global dust storm

Introduction

Many imagers tend to exaggerate contrast during major obscuration events, so visual impressions provide a reality check. The drawings of Figure 2 introduce the event; drawings by the Director of the storm and its aftermath appear in Part II, Figure 13. Morales (Puerto Rico) on May 30 ($Ls = 184°$) took the first image to show the storm,[12] but Rueck (USA), after imaging it on the

Table 2. Observers of Mars, 2018

Name	*Location*	*Instrument(s)*
P. G. Abel **V**	Leicester	203mm refl.
	Univ. of Leicester Obsy.	508mm DK Cass.
& P. Lawrence	Lowell Obsy., AZ, USA	610mm OG
& J. Culshaw	Hampstead, London	152mm SCT
M. Adachi **V**	Ōtsu, Japan	310 & 355mm refls.
	Dynic Obsy., Shiga, Japan	200mm OG & 600mm Cass.
G. Adamoli **V**	Verona, Italy	125mm MKT
B. Adcock	Melbourne, Australia	245mm OG
L. Aerts	Heist-op-den Berg, Belgium	150mm MKT
T. Akutsu	Tochigi, Japan	320mm refl.
J. Albert	Lake Worth, FL, USA	203mm SCT
T. Arakawa	Nara, Japan	300mm refl.
M. Araújo	Évora, Portugal	279mm SCT
D. L. Arditti	Edgware, Middlesex	355mm SCT
D. Ashton & B. Ewan-Smith	COAA, Algarve, Portugal	500mm refl.
K. N. L. Bailey	Wroughton, Wilts.	279mm SCT
T. Barry	Broken Hill, Australia	406mm refl.
D. R. Bates	Dodge City, KS, USA	254mm refl.
G. Bertrand	Nantes, France	254mm refl.
N. D. Biver **V**	Versailles, France	407mm refl.
J. Boudreau	Saugus, MA, USA	368mm DK Cass.
S. Buda	Melbourne, Australia	405mm DK Cass.
F. & G. Carvalho	Ribeirão Preto, Brazil	406mm refl.
A. Casely	Sydney, Australia	355mm SCT
E. Chappel	Cibolo, TX, USA	203mm SCT
M. Collins	Palmerston North, New Zealand	90mm MKT & 110mm OG
E. Colombo **V**	Gambarana, Italy	150mm refl.
M. Delcroix	Tournefeuille, France	320mm refl.
& F. Colas and E. Kraaikamp	Pic du Midi Obsy., France	1.06m Cass.
D. Dierick	Ghent, Belgium	235mm & 279mm SCT
J. Dijon	Namibia, Africa	400mm RCT
C. Dole	Newbury, Berks.	180mm MKT
D. Eagle	Higham Ferrers, Beds.	190mm Mak–Newt.
P. Edwards	Horsham, W. Sussex	355mm SCT
H. Einaga	Kasai, Hyōgo, Japan	300mm refl.
C. Fattinnanzi	Montecassiano, Italy	102mm OG
D. Finnigan	Halesowen	305mm SCT
W. D. Flanagan	Houston, TX, USA	355mm SCT
C. Foster	Centurion, Gauteng;	355mm SCT
	Boyden Obs., Bloemfontein, South Africa	330mm OG
S. Gale **V**	Landing, NJ, USA	310mm refl.
M. Giuntoli **V**	Montecatini Terme, Italy	152mm refl.
C. Go	Cebu, Philippines	355mm SCT
P. Gorczynski	Oxford, CT, USA	180mm MKT & 355mm SCT
D. L. Graham **V**	Barton, Richmond, N. Yorks.	230mm MKT
D. Gray **V**	Kirk Merrington, Co. Durham	76mm OG & 415mm DK Cass.
P. Haese	Glenalta, Australia	355mm SCT
N. J. Haigh	Southampton	305mm refl.
A. W. Heath **V**	Long Eaton, Notts.	203mm SCT
R. Heffner	Aichi, Japan	235mm SCT
M. Hezzlewood **V**	Burnley, Lancs.	100mm OG
R. Hill	Tucson, AZ, USA	203mm MKT
R. A. Hillebrecht	Bad Gandersheim, Germany	355mm SCT
I. Hirabyasahi	Tokyo, Japan	254mm refl.
M. Hood	Kathleen, GA, USA	200mm OG & 355mm SCT
T. Ikemura	Nagoya, Japan	380mm refl.
S. Ito	Kasugai City, Aichi, Japan	250mm refl.
R. Iwamasa	Yokohama, Japan	355mm SCT
M. Justice	Melbourne, Australia	305mm refl.
M. Kardasis	Athens, Greece	355mm SCT
	Pic du Midi Obsy., France	1.06m Cass.
J. Kazanas	Melbourne, Australia	318mm refl
A. S. Kidd	Cottered, Herts.	355mm SCT

Table continuation and explanatory notes on p.288

Table 2. Observers of Mars, 2018 (Cont'd from p.287)

Name	*Location*	*Instrument(s)*
D. Kolovos	Athens, Greece	279mm SCT
T. Kumamori	Osaka and Okinawa, Japan	355mm SCT
S. Kurisu	Mitoyo Kagawa, Japan	355mm SCT
G. D. Lewis	Bunwell, Norfolk	355mm SCT
M. R. Lewis	St. Albans, Herts.	444mm refl.
W. M. Lonsdale	Canberra, Australia	279mm SCT
S. Lukas	Canberra, Australia	305mm SCT
P. Lyon **V**	Birmingham	203mm SCT
T. McCague **V**	Mesa, AZ, USA	410 & 457mm refls.
R. J. McKim **V**	Upper Benefield, Northants.	410mm DK Cass.
	Mnichovo Hradiště, Czech Republic	254mm refl.
N. MacNeill	Wattle Flat, NSW, Australia	355mm SCT
S. Maksymowicz **V**	Ecquevilly, France	127mm & 152mm OGs, 130mm Cass., etc.
E. Mariani	Tradate (VA), Italy	203mm SCT
S. Massey	Hervey Bay, Queensland, Australia	305mm refl.
P. W. Maxson	Surprise, AZ, USA	250mm DK Cass.
K. J. Medway **V**	Southampton	200mm refl.
F. J. Melillo	Holtsville, NY, USA	254mm SCT
J. Melka	Chesterfield, MO, USA	457mm refl.
P. Miles	Rubyvale, Queensland, Australia	508mm refl.
D. P. Milika & P. Nicholas	Adelaide, Australia	355mm SCT
T. Mishina	Yokohama, Japan	200mm refl.
E. Morales	Aguadilla, Puerto Rico	310mm SCT
Y. Morita	Hiroshima, Japan	355mm SCT
P. U. Neville **V**	Maidenhead, Berks.	152mm OG
D. Niechoy **V**	Göttingen, Germany	203mm SCT
C. Nuttall **V**	Bishopthorpe, Yorks.	300mm refl.
G. Okša & J. Pecháč **V**	Nitra, Slovak Republic	180mm MKT
T. Olivetti	Bangkok, Thailand	505mm DK Cass.
A. Pace	Malta	355mm SCT
D. A. Peach	Chilescope Observatory, Andes Mts., Chile	1m RCT
	Barbados, West Indies	355mm SCT
C. E. Pellier	Paris, France	305mm refl.
J. H. Phillips	Charleston, SC, USA	254mm MKT
J. Press	Burnham-on-Crouch, Essex	203mm SCT
G. Quarra & M. Caponera	Valmontone, RM, Italy	235mm SCT
M. Radice	Salisbury	279mm SCT &
	Tenerife, Spain	150mm MKT
M. R. Ratcliffe	Wichita, KS, USA	355mm SCT
	Lowell Obsy., AZ, USA	610mm OG
	Lamont Hussey Obsy., South Africa	330mm OG
J. Rueck	Sebastian, FL, USA	410mm refl.
R. W. Schmude	Barnesville, GA, USA	90mm MKT
R. Schulz	Hakos, Namibia	500mm Cass.
A. Snook	Dover	500mm refl.
D. Storey	Foxdale, Isle of Man	200mm SCT
D. Strange	Salcombe Regis, Devon	digital camera
J. Sussenbach	Houten, Netherlands	355mm SCT
E. Sussenbach	Willemstad, Curaçao, Dutch Caribbean	203mm SCT
R. Tatum	Henrico, VA, USA	305mm SCT
P. Tickner	Lower Earley, Berks.	305mm SCT
D. B. V. Tyler	Flackwell Heath, Bucks.	355mm SCT
M. P. Valimberti	Melbourne, Australia	305mm refl. & 355mm RCT
A. G. Vargas	Cochabamba, Bolivia	203mm refl. & 152mm SCT
V. della Vecchia	Aversa, Italy	203mm SCT
D. Vidican **V**	Bacău, Romania	150mm refl.
G. Walker	Macon, GA, USA	254mm OG & 300mm DK
J. Warell & C. Svenske	Skivarp, Sweden	254mm refl.
	Tenerife, Canary Isles	300mm refl.
A. Wesley	Rubyvale, Queensland, Australia	406mm refl.
K. Yunoki	Osaka, Japan	355mm refl. & 355mm SCT

Abbreviations: OG = object glass (refractor); refl. = reflector; Cass. = Cassegrain; DK = Dall–Kirkham; MKT = Maksutov–Cassegrain, RCT = Ritchey–Chrétien and SCT = Schmidt–Cassegrain (Telescope).

Delcroix sent images taken in conjunction with other observers at Pic du Midi.

All observers sent images except those marked **V** (for visual observations *only*).

following day, was the first to announce it on an online forum. The Director alerted active observers by e-mail on Jun 5, when it was clear that it was not merely a small Regional event, and issued BAA *e-Bulletin* no. 1007 (Jun 10). Commencing in SE *Mare Acidalium–Niliacus Lacus,* in the *northern* hemisphere, the Director did not at first believe it could become encircling.

As always, dust was recognised by its brightness in near-infrared (IR) and red (R), moderate brightness in green (G), and obscurity in blue (B). A wide range in image processing was in use, and we have generally avoided including the highly contrast-enhanced IR images that some contributors produce, except where available R or RGB composite images would not have given a sufficiently clear indication of particular features. Occasionally the Director composed IR–RGB images as a compromise. We have chosen sets of images to represent each successive rotation for the first four weeks until Day 28, Jun 26–27 (Figures 3–6), and then less frequently while the event decayed. Naturally, there are occasional gaps and occasionally we had to include lower resolution work. In each complete row, the storm's origin is located around or just right of centre. A token attempt was made to make images within each row a similar size and brightness, and to reduce large variations in contrast. Maps for selected dates appear in Figure 7.

Encirclement can only occur as the result of the merging of the primary dust core with other cores at different longitudes. For a long time in the case of the 2018 storm, no secondary core appeared: coupled with the event's unusually slow progression in longitude, a slight decay was even suspected in some areas. But then on Day 22, another core appeared at *Solis Lacus* (and environs) after which its expansion ultimately led to encirclement on Day 25. From the global maps (Figure 7), it was estimated that the dust did not spread north of latitude +54°. This is similar to another estimate.[24] The S. polar cap was considerably affected by dust, but never completely covered.

Daily descriptions up to encirclement (Day 25)

May 27: An inclined yellowish-white band oriented N*p.* to S*f.* (not present the previous day, and contrasting with the bluish N. polar hood) was located across N. *Mare Acidalium*; it had a bright, dusty core at the N. limb. Another inclined light band, suggesting a further front following, lay to its N*f.* side.

May 30 / Day 1: The global dust storm formally began as a compact elliptical bright area, centred at *ca*. +36°, 018° in SE *Mare Acidalium – Niliacus Lacus*, with its E. end in *Cydonia*. There is no particular topographic feature here; the terrain merely slopes gently from SE to NW. But this was adjacent to the track of the front that had evidently moved south from the North Polar Region (NPR). (The latitude of the subsolar point (D_S) was then –2°.)

May 31 / Day 2: The location of the bright core over SE *Mare Acidalium / Niliacus Lacus* (*Acidalia Planitia*) was similar, having expanded to the SW and appearing dumbbell-shaped. Its latitude ranged from *ca.* +25° to +40°. There was no obvious change during three hours' observation.

Jun 1 / Day 3: The original cloud moved south to form two discrete bright nuclei in southern *Chryse*; there was also some dust as far west as the E. edge of *Ganges*, while SE *Acidalium* was faded.

Jun 2 / Day 4: New dust cores appeared at *Aram/Thymiamata*. There was a resurgence of the original nuclei.

Jun 3 / Day 5: A dust core appeared in E. *Valles Marineris* at *Eos*, and the N. part of *Margaritifer Sinus* was blotted out.

Jun 4 / Day 6: To the east, dust was spreading across *Eden*, but its boundary was already ill-defined. On the west, dust had begun to cross *Ganges*. The *Tharsis Montes* orographic clouds disappeared.

Jun 5 / Day 7: A general expansion; dust obliterated much of *Margaritifer Sinus* and cut across N. and S. *Ganges*.

Jun 6 / Day 8: Dust expanded further east–west, moved into W. *Deucalionis Regio*, hid W. *Meridiani Sinus* and ran along *Valles Marineris*. There appeared to be a weak dust core in *Argyre*.

Jun 7 / Day 9: Central *Ganges* (the only part remaining) showed an anomalous darkening. The dust expanded southward to reach E. *Mare Erythraeum*. There was now a definite core in *Argyre*.

Jun 8 / Day 10: The *Argyre* dust was moving south towards the South Polar Cap (SPC). (Dust over the cap is further discussed separately.) *Syrtis Major* was not yet affected. Peach's image showed a loss of contrast north of *Syrtis*, the very

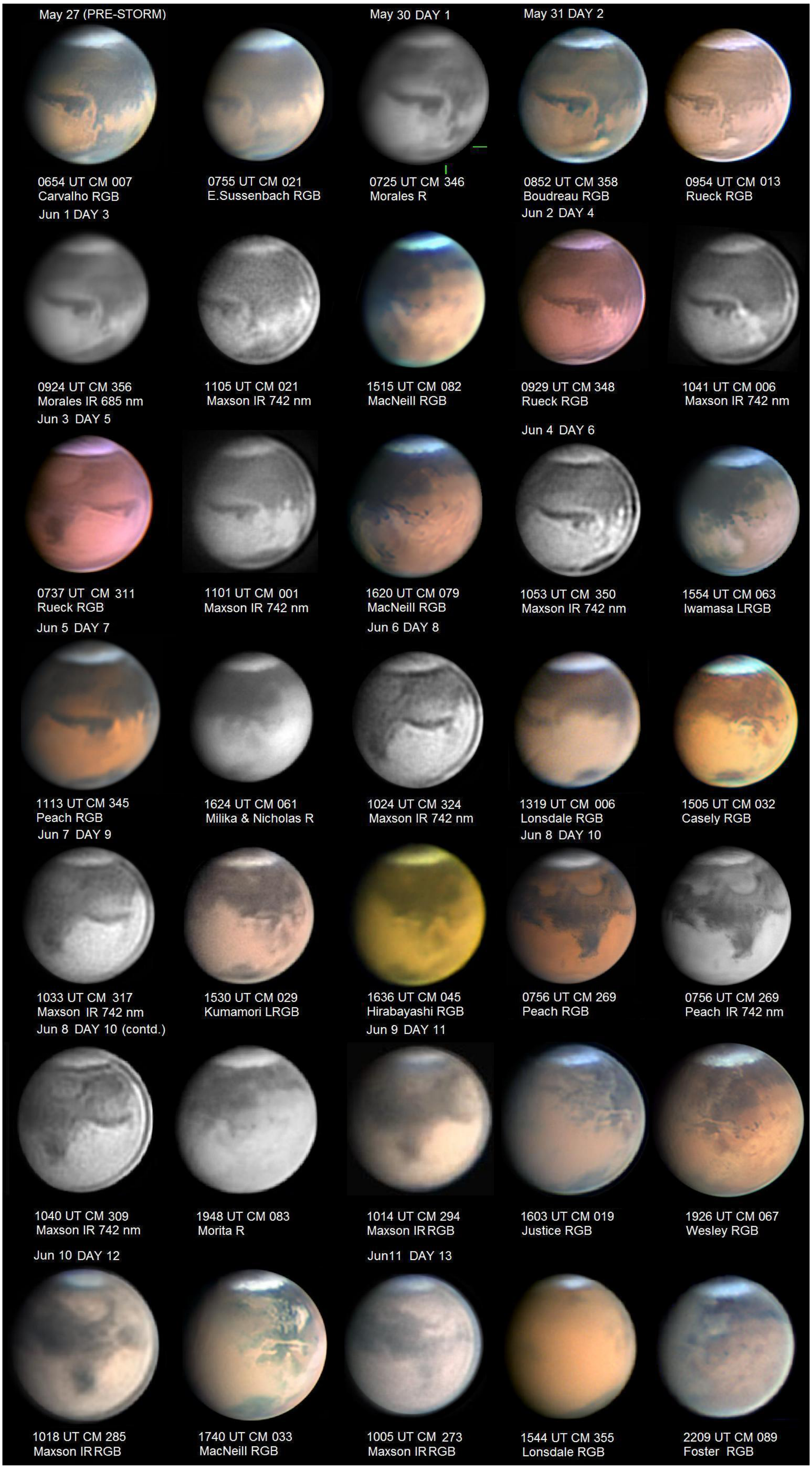

Figure 3. Daily image collages to show the origin and progress of the 2018 global storm, up to and including Day 13. Some IR–RGB combinations were made by M. R. Lewis or the Director. *Note*: The wavelengths specified are for cut-on filters: 'IR 685nm' means the filter passes $\lambda > 685$nm. As the visible waveband extends to 780nm,[40] it will also pass long-wave red light. All images in Figures 3–6 are by Peach with the 1m RCT Chilescope.[39]

ill-defined E. front having passed and faded *Nodus Alcyonius*, with *Arabia* dusty towards the yellowish limb; high-latitude dust at the SPC N. edge had reached SW *Hellas*, though at this latitude too the dust front was not very bright.

Jun 9 / Day 11: Longitude 0° was now completely unrecognisable. Complex dust cores existed over *Mare Erythraeum* (though the W. part was still dark), and bright dust had travelled all along *Valles Marineris* (a striking development which picked out the detailed topography of the canyon) and over *Noachis*, while *Deucalionis*, *Margaritifer*, *Meridiani* and W. *Sinus Sabaeus* were blotted out. A small dust core had formed at *Juventae Fons*. Dust began to spill onto the cap and was crossing *Bosporos* to approach *Thaumasia* at its western limit. Dust was crossing southern *Hellas*. In the north, *Mare Acidalium* remained clearly visible.

Jun 10 / Day 12: Some dust from central *Hellas* had crossed into *Ausonia* as far east as longitude ~260°. A finger of dust had crossed E. *Noachis/Deucalionis* into S. *Iapigia*. Dust had filled *Argyre*. A new bright dust-storm nucleus had formed over E. and central *Solis Lacus*, with a complex pattern comprising many small cores. Dust could be seen over *Tharsis*.

Jun 11 / Day 13: Dust had moved east across *Iapigia*; N. *Hellas* was now full of dust. *Syrtis Major* had greatly faded, and only a trace of *Sinus Sabaeus* remained. A large fraction of the SPC had been covered.

Jun 12 / Day 14: The N. hemisphere was now widely affected around a central-meridian (CM) longitude of 200°, so that *Elysium* and environs were starting to fade. Dust had reached *Ausonia* and was crossing *Mare Tyrrhenum* and *Hesperia*. *Cimmerium* and *Sirenum* were the only major southern maria unaffected. The *Solis Lacus* core was fading, but a new one had appeared over *Daedalia*. The *Hellas* basin was full of dust. (Very likely further dust-raising had occurred there, but the area did not become as bright as it can on such occasions, suggesting lower activity than usual.)

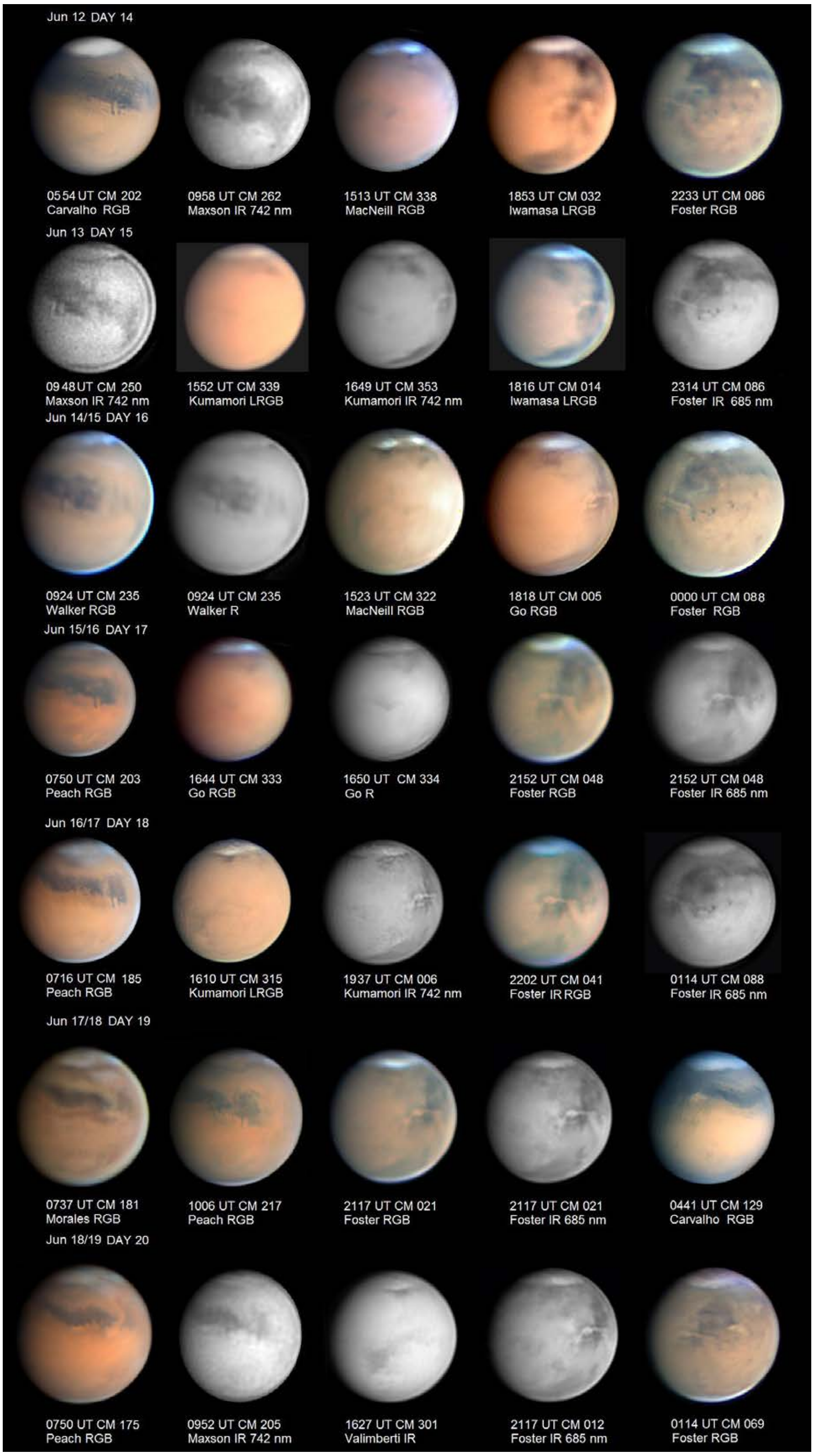

Figure 4. Further daily image collages showing the growth of the global storm, Days 14–20.

Jun 13 / Day 15: The fresh *Daedalia* core had greatly faded, and *Solis Lacus* had recovered somewhat, suggesting for the moment that the storm would not develop further. *Mare Tyrrhenum* was starting to become obscured.

Jun 14–15 / Day 16: Dust obliterated *Mare Tyrrhenum* and W. *Mare Cimmerium*, and small patches were seen over other parts of the latter. Nothing was now visible of *Elysium* and its surroundings. By now, the only longitudes not affected in the south were those from west of *Daedalia* to the E. half of *Mare Cimmerium*. However, the presence of dust in the north was betrayed by the *Tharsis Montes* which, together with *Olympus Mons*, now showed up more distinctly as dark spots, their summits poking through the dust layer. They would now darken further over several days.

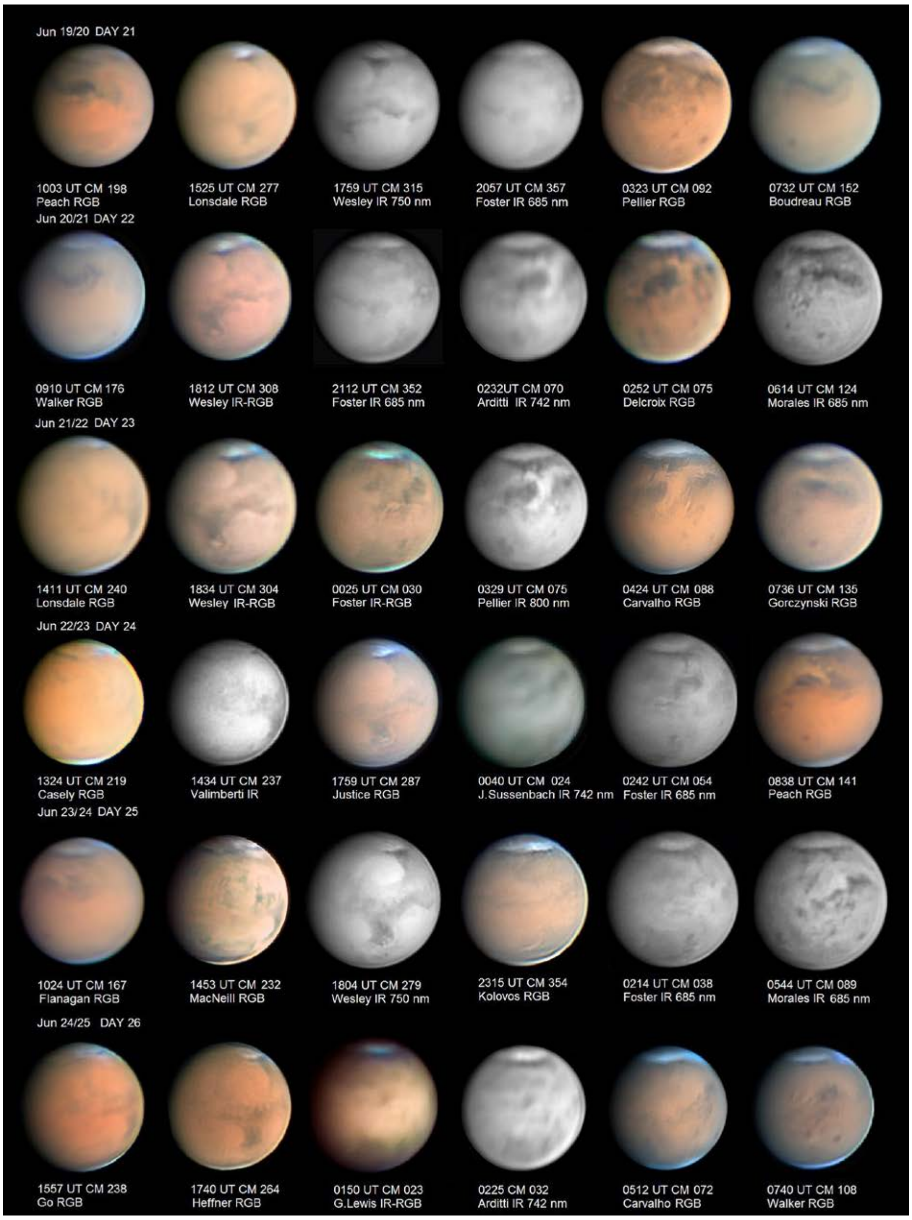

Figure 5. Further daily image collages of the global storm up till encirclement, Days 21–26.

Jun 15–16 / Day 17: The dust had not covered any more of *Mare Cimmerium*. The Director was still not convinced that the storm would become encircling, due to the lack of an active secondary core and its slow spread in longitude.

Jun 16–17 / Day 18: As Day 17, but there was a new dust core present at the NW corner of *Syrtis Major*, over Antoniadi crater.

Jun 17–18 / Day 19: Dust cut across *Cimmerium* in the N–S direction, and the *Daedalia* core had flared up again, increasing the chance of there being a planet-encircling event.

Jun 18–19 / Day 20: Dust bisected *Cimmerium* from north to south. The *Daedalia* core had again quietened, but a core SE of *Phoenicus Lacus* was newly active. Encirclement now seemed inevitable.

Jun 19–20 / Day 21: A small new core appeared in S. *Thaumasia*, while the remaining W. part of *Mare Cimmerium* was disappearing. *Mare Sirenum* remained partly and faintly visible, but was distorted by dust.

Jun 20–21 / Day 22: The core north of *Syrtis* was brighter. The *Daedalia* and *Thaumasia* cores had merged and now exhibited great activity by having formed a huge Y-shaped dust cloud whose vertical stroke largely hid *Solis Lacus* and whose N. limit was at *Tithonius Lacus*. There was an anomalous broadening and darkening of *Nectar*, which now mimicked the invisible *Solis Lacus*. On its SW branch, the storm continued west across the S. deserts adjacent to the SPC, towards the dust that had reached *Ausonia* from the west.

Jun 21–22 / Day 23: The Y-shaped dust cloud was very active, the W. branch of the 'Y' having propagated further west over *Phaethontis*.

Jun 22–23 / Day 24: The *Phaethontis* dust front turned NW to cut across *Mare Sirenum*, and the N. branch of the 'Y' sloped more in a N*p*. to S*f*. direction. Around this time it was possible to recognise certain features a little better again, suggesting some temporary local thinning of the dust. However, the process of encirclement was nearly complete.

Jun 23–24 / Day 25: An anomalous surface darkening along the N*f*. edge of the 'Y' cloud was conspicuous. The dust travelling west over *Phaethontis* appeared to meet the dust that had reached *Electris* from the west. The planet was encircled.

The loss of Opportunity

On Jun 10, with its solar batteries depleted by loss of sunlight to critically low levels, the *Opportunity* rover was shut down in the hope of reviving it later. Such attempts did not succeed. On 2019 Feb 13 its mission was officially declared to be complete. With a design lifetime of 90 days, *Opportunity* had operated for nearly 15 years.[25,26]

The volcanoes during the storm

The *Tharsis Montes* and *Olympus Mons* had begun to show up as much more obvious darker patches from Jun 15, darkening and broadening further through late June and into mid-July. These effects are seen during every such storm, and the volcanoes looked distinctly reddish during its existence. It is clear the volcanoes have a lower albedo than the lofted dust, which their summits are often above, and that their slopes must be further darkened through dust removal by winds associated with the storm. The volcanoes were much less obvious as large, dark albedo features by the start of the last week of July, as dust started to settle.

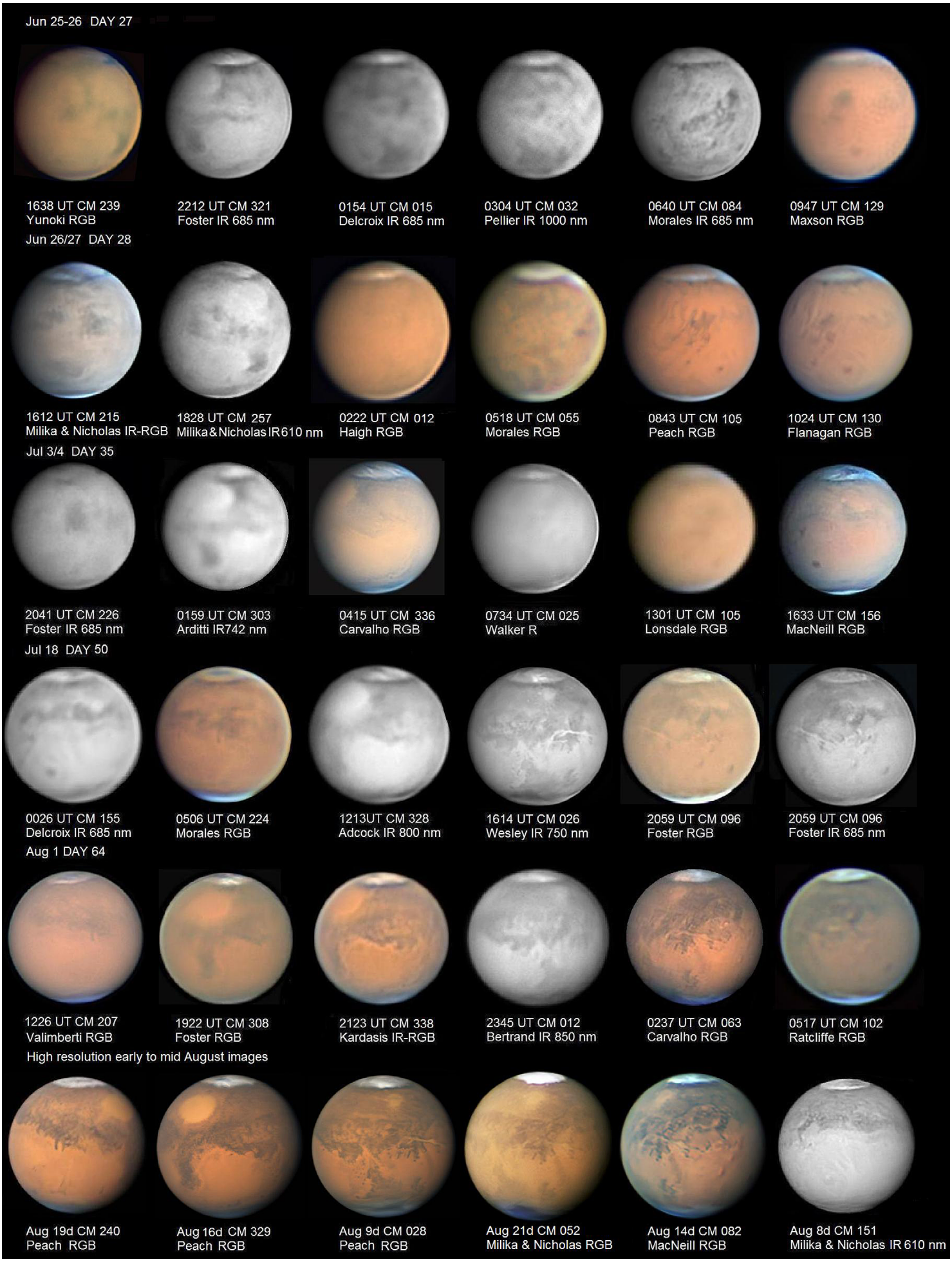

Figure 6. Further daily image collages of the global storm and its decline, Days 27–64. The lower row shows the planet at or just after the end of the storm.

The mature storm (Day 26 onwards)

After encirclement, the storm became more static, with the exception of specific bright clouds to be mentioned later. Eventually, large areas of bright yellow fallout became apparent, while there were many albedo feature changes. We include excerpts from selected observations below.

The MRO weekly bulletin for Jun 25 to Jul 1 noted that although 'active dust-lifting was not occurring everywhere across the planet, regional lifting centres in *Solis–Sinai*, *Hellas*, and *Elysium* continued to sustain a planet-encircling dust cloud of varying optical thickness'.[9]

On Jun 26, Milika & Nicholas showed very clearly the course of a belt of dust over the SPC (Figure 6). The cap was slowly returning to normal.

On the morning of Jun 27, during the Director's visual inspection from *Syrtis Major* to *Aurorae Sinus* (Part II, Figure 13A), the SPC was off-white and less bright than usual, but exhibited a definite N. edge in the best moments. One part was whiter. All albedo markings were relatively faint, with nothing above intensity 3.5 on the usual scale of 0 (bright white) to 10 (black sky). *Sinus Sabaeus* took a slightly anomalous course to *Iapigia* and the still faint *Syrtis Major*, while *Meridiani Sinus* was clearer. Part of the dust-affected *Margaritifer Sinus* showed up, and towards the morning limb was the brighter and slightly more intensely yellow dust-filled *Valles Marineris*. The limb was wide, yellowish and diffuse. There were signs of *Hellespontus*, darkest at the SPC N. edge, and several other dusky patches at the SPC edge or nearby. Dust irregularly covered *Mare Erythraeum* and *Argyre*, with a mottled patchwork of details over the southern disc.

On Jun 28, Peach's image showed a streaky, incomplete outline of the base of *Olympus Mons*, and the *Tharsis Montes* appeared as large dark smudges amidst a sea of yellow suspended dust. Albedo anomalies could now be seen in numerous areas, *Solis Lacus* remained hidden, and *Mare Sirenum* looked to be cut in two by dust fallout, but a new dark feature was visible between it and *Solis Lacus*, like the '*Sirenum* extension' at the close of the 2007 global storm. On Jul 8, the Director made a detailed visual inspection from *Mare Cimmerium* through *Syrtis Major* (Part II, Figure 13B). Contrast was still very low, and he was surprised by the amount of fine detail to be made out. The longitudes of *Cimmerium* and *Tyrrhenum* had large interruptions to their usual outlines. *Hellas* (bright, but clearly no longer actively dust-raising) was easily spotted, with *Hellespontus* quite prominent. Recent images had showed the N. end of *Syrtis Maj*or faintly, with a broad enlargement upon the W. side where there had been a specific dust cloud.

As of Jul 14, there were few brighter regions remaining, and it might be assumed from their lack of movement that they represented areas of settled dust. One such area was the *Valles Marineris*, and another was *Hellas*, with other brighter areas existing south of *Mare Sirenum*. Some fallout remained upon the SPC. Images showed that *Sinus Meridiani* had reappeared, albeit weakly. The Director on Jul 15 (Part II, Figure 13C) could see the still-dark *Olympus Mons* and several albedo anomalies from *Claritas* through *Mare Tyrrhenum*. The maximum feature intensity was then about 4.5. The MRO bulletin for Jul 9–15 noted that local-scale dust-lifting was still occurring, but the following one, for Jul 16–22, remarked that the storm had transitioned to the decay phase.[9]

The decay phase

As of Jul 25, the global storm was definitely decaying, and yet there were several very small bursts of dust north of *Solis Lacus*, witnessed by more than a dozen observers and demanding an e-mail alert. Figure 8 shows some of the extraordinarily high-resolution images secured. On Jul 24/25 (Part II, Figure 13D), nothing was seen. On Jul 25/26, there was an obvious local storm centred at –19°, 089° – independently recognised by the Director (Part II, Figure 13E) – which was smaller the next day, and invisible on Jul 27/28. On Jul 28/29, there was a resurgence at precisely the Jul 25/26 location, with an additional tiny plume to the SW. Apparently coalescing next day, the nuclei then separated and faded till disappearing after Aug 1/2.

As of early August, *Solis Lacus* still looked odd, with the new dark marking at *Phasis*. *Mare Cimmerium*'s gaps due to dust fallout were returning to normal. The *Tharsis Montes* and *Olympus Mons* were somewhat less dark. *Hellas* was bright and featureless, with a diffuse halo of dust visible outside the basin's canonical limits. *Hellespontus* looked very wide, invading E. *Noachis*: a typical large-storm scenario. The NW corner of *Syrtis Major* was still protruding (a highly unusual phenomenon), while the region of *Margaritifer Sinus*, which was at the longitude most thickly veiled by dust at the height of the storm, showed a number of albedo anomalies (see later). Bright yellow fallout along *Valles Marineris* remained visible. The limb brightening seemed to be weakly returning to normal.

After monitoring Mars visually for the three consecutive nights, the Director on Aug 3 noticed a further increase in contrast, though the limb brightening still seemed not as well-defined as normal. Observations on Aug 6–7 showed the N. part of *Mare Hadriacum*, outlining the NE side of *Hellas*. The N. part of *Solis Lacus* was returning to visibility, but its centre was still hidden by fallout. The MRO bulletin for Aug 6–12 remarked that across the northern highlands, 'some crater rims, dune fields, and wind streaks faintly came into view'.

The final clearing of the storm is described in more detail separately.

Dust over the S. polar cap, Jun 9 onwards

By late May, there were already a number of seasonally bright, small circular areas, appearing near the edge of the SPC. These are taken to be regions which are subliming faster. The southern part of the cap was seasonally dull, due to the retreating (but less bright) polar hood. (Dust-fountaining,[27] though not witnessed in 2018, can also selectively darken and colour a smaller area of the SPC.)

Dust from the global storm moving south reached the N. edge of the cap near longitude 70° on Jun 9, but during the rest of the month, incursions over the cap seem to have been mainly over that half of the SPC from longitude 180 through 0°. Obscuration of the cap edge commenced around longitude 200°, with a heavy dimming of the edge extending to the S. limb, continuing around the periphery to *ca*. 280°, followed by a brighter part corresponding to the general area of a feature which was subliming faster and would become an outlier: *Novus Mons*. This was followed by a weak obscuration of the edge around 320°, a clear zone, then a strong obscuration extending well to the south around 340°, and again clear from 350° onwards. In Figure 6 for Jun 26/27, Day 28, a wide belt of dust is seen especially clearly upon the CM = 215° image. Next month, there was a strong incursion at about CM = 104° as witnessed by Morita and others around Jul 10, but by then a general clearing and brightening of the cap was under way.

This dust settled in patches upon the cap, often surrounding and enhancing pre-existing seasonal light areas, while also seeming to accentuate seasonal dark rifts such as *Rima Australis* that were then appearing. Such fallout was still visible, though already dispersing, in August. For a time there existed a banding pattern of dusty deposits parallel to the direction of *Rima Australis*, which Kumamori's images of Jul 25 showed clearly.

In Part II, we shall see that when the dust covered part of the SPC, the cap recession was temporarily accelerated (due to increased atmospheric warming). The enhanced sublimation rate must have caused a higher atmospheric water-vapour concentration at the edge of the cap, and logically this would have partly condensed as a discrete morning cloud at the following limb. The acceleration of the SPC recession was most significant during *Ls* ~ 191 to 205°, or ~ Jun 10 to July 5; visible acceleration of the sublimation and consequent northward migration of water vapour would inevitably have been a few days in advance. There seems then to be a direct link between the acceleration of the recession by the dust, and the presence of the high-latitude morning white cloud.

In most images taken at the height of the storm (more strongly through blue and ultraviolet (UV) filters), a characteristic, thin, bluish-white, non-rotating limb cloud was seen to project several degrees north of the SPC N. edge. During the global storm of 2001 this had appeared from Days 11–52 of the global storm. In 2018, the effect lasted for a similar time, from Days 17–50 (Jun 15 to Jul 18), and as in 2001 it was most strongly marked in the middle of that period, being independent of CM longitude.

The high-altitude dust over the cap gave rise to a large number of terminator projections, which are discussed next.

Terminator projections at peak dust-lifting, Jun 24 – Jul 9

On Jun 25, J. Shirley (NASA, JPL) e-mailed that spacecraft thermal infrared data were showing higher temperatures 'due to dust lifting to 80km or higher over *Tharsis* in the last couple of days'. Sánchez-Lavega *et al*. (2019) also stated that dust rose to 70km.[24] Terminator projections have been seen during all global events. A number of actual terminator projections appeared in the ground-based data during Jun 24 – Jul 9. (The phase defect was still considerable on the last dates.) Examples are illustrated in Figure 9A.

The following were the main terminator projections, which unless otherwise stated occurred at the latitude of the SPC, and when it was obviously discoloured by dust: Jun 24, Foster (under CM = 038°); Jun 25, Foster (CM = 321°; see Figure 9A); Jun 26, Foster (CM = 045°); Jun 26, Rueck (CM = 086°; Figure 9A); Jun 27, Haigh (CM = 010–021°); Jun 28, Wesley (CM = 220–232°); Jun 30, Milika & Nicholas and Heffner (CM = 183–208°; Figure 9A); Jun 30, Iwamasa (CM = 184°), SPC and south of *Arsia Mons*; Jul 1, Buda and Valimberti (CM = 136–154°), SPC and in several locations to the north; Jul 1, Akutsu, Heffner and Iwamasa (CM = 169–201°); Jul 5, Wesley (CM = 150°); Jul 6, Wesley (CM = 162–166°); and Jul 9, Rueck (CM = 330°).

Thus the most active dust-raising phase – in terms of the height to which dust was lofted – followed encirclement and lasted from Jun 24 to Jul 9. The most populated CM longitudes were 136–208°, and if we subtract 90°, we find that the high terminator clouds occurred most often over surface longitudes ~046–118°, while on Jun 28 Wesley made a direct measurement of *ca*. –67°, 133°. Using the formulae and procedure published in the Appendix to Part I of the 2012 BAA report,[2] the elevation of the Jun 26 projection seen by Rueck (Figure 9A) was measured by the Director at 78±8km.

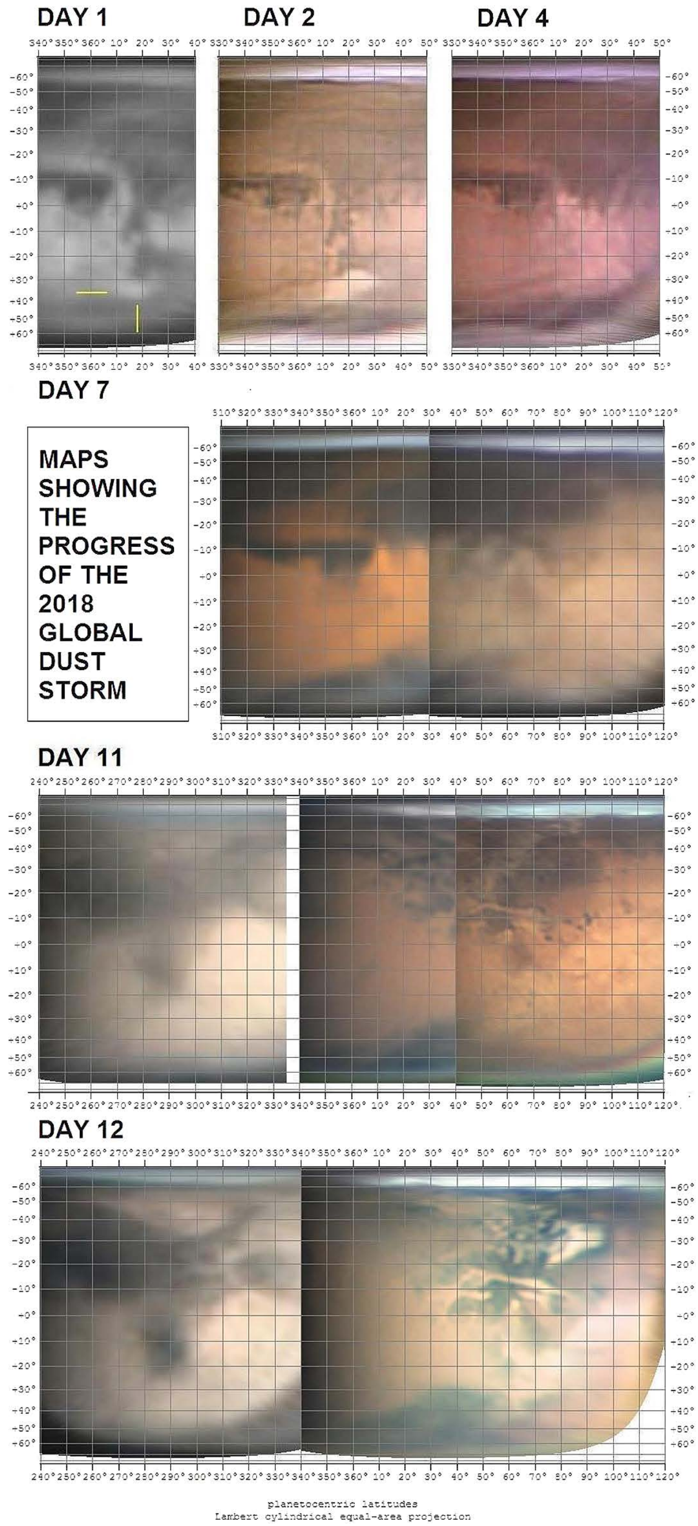

Figure 7. Map projections produced using *WinJUPOS* to show the growth of the 2018 global storm for selected days, nearly till encirclement. Images used mostly from Figures 3–5. *Above:* **(A)** Days 1–12. *Opposite page:* **(B)** Days 18–23.

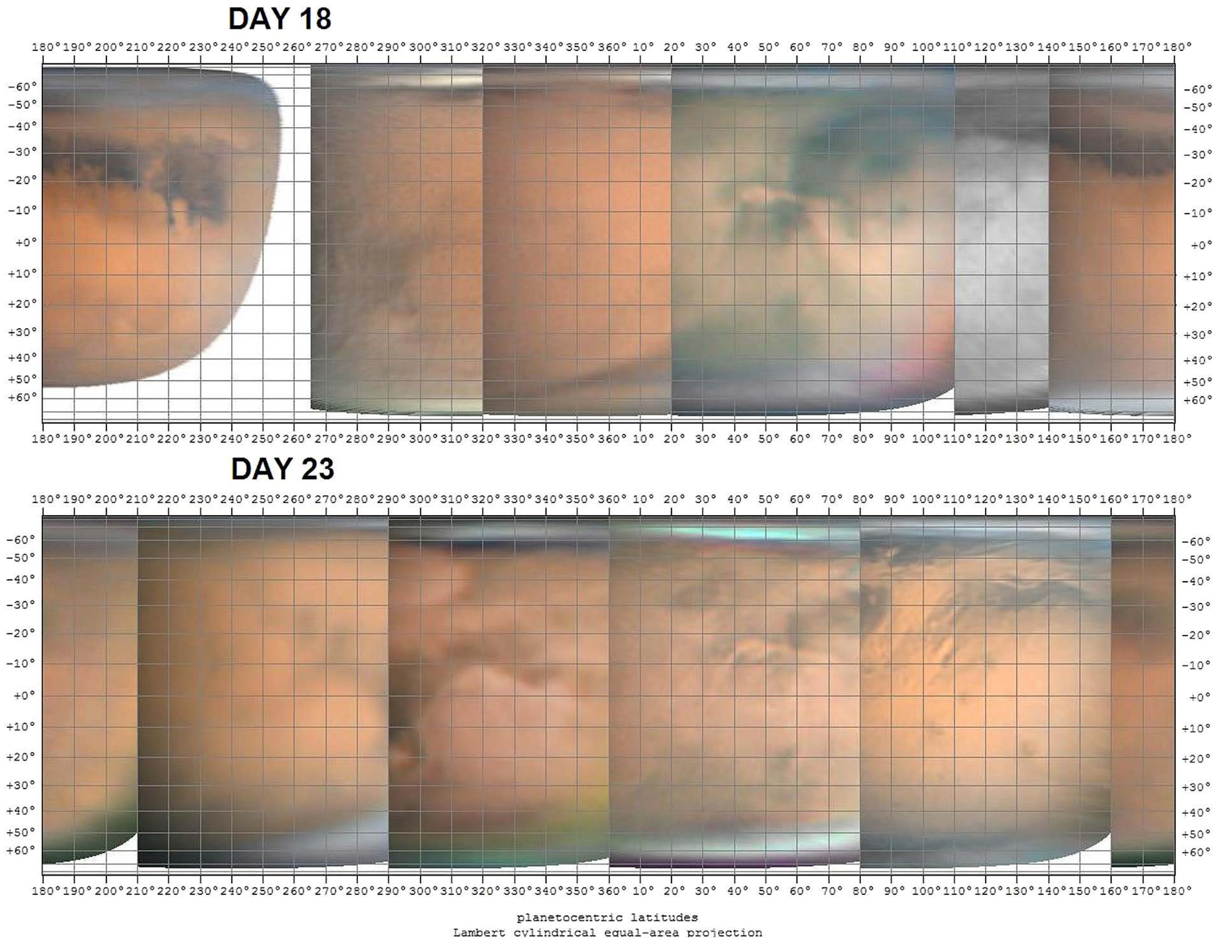

Figure 7. (B) *See opposite page for caption.*

Bright N–S elongated dust clouds, Jun 10 – Jul 12

Many images taken during Jun 10 – Jul 12 showed an apparent ‘wrinkled’ effect of the cloud-tops, with thin bright dust clouds elongated roughly in the north–south direction. Peach’s Jun 28 image (Figure 9B) provides a fine example. At first sight the presence of thin, darker *p*. edges to these bright clouds (*i.e.*, towards the evening terminator) suggest a simple shadowing effect, but the dark features did not change perspective with rotation. Moreover, they could be seen over much of the southern hemisphere and looked just the same during the following days on the morning side of the disc, at much lower CM longitude. They therefore represent underlying terrain darkened by local dust removal: the dust clouds so generated had moved off towards the west. The effect did not show up upon the blue images; just in RGB, red, green and IR, showing the bright streaks to have been dust clouds.

Here we list the most obvious phenomena: Jun 16, Kumamori (both hemispheres, under CM = 315–323°); Jun 24, Kumamori (southern hemisphere only, CM = 256–263°); Jun 27 & 28, Flanagan (CM = 120–130°); Jun 28, Peach (CM = 107°; see Figure 9B); Jul 1, Akutsu and Buda (CM = 154–179°); Jul 3, Flanagan (CM = 071°); Jul 3, Iwamasa and MacNeill (CM = 130–152°); Jul 4, MacNeill (CM = 156°); Jul 6, Kumamori and Wesley (very strong in the southern hemisphere at *Solis Lacus – Claritas*, CM = 155–166°); and Jul 12, Kumamori (strong in both hemispheres, CM = 079–086°).

The affected longitudes did not extend all round the planet. The most frequently affected CM longitudes were 071–179°.

The N. polar hood during the storm

The positive value of D_e had allowed an exceptional view of the NPH during the 2001 global storm.[28] In 2018, the tilt was less favourable – latitude +75° marking the northern limb – but the NPH was easily followed throughout.

The NPH was barely visible along the N. limb at the start of the storm in late May of 2018. Rather than declining at the onset of the storm, it behaved as it had in 2001, and increased steadily in visibility, widening and brightening throughout June, and becoming equal to the SPC in brightness around Jun 18, prior to the event reaching the encircling stage. By then the hood tended to reach down to lower latitude on the morning side, as it did in 2001. It continued to brighten and widen into July, reaching a peak just after mid-month. When the SPC was partially veiled and dimmed by dust, the NPH appeared significantly brighter than the cap. Quickly fading during the last week of July, it remained thin and faint for months. (It would increase again in size late in the year in a normal, seasonal, response.) The increased visibility of the NPH from mid-June to late July was only very slightly longer in timescale to that of the small morning limb cloud at the N. edge of the SPC mentioned earlier, and this pattern fits in with the 2001 observations except that the hood was more active then. (In 2001

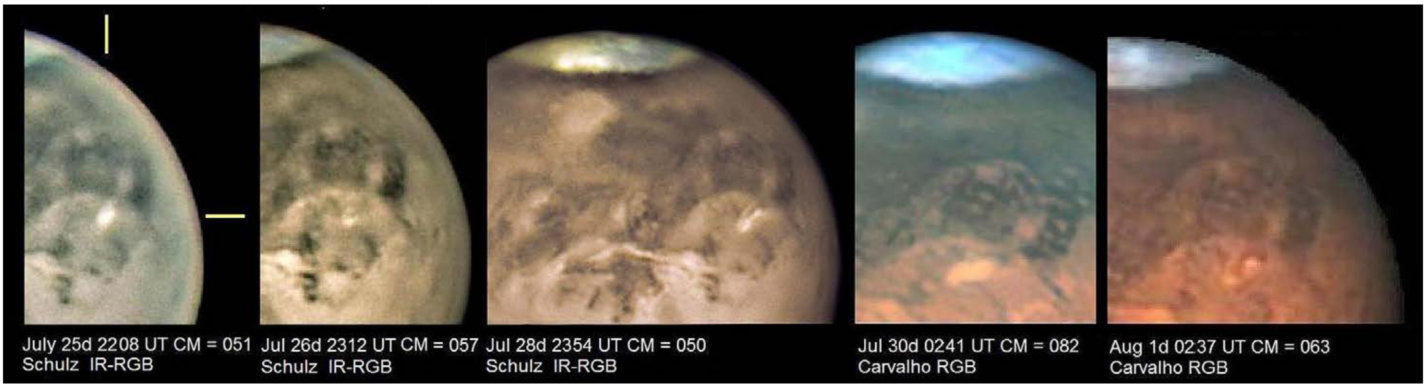

Figure 8. Specific dust outbreak north of *Solis Lacus*, 2018 Jul 29 – Aug 1, according to contrast-enhanced IR–RGB images by R. Schulz (500mm Cass., ASI 290MM camera, 6–12min derotations) and RGB images by F. & G. Carvalho. Note also the outlines of some dust-fallout-filled craters on the E. (*p.*) side of *Argyre* on Jul 28.

the hood had increased in prominence from Jul 2 till ~ Aug 7, and often showed bright spots and protrusions to the south.)

The observed latitude of the NPH on Days 18 and 23 (Figure 7B), measured near the CM, ranged from *ca*. +50 to 60°. Dust did not travel further north than +60° in either 2001 or 2018, and this is consistent with the hood having shown hardly any brightening in the red or IR.

In 2001 a temporary dark belt at the S. edge of the enhanced NPH became rather intense during the global storm, appearing bluish-black at some times. The best 2018 images showed the effect clearly, and the darkness and colour were intense enough to draw surprised comments from some observers. Especially around mid-August, whenever a dark marking adjoined the bluish-white NPH, it often looked dark and bluish; see the bottom row of Figure 6. The effect was most obvious around N. *Mare Acidalium*, and the strongest examples the author found were observed by Morales, Aug 4, and by Akutsu and Milika & Nicholas, Aug 21. We assume the darkening was due to jetstream winds at the edge of the hood.[28]

Dust fallout in Hellas, Valles Marineris & Argyre

The bottom row of Figure 6 shows characteristic immediate post-storm views, with generally lower contrast and typical fallout in *Hellas*, *Argyre*, *Valles Marineris*, *etc*. The high-resolution images of Figure 10 (2018 August–September) show fallout in *Marineris* being gradually dispersed: it is possible to identify many topographic features from the NASA map included. In comparison with amateur images from 2001 and 2007, those of 2018 reveal far more. (The 2001 storm occurred prior to developments in image processing, while the 2007 event fell too long before opposition.)

The clearing of the storm may be followed by the revelation of more and more ground details, at least in the near-IR images. High resolution enabled some novel details to be seen. An image by Foster on Jun 22 – during a momentary relapse in the storm – shows dust-filled craters E. of *Argyre*. There were many more such images from late July onwards, when the storm was abating (*i.e.*, Figure 6, Jul 18, Aug 1 and bottom row; and Figure 8, Jul 28), and the craters Galle, Helmholtz, Lohse and Wirtz were nicely resolved as light patches. They were still visible, but less contrasty, in September.

On Sep 25 the Director found the *Argyre* fallout significantly less bright than in August, showing it was dispersing, while on Oct 29, Milika & Nicholas commented that it had been reduced to a well-defined yellow patch; only the W. part remained.

Velocity measurements

For the following calculations, spherical trigonometry has been used.

(A) Daily velocities in the expansion phase

From maps (Figures 7A & B) and individual images, a number of velocities can be measured. Several observers made animations over periods from hours to weeks, which helped in the interpretation of the event.

From Day 1 to Day 2, the storm's 'centre of gravity' moved from *ca*. +36°, 018° to +33°, 021° at 9km h^{-1} to the SW, its area expanding by over 200%. At the same time, the nascent storm's W. end moved from *ca*. +30°, 028° to +30°, 031° at 6km h^{-1} to the SW, while the E. end essentially remained static.

From Day 2 to Day 4 the expansion was faster: the NW corner of the storm moved from *ca*. +32°, 031° to +30°, 040° at 20km h^{-1} to the WSW, while the NE corner moved from *ca*. +41°, 010° to +34°, 010°, at 18km h^{-1} due north. The storm's area grew at an even faster rate than between Days 1 and 2. A complex pattern of dust cores to the south had also developed by Day 4.

From Day 4 to Day 7, when the edges of dust clouds were becoming harder to measure, the NW limit of the storm had reached *ca*. +23°, 075°, corresponding to an average velocity of 24km h^{-1} towards the SW over three days. Thus, the expansion was continuing at a fast (or even faster) pace. On Day 7, dust was moving more slowly east at the northern edge of the storm, having reached *ca*. +38°, 350°, corresponding to a velocity of 12km h^{-1} towards the ENE over three days. Between Days 4 and 7, the fresh dust cores at *Aram* and S. *Chryse* had expanded even more slowly southward, with a mean velocity around 5km h^{-1} being deduced for three cores between longitudes 10 and 40°.

From Day 7 to Day 11, the edge of the storm to the east was not precisely shown upon the available images, though it had covered *Meridiani Sinus* and W. *Sinus Sabaeus*. However, two striking changes can be measured, namely the expansion along *Valles Marineris* as far as *Melas Lacus*, and the expansion up to the SPC boundary. On Day 7, dust was about to enter *Valles Marineris* at *ca*. –15°, 059°, and four days later it arrived at –10°, 073° to the west: a westward velocity of 12km h^{-1}. On Day 7, an already southward propagating front near –16°, 056° had apparently travelled SW across *Bosporos* to reach the cap edge near –60°, 089°, yielding a much higher velocity of 40km h^{-1}. It is possible that the latter dust stream was fed from a secondary source that apparently developed independently on Day 8, at *Argyre*. It is likely that the dust core at *Aram* on Day 7 was responsible for the main progress of the storm to the SE, and that the dust seen near +38°, 350° on Day 7 had moved north to around latitude +54°, perhaps as far north as it reached, as well as spreading eastward. On the western side, dust does not appear to have penetrated north of latitude 50° by Day 11 (or indeed later). The presence of more and more small-scale dust cores greatly complicates the analysis from around this time onwards.

From Day 11 to Day 12, the striking appearance of a bright core at W. *Solis Lacus* dominated the picture, while no less importantly, a finger of dust travelling across *Deucalionis Regio* reached *Iapigia*. If we (reasonably) assume that the latter had simply propagated from the *Aram* core after Day 7, the motion was from *ca*. –12°, 010° to –20°, 297° in five days, corresponding to a velocity of 35km h^{-1}. A complex finger of dust had been moving west along *Nectar* on Day 10, and the following day there was a large, new bright core west of *Solis Lacus*. The western limit of the dust on Day 11 was at *ca*. –31°, 078°, and on Day 12 the new bright core was centred at *ca*. –30°, 087°: velocities of 24, 44, 41 & 33km h^{-1} for expansion to the S, SW, WNW and NE respectively over the course of one day were deduced.

From Day 12 to 16, dust at *Iapigia* travelled north to hide the southern part of *Syrtis Major*. A movement from *ca*. –20°, 297° to 0°, 288° over four days yields a velocity of 13km h^{-1}. After this time, precise measurements could not easily be made except when specific new bright cores appeared.

(B) Estimates of the velocity of encirclement

For the period up to encirclement, the general expansion in longitude in the southern hemisphere can be approximated.

For the eastward (SE) expansion near the equator, dust reached E. *Iapigia* on Day 12, implying a mean velocity of *ca*. 19km h^{-1}. According to Jun 8 images by Peach, high-latitude dust at the N. edge of the SPC had just reached SW *Hellas* on Day 10, at *ca*. –50°, 307°, requiring a higher mean velocity of *ca*. 26km h^{-1}. (Other investigators claimed dust had already crossed SE *Hellas*, which is contradicted by near-IR images.[24]) In the westward (SW) direction, dust reached the W. side of *Solis Lacus* on Day 12, giving a mean velocity of *ca*. 18km h^{-1}.

With fewer landmarks, the general expansion in the northern hemisphere is harder to judge. Dust had just reached the E. side of *Elysium* according to a Peach image of Jun 15, and since May 30, over 17 days the dust front must have travelled due east at a mean velocity of around 16km h^{-1}. The *Tharsis Montes* and *Olympus Mons* seemed considerably darkened on Foster's image of Jun 15, compared with the previous day, showing that the dust front had reached that general area. A rough estimate of dust movement to the west (WSW) to *Olympus Mons* (+18°, 133°) over 17 days gives a velocity of 14km h^{-1}.

Both the northern and southern hemispheres thus showed faster expansion to the east rather than to the west.

(C) Local velocities during the mature storm phase

Movements of dust during the mature storm were less obvious, but the following definite results were obtained.

MacNeill fortunately obtained remarkable high-resolution images and videos on Jul 9 (Figure 11) as dust was moving rapidly east along *Valles Marineris*. Here, strong topographic variations may lead to enhanced velocities. In 133 minutes, the eastern front travelled due east near the equator at a velocity measured by the observer at 118km h^{-1} (33m s^{-1}). In this interval, other nearby dust clouds showed northeasterly or even circular motions.

For the local activity north of *Solis Lacus* during Jul 25 – Aug 2 (Figure 8), daily velocities were very small, from 0 to 5km h^{-1}, mostly to the north and east.

Indicators for the return to normal

Brightness & polarisation data

Limited brightness and polarisation data were acquired and discussed by Schmude (2020).[4] He found a dust-induced brightening that reached 0.25 magnitudes on Jul 10, at the height of the storm.

Disc & naked-eye colour

During the storm, a change in the planet's naked-eye colour became apparent. The Director found it still obviously yellowish on Jun 27 and Jul 8. With Mars near the zenith from Australia on Jul 18, Milika & Nicholas described it as a pale golden-yellow ('like 9-carat gold'). It was yellowish-orange to the Director on Jul 19, orange – virtually normal – on Jul 24 & 31, and indistinguishable from its normal colour on Aug 2, 9, *etc*. A 'glitter trail' photograph by D. Strange on Aug 5 (Figure 22A, Part II) shows the colour close to usual. These data support a return to normal in August.

Telescopic notes upon the coloration of the desert areas also help. Already on Jul 31, Valimberti wrote: 'To my eyes the dust seems to have settled a bit more and Mars seems to be showing more of its traditional 'salmon' colour'. And on Aug 4, MacNeill considered that his image showed the transition 'from a yellow-coloured dusty Mars to the more familiar brick red terrain'; on Aug 16 he felt that the transition to reddish was complete. By Aug 29, Giuntoli found the deserts 'light orange'.

White cloud activity

White cloud activity (see Part II) was seasonally normal up till early June. The planet's limb was bright and white. It became tinted yellow – and its brightness was markedly reduced – in early June. White clouds, other than those constituting the N. polar hood, were not observed from June to mid-August, except near the NPH. From early August, there were records of a rather dull morning cloud over *Mare Acidalium* and *Tempe*. In the second half of August, an E–W elongated cloud appeared in the longitude of *Arcadia–Tempe*, just off the S. edge of the NPH.

Parts of the limb or terminator looked white to Adachi and Adamoli from Aug 14–15. Adamoli saw a small white limb cloud on Aug 20. Maksymowicz had found the limb still ochre on Aug 13, but on Aug 22 he showed some local brightenings that appeared brighter in blue light. In common with other visual observers, the Director found the limb brightening wide, pale and yellowish throughout the storm. He observed a slow return to normal, as these notes show:

Aug 17: Limb brightening on *p*. side off-white and still diffuse. [The final suggestion of yellowness; it was still less sharp or bright than normal.]

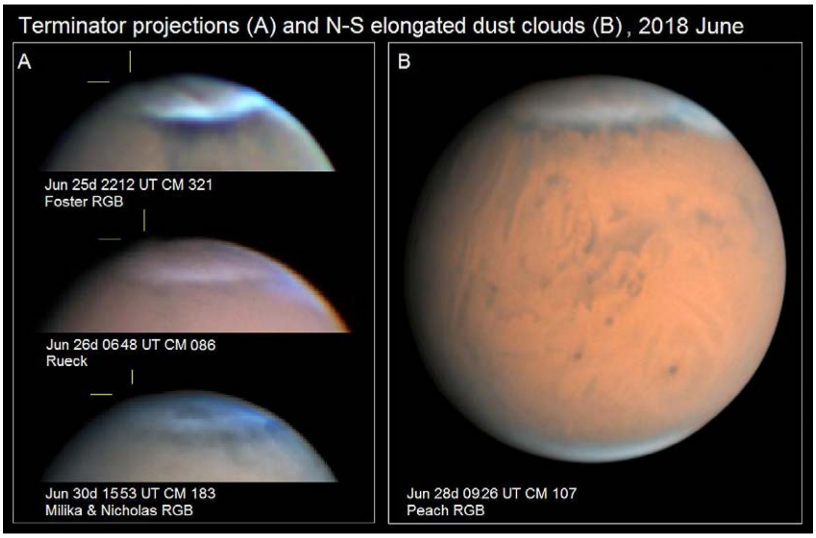

Figure 9. The effects of dust-lifting, 2018 June. **(A)** Terminator projections over the evening terminator (indicated), due to high-altitude dust clouds above the SPC. **(B)** Bright N–S elongated dust clouds, with darker terrain on their eastern (*p.*) borders, demonstrating a common drift to the west.

Aug 21, 22: Limb brightening more normal, with a brightness enhancement (due to diurnal cloud) at *Ophir–Candor*.

Aug 26: Limb brightening more normal.

Aug 27: Several evening white clouds, *etc*.

On Aug 26, Adachi found a light patch of a.m. cloud on the S*f*. side, and on Aug 28 he found *Syrtis Major* slightly bluish, an effect of thin evening cloud.

Many observers stopped taking blue images during the storm, and those that did mostly obtained broadband blue rather than the more useful blue-violet (or UV) images. Thus surprisingly few are really useful for analysis, but Akutsu on Aug 21 first recorded a specific bright cloud in the UV at the SW terminator, under CM = 044°. This date is the same as the Director's first sighting of specific evening cloud not associated with the NPH. (Less obvious UV equatorial terminator brightenings were recorded by Akutsu on Aug 14, Bertrand on Aug 15 and Pellier on Aug 10–21.) Significantly, the MRO bulletins first mention the return of patchy water-ice clouds above *Arsia Mons* in the week ending Aug 19.[9]

Spacecraft observations

For historical continuity we prefer to draw our conclusions independently, but we quote from the MRO weather reports for Aug 6–12:[9] 'Across the northern highlands, some crater rims, dune fields, and wind streaks faintly came into view', and Aug 13–19: 'Patchy diffuse water-ice clouds were observed above *Arsia Mons*, the southernmost volcano of the *Tharsis Montes*; a sign of cooling afternoon atmospheric temperatures in the area'. This return of the orographic clouds is close to our timings.

Summary

The crude evidence of naked-eye colour, coupled with the more subtle telescopic desert coloration, suggests mid-August for the ending of obscuration. The return to a more normal appearance and limb colour in mid-August is in perfect accord. An east–west strip of white cloud just south of the NPH was seen from early August. A still better indicator is the return of morning or evening equatorial white cloud, and here the telescopic evidence suggests Aug 20 or 21 (with confirmation *via* imaging on Aug 21). Pertinent polarisation data would have greatly helped but were not available. Looking at these indicators, together with the visual and electronic evidence of returning contrast, also points to mid-August. As the return of diurnal cloud is the most sensitive indicator (and the one we prefer), a duration of *ca*. 84 days may be inferred, if we adopt Aug 21 as the date of termination.

Albedo features following the global storm

Figure 12 is a post-storm map derived from Peach's Chilescope images. Numerous albedo variations on account of the event, mentioned in an interim report,[13] can be traced by comparison with Figure 1 (or from the 2016 map).[1]

Region I: long. 250–010°

From the very start of the clearing process, *Syrtis Major* was observed to have become extended on the NW side (Figure 2M and

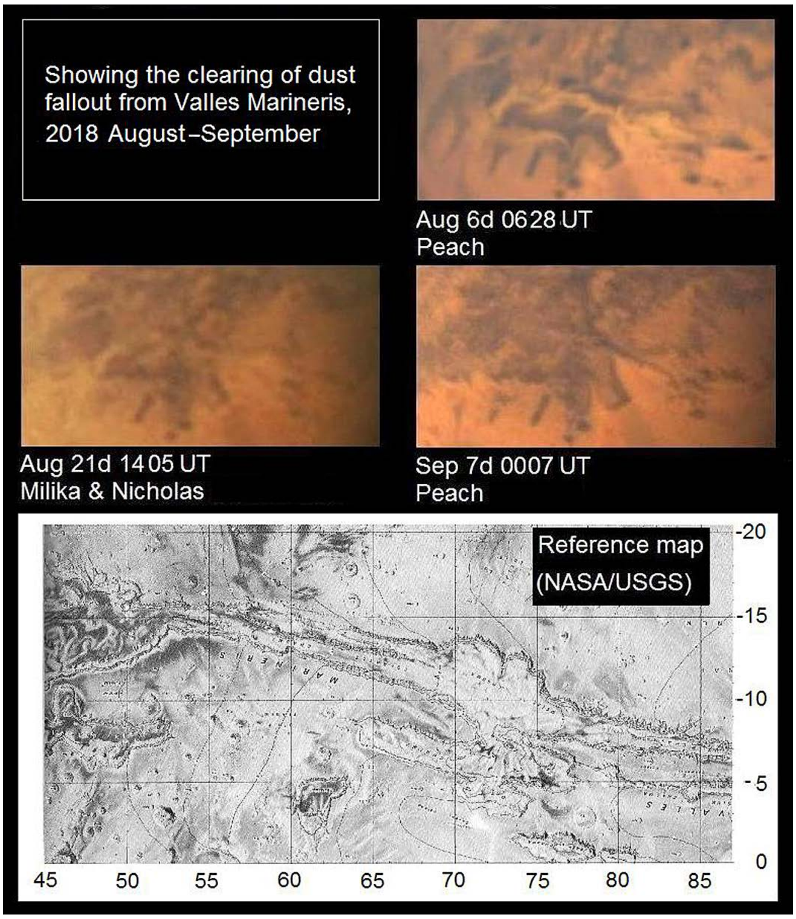

Figure 10. High-resolution images by D. A. Peach (1m RCT) and D. Milika & P. Nicholas, to show the clearing of dust fallout from the floor of *Valles Marineris* in 2018 August–September, compared with a NASA / US Geological Survey shaded relief map (from Batson R. M., Bridges P. M. & Inge J. L., *Atlas of Mars*, NASA, 1979). The height contour interval is 1km.

Figure 6 (bottom row)). At one point a bright yellow dust cloud had originated at this very location on Day 18, centred upon Antoniadi crater. The extension slowly faded by solar conjunction.

A very large area of bright yellow fallout occurred in *Hellas*, enlarging its canonical boundaries, particularly to the east and NE (Figures 2J, 6 (bottom row)). The brightness and extent of the fallout gradually faded, with the basin starting to show floor details such as *Zea Lacus* by November.

Mare Serpentis darkened, with a broadening of *Hellespontus* which darkened the E. part of *Noachis* (Figures 2L, 6 (bottom row)). The area had returned to its pre-global-storm state by the end of the following solar conjunction.

Pandorae Fretum was also darkened, appearing broad and dark by December (Figures 2L, 6 (bottom row)). The Regional storm of 2019 January (to be discussed later) caused further temporary albedo changes within *Pandorae Fretum – Noachis*. The area had returned to its pre-global-storm state by the end of the following solar conjunction.

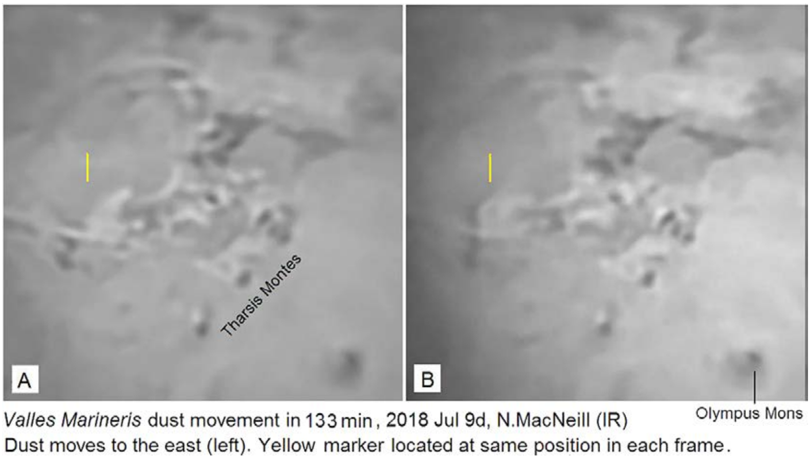

Figure 11. The rapid eastward motion of dust along *Valles Marineris*, 2018 Jul 9, 14:45–16:58 UT. Two frames taken from the start and finish of a movie by N. MacNeill (355mm SCT, ASI 174MM, IR filter).

Region II: long. 010–130°

Bright yellow fallout accumulated in the *Argyre* basin (Figure 6 (bottom row)). As mentioned already, *Argyre* exhibited a number of bright, dust-filled craters around its rim, according to the highest-resolution images (Figures 6 (bottom row) & 8 (Jul 28)). There was a strong reappearance of *Phasis* (Figures 2K, O & 6 (bottom row)) between an enlarged and darkened *Gallinaria Silva*, and a deformed *Aonius Sinus*. On this occasion *Phasis* was rather broad and dark, persisting till solar conjunction and beyond. It was still present in 2021.

The dark patches at the S. borders of *Chryse–Xanthe* (namely *Orestes* and *Electra*) had a slightly different appearance after the storm, these alterations persisting into the following apparition. Southern *Margaritifer Sinus* was considerably faded, but this part was returning to normal in August. NE *Margaritifer Sinus* was effaced by fallout, with its NW part still extended slightly into the *Hydaspes* streak and the halftone connection to *Oxia Palus* missing. These circumstances gave the area a peculiar and unprecedented appearance, with *Oxia* isolated. The weak halftone *Hydaspes* reached a long way north.

An anomalous dark extension to the SE corner of *Mare Acidalium* at *Niliacus Lacus* appeared suddenly during the event, adjacent to the initiation site (Figures 2L, 6 (bottom row)). The feature strongly connected SE *Niliacus Lacus* to the NW of the now isolated *Oxia Palus*, at the exact location of the thin, pre-existing *Indus* 'canal' which was now unrecognisable: *Indus* became broader and more extensive than ever, and subsequently the change has turned out to be unprecedented in longevity. It was still obvious in 2021 May, altered somewhat by further dust activity during the 2020 opposition.

In 2003 there had been a temporary example of the intensification of *Indus* witnessed by spacecraft, resulting from a storm moving south from the N. polar region. The author recently noticed that a drawing by J. B. Murray from Pic du Midi, dated 1974 May 11 and made in the wake of the 1973 global storm, shows a similar SE extension of *Acidalium–Niliacus*, similar to what developed in 2018.[29]

The N. and central parts of *Solis Lacus* were irregularly effaced by fallout, but the area slowly returned to normal by solar conjunction (after further dust activity in that area: see Part II). The floor of *Valles Marineris* was for some months brightened by dust fallout, as already described (Figures 6 (bottom row), 8 & 10).

Region III: long. 130–250°

The central part of *Mare Sirenum* was initially cut and faded by fallout, but it recovered as the storm cleared. Its NW end was darkened compared to the pre-storm appearance (Figures 2N & 6 (bottom row)) which had been anomalous since 1986; it now is closer to its classical form.

The *Aetheria* darkening was much faded by dust deposition (Figure 6 (bottom row)), as were some other northern markings that had already faded due to long-term changes. It also became narrower. The long-lived patch of fallout NW of *Elysium* was no longer visible.

During the storm, central *Mare Cimmerium* looked peculiar, having been bisected by dust in a N–S direction at one stage, but this appearance vanished as soon as the event cleared. Moreover, around longitude 230°, there had arisen a very odd-looking hooked dark feature which temporarily extended to the south.

The large size of the dark patch of *Olympus Mons* is very noticeable upon Figure 12.

General discussion

The planet-encircling storm of 1973 encircled Mars after only nine days, but the 2018 event progressed leisurely, taking 25 days. Though long-enduring, the 2018 global storm hardly lasted as long as the preceding two:

Start date	*MY*	*Ls (deg.)*	*Location*	*Time for encirc. (days)*	*Duration (days)**	*Ref.*
2001 Jun 26	25	185	Hellas	15	159	[28]
2007 Jun 23	28	263	Noachis	15	107	[30]
2018 May 30	34	184	SE Niliacus Lacus/ Mare Acidalium	25	84	This paper

* Durations were judged from telescopic data by the author using consistent criteria and are quoted for the S. hemisphere.

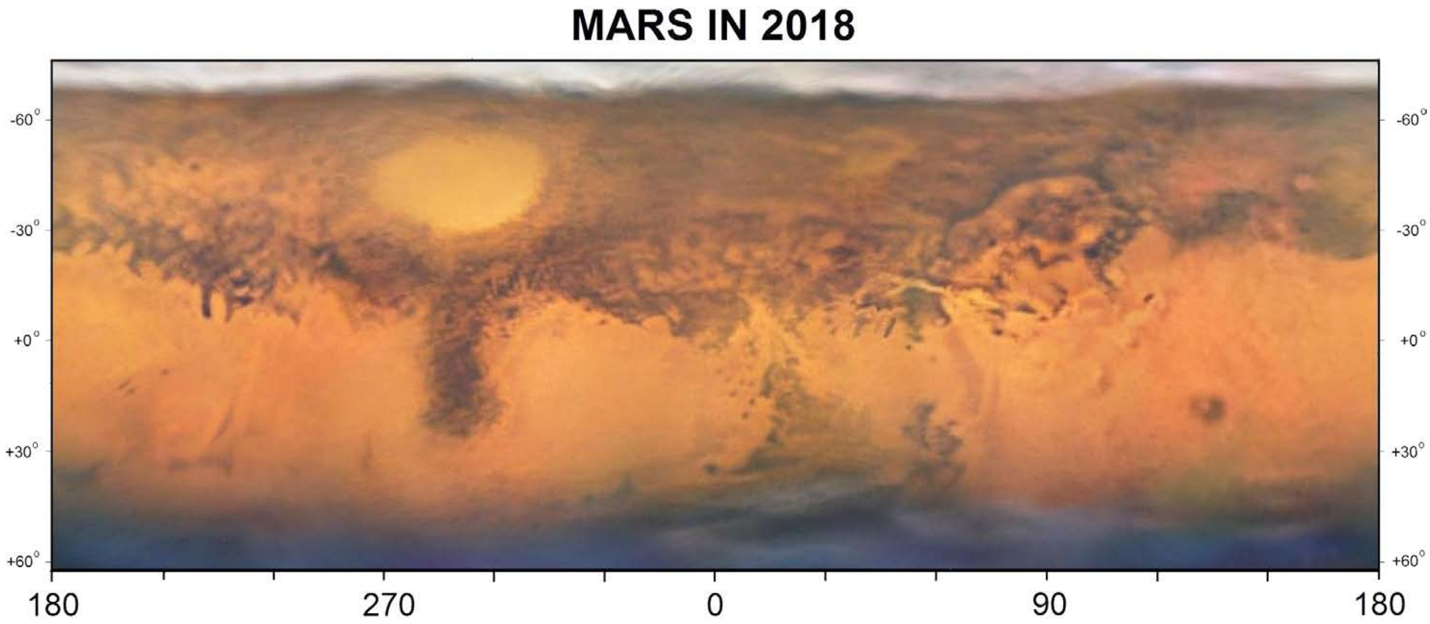

Figure 12. Whole planet map, made by S. Voltmer from 2018 early August to late September, from Chilescope images by D. A. Peach (1m RCT, ASI 174MM).

The 2018 global event, seasonally one of the earliest ever observed, was also the first-ever known to have begun in the northern hemisphere. According to the changing visibility of classic albedo patterns, the net accumulation of dust in the northern hemisphere has been continuing for decades.[31] Continuing accumulation of dust there is also suggested by two 2016 September events that began in unusual or unique locations:[1] at the E. end of *Niliacus Lacus* and in SW *Arcadia* or *Diacria*. The former was close to the location of the 2018 global storm's commencement. Another point is that during the apparition there were two other events that arose in much the same longitudes, both to be described in Part II. First, in 2018 March a local storm affected S. *Chryse*, *Valles Marineris* and *Margaritifer Sinus*. Second, a large regional event commenced in 2019 January over S. *Chryse* / E. *Valles Marineris*, and ultimately stretched from *Hellas* to *Claritas*. This longitude band would be active several times again in the following apparition.

The 2018 storm had finally become encircling only because of a major secondary source emerging on Day 22 over *Solis Lacus* and environs. This frequently active source longitude often seemed to coincide with the brightest and densest part of the storm, as noted in the earlier discussion of terminator projections. Although *Hellas* was also filled with dust, it did not seem so active as in some former global events: rather, it seemed more impressive when full of fallout after the storm.

That the northern hemisphere would produce more storms as a result of net dust accumulation over decades was inevitable: what could not have been anticipated was the fact that any northern storm could become encircling. At the other extreme, we know that the systematic removal of dust from a much-frequented initiation site causes it to become inactive for decades,[32] and *Hellas* has seemed less active in recent apparitions.

Other recent dust storm research

In addition to discussing the 2018 storm, a recent paper by Shirley, McKim *et al*. (2020), makes predictions of global dust storms on dynamical grounds based upon the first and second derivatives of the overall solar-system angular momentum ω with respect to Mars:[23] $d\omega/dt$ and $d^2\omega/dt^2$. Heavens *et al.* (2018) have described a mechanism whereby global dust storms can significantly enhance the loss rate of hydrogen from the Martian atmosphere, a factor in the planet's massive atmospheric losses over a geological timescale.[34] Studies of albedo changes using MRO data (in MY 28–33) have been published by Wellington & Bell (2020).[35]

Battalio & Wang (2020) have discussed and categorised dust storm trajectories for MY 24–32 from a large new statistical database.[36] The latter authors have specifically discussed the MY 24–31 *Aonia–Solis–Valles* storms.[37] Finally, Hernández-Bernal *et al.* (2019) have discussed the 2018 global storm's interaction with the S. polar region, confirming our finding that the cap was never completely covered.[38] Velocities up to 100m s^{-1} and altitudes of 10–70km were recorded.

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Martin Lewis and Dr Mark Lonsdale greatly helped with the image processing and mapping needed for making the illustrations of the global dust storm in Figures 3–7. The author also thanks Dr Gary Rosenbaum and Dr Jim Shirley for papers from the professional literature.

Address: 16 Upper Main Street, Upper Benefield, Peterborough PE8 5AN *[richardmckim@btinternet.com]*

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