The opposition of Mars, 2016: Part I

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

The opposition of 2016 May 22, during Martian Year 33, was the last in a series of aphelic approaches. There had been no obvious albedo changes since the previous opposition. The light yellow area of dust fallout on the NW side of *Elysium* showed an obvious opposition brightening, and there was also a brightening of the outer rim of *Olympus Mons*. Three of the various dust storms commenced in unusual or unique locations: in particular, a Regional one in SW *Arcadia*, and two around *Mare Sirenum*. A darkening and broadening of *Mare Serpentis* and a reappearance of *Pandorae Fretum* resulted from a Regional storm in September. There was no planet-encircling event, but just beyond the recognised seasonal limit for this phenomenon, two Regional events began in the north and expanded in the south; these occurred unusually close together in time. Part II will discuss meteorological aspects and the behaviour of the polar regions.

Introduction

This report discusses observations from 2015 Aug 29 to 2017 May 16, obtained during Martian Year (MY) 33,[1] and continues from the previous opposition.[2]

At opposition in Sagittarius on 2016 May 22, Mars reached areocentric longitude (*Ls*) 156°: late northern summer. At just over 90° in *Ls* before perihelion (*Ls* = 250°), this was the last aphelic one in the series. Figure 1 compares recently observed *Ls* limits. When it reached opposition at declination –21° 40′, Mars lay further south than in 2014, but presented a larger disc (diameter 18.4″). Closest approach (18.6″) occurred on May 30.

The planet's diameter was 6″ or greater from 2016 Jan 13 till Dec 20. The latitude of the centre of the disc (D_e) equalled +10.5° at opposition. In late August of 2015 it reached +19°, rising to +25° by mid-October, steadily falling to +6° in 2016 April before rising again till early July (+15°), and falling to 0° on Sep 24 before reaching –26° in 2017 mid-January, finally declining to –3° by mid-May. For key dates, see Table 1.

The first image was submitted by Paul Maxson for 2015 Aug 29 at *Ls* = 034°, and the last by Ryuichi Iwamasa on 2017 May 4, with a final drawing by Gianluigi Adamoli on May 16 at *Ls* = 006°, representing 92% of a 360° span in *Ls*.

The Director received 5,571 observations (5,009 images and 562 drawings) from 98 observers (Table 2). The distribution by month (days observed/possible) was: 2015 Aug 1/31, Sep 14/30, Oct 13/31, Nov 21/30, Dec 25/31, 2016 Jan 25/31, Feb 24/29, Mar 28/31, Apr 29/30, May 31/31, Jun 30/30, Jul 31/31, Aug 31/31, Sep 30/30, Oct 30/31, Nov 27/30, Dec 29/31, 2017 Jan 29/31, Feb 20/28, Mar 19/31, Apr 8/30, May 2/31.

Excellent support came from lower and southern latitudes, but even in the UK the seeing was sometimes unexpectedly good. The author was able to make 106 drawings.

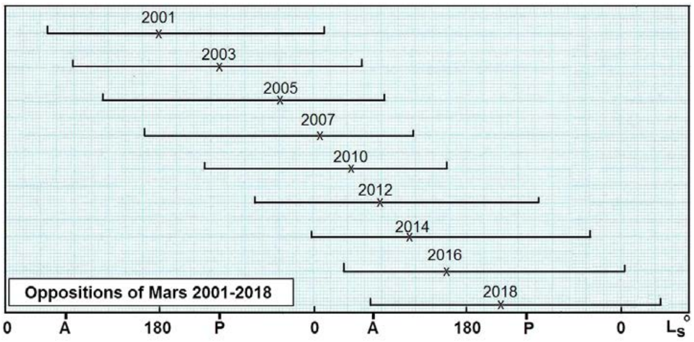

Figure 1. Diagram showing the observed *Ls* limits of recent oppositions. Aphelion (A) and perihelion (P) are marked.

Table 1. Physical details of the 2016 apparition

	Ls (°)	*Date*
Solar conjunction	358	2015 Jun 14
N. spring equinox / S. autumn equinox (MY 33 commences)	0	2015 Jun 18
Aphelion	70	2015 Nov 18
N. summer solstice / S. winter solstice	90	2016 Jan 3
Opposition	156	2016 May 22
N. autumn equinox / S. spring equinox	180	2016 Jul 4
Perihelion	250	2016 Oct 27
N. winter solstice / S. summer solstice	270	2016 Nov 28
N. spring equinox / S. autumn equinox (MY 34 commences)	0	2017 May 5
Solar conjunction	39	2017 Jul 27

UK weather deteriorated badly in June, and the altitude became challenging during 2016 August to October, with Mars at declination 23–25°S. Mike Hezzlewood made an impressive painted globe from his visual studies. Damian Peach's exceptional images were secured during two Barbados trips. Jean Dijon travelled to Namibia; Makoto Adachi obtained visual data on 134 dates, Clyde Foster made 227 image sets, and Paul Maxson secured 232.

The seasonally most comparable oppositions in our records are 1905 (*Ls* = 144° at opposition),[3] 1922 (175°),[4] 1937 (154°),[5] 1952 (136°),[6] 1969 (166°),[7] 1984 (146°),[8] and 2001 (177°).[9] The Section website offers a collection of current and past reports and observations,[10] while three interim reports were published in the *Journal*.[11–13] Other online image galleries are available.[14–18]

NASA's *Mars Odyssey* (arrival 2001) and *Mars Reconnaissance Orbiter* (MRO, arrival 2006) remained active, as did ESA's *Mars Express* (2003). NASA rovers *Opportunity* (2004) and *Curiosity* (2012) were still at work. Since the last opposition came NASA's *Mars Atmosphere and Volatile EvolutioN* (MAVEN) spacecraft (2014),[19] and India's *Mars Orbiter Mission* (MOM) spacecraft *Mangalyaan* (2014). Alas, the

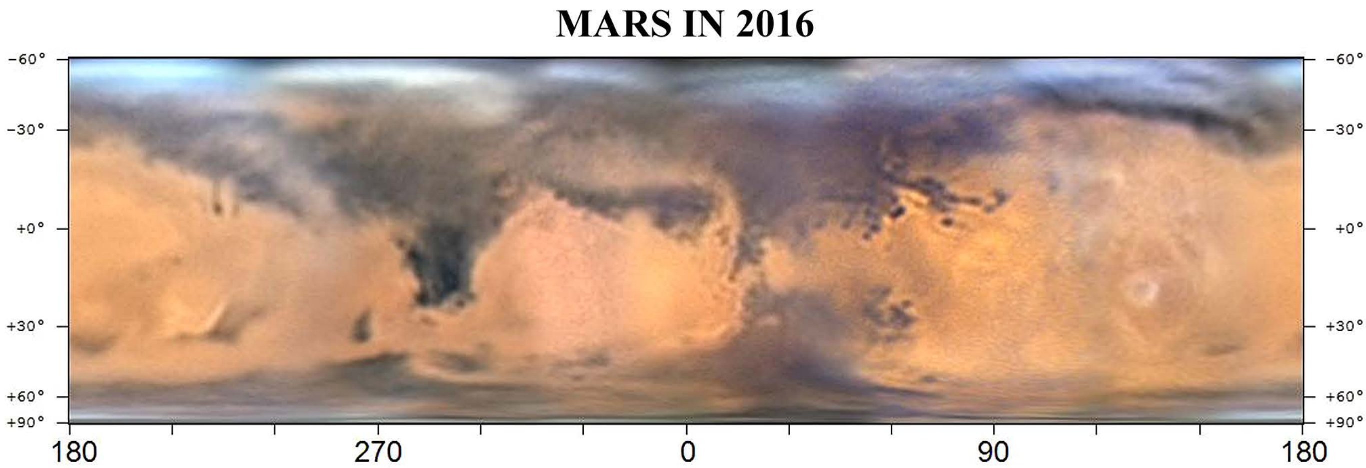

Figure 2. Apparition map on a cylindrical projection, from images taken with an ASI 224MC camera during 2016 May 13 – Jun 10. *Note*: Here and in the other telescopic figures, south is uppermost. *T. Kumamori*

ESA/Roscosmos *Schiaparelli* mission to Mars crashed at *Meridiani Planum* on 2016 Oct 19, when the craft jettisoned its heat shield and parachute too soon, turning off its braking rockets at 2–4km altitude. MRO spotted the wreckage.[20] *Schiaparelli* was part of the *ExoMars* programme, of which the *Trace Gas Orbiter* was fortunately working normally during the period of this report. From its final 400km near-polar orbit, it is seeking evidence of possible Martian life *via* methane emissions (until 2022).[21] Elsewhere,[11] we reported that 'recurring slope lineae' are no longer regarded as an indication of subsurface water.[13] The original announcement had made international headlines.[22]

As ever, our analyses are independent of spacecraft images, though we sometimes use them to confirm transient phenomena. We use telescopic nomenclature.[23]

Surface features

General

The familiar albedo markings were mapped by Kumamori (Figure 2). (See also Figures 3–4 as well as the sequences of images

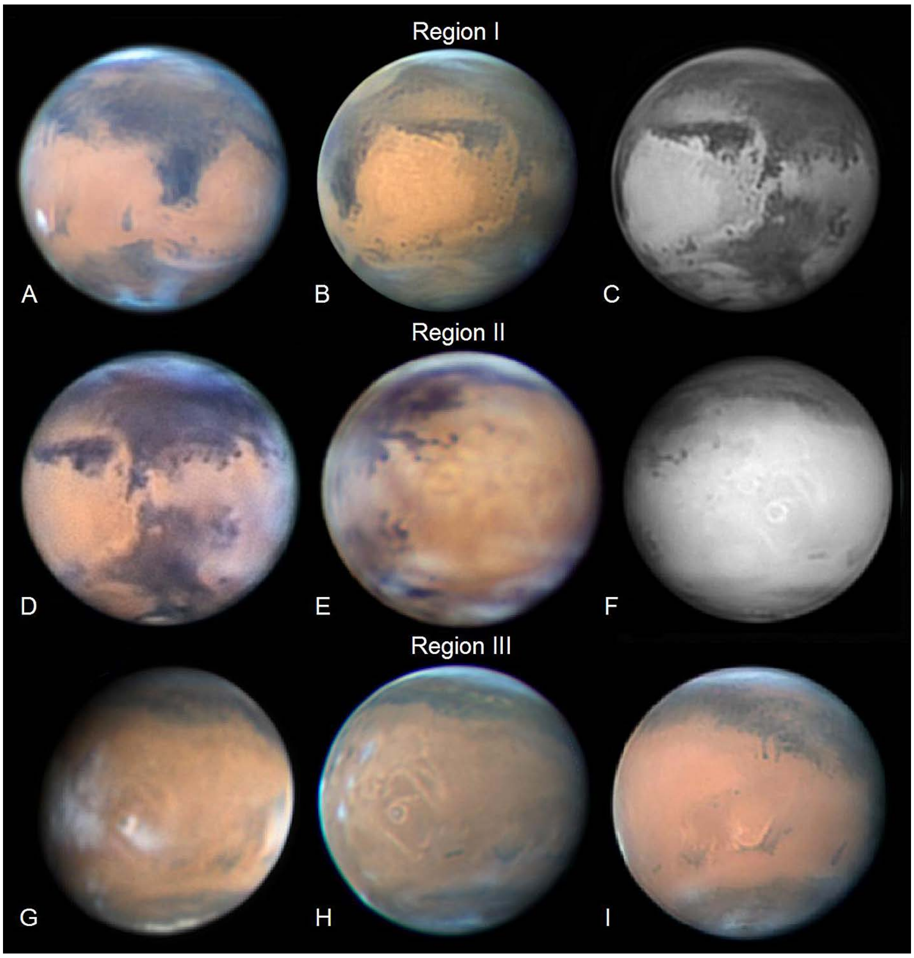

Figure 3. Images of Regions I (A–C), II (D–F) and III (G–I).

(A) 2016 Jun 2, 13:29 UT, CM = 278°, ASI 290MM camera. *(Milika & Nicholas.) Elysium Mons* orographic; discrete N. polar clouds.

(B) 2016 Jun 18, 03:08 UT, CM = 344°, ASI 120MM-S. *Pandorae Fretum* not visible; crater chain N. of *Meridiani Sinus* resolved in (B)–(D). *(Peach)*

(C) 2016 Jun 3, 20:10 UT, CM = 007°, monochrome ASI 174MM. *Juventae Fons* visible in (C)–(F). *(Dijon)*

(D) 2016 May 23, 14:58 UT, CM = 028°, ASI 178MM and ASI224MC. *(Kumamori)*

(E) 2016 Jun 5, 02:47 UT, CM = 095°, Flea 3. *Solis Lacus* is complex; *Tithonius Lacus* shows fine details in (F)–(H); *Gallinaria Silva* is a very small spot *f. Solis Lacus* in (E)–(F); *Tanais* is anomalously dark. *(Morales)*

(F) 2016 May 10, 13:46 UT, CM = 125°, Blackfly PGE-31S4M-C, ≥685nm filter. Outer caldera of *Olympus Mons* shows opposition brightening; NPC outlier *Ierne* resolved into icy fragments. *(Wesley)*

(G) 2016 Mar 18, 06:51 UT, CM = 148°, ASI 120MM-S. Afternoon orographic clouds forming over *Olympus Mons* and the *Tharsis Montes*, with *Olympus* trailing a banner cloud; NPC outlier *Olympia*; compare with (H). *(Peach)*

(H) 2016 Jun 18, 15:12 UT, CM = 161°, Blackfly ICX692. *Tharsis Montes* show much smaller orographics than in March; *Olympus Mons* still shows a marginal opposition brightening around its periphery. (This image is partly enlarged in Figure 6.) *(Olivetti)*

(I) 2016 Jun 8, 12:57 UT, CM = 218°, Blackfly PGE-31S4M-C. *Trivium Charontis–Cerberus* consists of two miniscule dark spots; *Aetheria* development is divided by a lighter streak; *Elysium Mons* is a tiny light patch. *(Wesley)* by Foster, and drawings by the Director, in Part II Figures 13 & 17.) The late southern hemisphere Regional storm in 2015 March, at the end of the last opposition,[2] had no lasting effect on albedo features: these appeared identical to how they did in 2014.

Many observers attained impressive resolution, previously matched only by the perihelic opposition of 2003. An excellent test area is the chain of small craters northwest of *Meridiani Sinus*. These appear as tiny dark dots in the appropriate images (Figures 2–3), though their brighter edges are the result of image processing.

Region I: long. 250–010°

As in 2014, images revealed much fine detail within *Syrtis Major*. The behaviour of the *Hellas* basin is described in Part II: the seasonal clearance of frost was well observed. *Mare Serpentis* was initially not prominent, but it exhibited its typical broadening and darkening following the southern Regional dust storm in 2016 September. *Pandorae Fretum*, initially invisible, was also observed to have darkened into a broad belt during that month: see Figure 9.

Region II: long. 010–130°

The 2014 and 2016 images show *Hydaspis* was well marked, and from SE *Niliacus Lacus* there was a short southward projection. From NW *Oxia Palus* there was a narrow dark extension. These small progressive changes, traceable since 2005, have become obvious. (The area would suffer striking changes in 2018.)

Solis Lacus remained large and broad in the N–S direction, but with its longer axis running east–west. It showed intricate interior details and there remained a lighter indentation upon the W. side. *Phasis* was not seen; *Gallinaria Silva* was a barely visible spot. *Ganges* was always a rather obvious halftone band.

On Jun 5, Peach captured the frosted *Lowell* crater at the south polar cap (SPC) boundary, south of *Solis Lacus* (Part II, Figure 14), while to the east of *Argyre*, the frosted floor of *Galle* crater was caught in images by Valimberti and Wesley on Apr 17.

Region III: long. 130–250°

Cerberus–Trivium Charontis bordering *Elysium* remained nearly invisible, in contrast to the conspicuous presence of the 1970s-epoch albedo feature at the NW corner of *Elysium*: the *Aetheria* darkening. The latter continued to appear faded in the centre, so that it looked more like a double ‘canal’ running NNE to SSW. One dust storm (see later) began east of *Elysium* (Figure 10), a location not previously observed to be an emergence site for such storms. showing that dust accumulation in the northern hemisphere has not been limited to the faded boundaries of *Elysium*.

Two features showed an opposition brightening. First, *Olympus Mons* (latitude +14 to 23°) appeared as a whitened ring near local noon during Apr 27 ~ Jun 18, an effect which was strongest around opposition. (Compare Figures 3F (May 10; strong effect) & 3H (Jun 18; weak effect), and Part II, Figure 17 (May 22; strong effect).) From mid-afternoon the volcano’s slopes were covered by bright orographic cloud, but at noon it was cloud-free, so the

Table 2. Observers of Mars, 2016

Name	*Location*	*Instrument(s)*
P. G. Abel **V**	Leicester	203mm refl.
	Leicester University Obsy.	508mm DK Cass.
	Griffith Obsy., Los Angeles, CA, USA	305mm OG
M. Adachi **V**	Otsu, Japan	310mm refl.
	Dynic Observatory, Shiga, Japan	200mm OG & 300mm refl.
	Kwasan Obsy., Kyoto, Japan	450mm OG
G. Adamoli	Verona, Italy	235mm SCT
B. Adcock	Victoria, Australia	245mm OG
L. Aerts	Heist-op-den Berg, Belgium	300mm Cass.
T. Akutsu	Tochigi, Japan	355mm SCT
	Utsunomiya University, Japan	400mm Cass.
	Cebu, Philippines	355mm SCT
J. Albert **V**	Lake Worth, FL, USA	279mm SCT
M. Araújo	Évora, Portugal	279mm SCT
K. N. L. Bailey	Swindon, Wilts.	279mm SCT
T. Barry	Broken Hill, Australia	406mm refl.
N. D. Biver **V**	Versailles, France	407mm refl.
S. Buda	Melbourne, Australia	405mm DK Cass.
F. & G. Carvalho	Ribeirão Preto, Brazil	406mm refl.
E. Chappel	Cibolo, TX, USA	203mm SCT
A. Clitherow	Fife, Scotland	254mm refl.
E. Colombo **V**	Gambarana, Italy	150mm refl.
E. Crandall **V**	Lewisville, NC, USA	254mm refl.
J-L. Dauvergne, E. Kraaikamp, J. P. Cazard & F. Colas	Pic du Midi Obsy., France	1.06m Cass.
M. Delcroix	Pic du Midi Obsy., France	1.06m Cass.
	Tournefeuille, France	320mm refl.
J. Dijon	Namibia, Africa	400mm RCT
C. Dole	Newbury, Berks.	180mm MKT
C. Ebdon	Fordham, Essex	178mm MKT
P. Edwards	Horsham, W. Sussex	355mm SCT
H. Einaga	Kasai, Hyōgo, Japan	300mm refl.
W. D. Flanagan	Houston, TX, USA	355mm SCT
C. Foster	Centurion, Gauteng, South Africa	355mm SCT
S. Gale **V**	Landing, NJ, USA	310mm refl.
M. Giuntoli **V**	Montecatini Terme, Italy	102mm OG & 150mm refl.
C. Go	Cebu, Philippines	355mm SCT
D. L. Graham **V**	Barton, Richmond, N. Yorks.	120mm OG
D. Gray **V**	Kirk Merrington, Co. Durham	120mm OG & 415mm DK Cass.
N. J. Haigh	Southampton	305mm refl.
D. J. Hanson	Chandler, AZ, USA	350mm Cass.
A. W. Heath **V**	Long Eaton, Notts.,	203mm SCT
C. E. Hernandez **V**	Miami, FL, USA	229mm MKT
N. D. Hewitt	Northampton	115mm OG
M. Hezzlewood **V**	Burnley, Lancs.	100mm OG
R. Hill	Tucson, AZ, USA	203mm MKT
R. A. Hillebrecht	Bad Gandersheim, Germany	355mm SCT
M. Hood	Kathleen, GA, USA	200mm OG & 355 mm SCT
C. J. Hooker	Didcot, Oxon.	254mm refl.
K. C. Howlett	Cwmbran, Gwent	203mm & 235mm SCT
	Wroughton, Wilts.	
T. Ikemura	Nagoya, Japan	380mm refl.
R. Iwamasa	Yokohama, Japan	355mm SCT
W. Jaeschke	West Chester, PA, USA	355mm SCT
R. W. Johnson	Ewell, Epsom, Surrey	Digital camera
G. Johnstone	Coventry, Warwicks.	203mm SCT
G. Jolly	Gilbert, AZ, USA	355mm SCT
M. Justice	Melbourne, Australia	305mm refl.
M. Kardasis	Athens, Greece	355mm SCT
A. S. Kidd	Cottered, Herts.	355mm SCT
R. Konnai **V**	Fukushima, Japan	410mm SCT
D. Kolovos	Athens, Greece	279mm SCT
S. Kowollik	Ludwigsburg, Germany	150mm MKT

Table continuation and explanatory notes on p.231

white ring imaged even in the near-infrared must have been a surface effect. Superior images around mid-May showed a similar effect at *Ascraeus Mons* and *Pavonis Mons*.

A second feature showed a stronger opposition brightening, namely the yellowish (to some eyes, pinkish) region of dust fallout over the NW slopes of *Elysium Mons* (latitude +23 to 26°). This unusual light area has existed since 2012. It was quite different in appearance and tint to the white seasonal orographic cloud at *Elysium Mons*. The yellow fallout area did not change shape with time, and yet around opposition it became so strikingly bright (becoming the brightest disc feature in red light) that the Director thought a dust storm could have been starting: he issued an alert to Section members on May 26, followed by BAA *e-Bulletin* No. 918 (May 28).[24] See Figure 5. However, it was a false alarm, for the area slowly resumed its normal brightness. The bright yellow feature is well shown in an animation prepared by Mishina.[25] Although there was a suspicion of tiny day-to-day changes in form, an impression also gained from MRO images, the point is marginal. The greater mystery is how a surface with settled dust could have shown an opposition effect so strongly. Was the reflector upon the flank of the volcano a flat, mineral-laden surface, to which the settled dust merely imparted colour?

Dust storms

Introduction

Observations continued long enough to be able to rule out any planet-encircling storm during MY 33,[26] though several Regional events took place. See Figures 6–11. Two emergence sites were in historically rare or unique locations.

Local activity in the N. polar region, 2016 May

Foster on May 6–9 imaged a yellowish-white cloud (visible in white light and more weakly in the infrared) expanding daily N*p. Mare Acidalium*, with the dust thick enough even to hide the S. edge of the north polar cap (NPC) on May 9. Morales had also captured this cloud closer to the central meridian (CM) on May 5 & 6: his filter work shows that it was composed mostly of water ice but mixed with a considerable dust component. Its location was similar to that of the *Baltia* spiral polar clouds described in Part II.

Local activity at *Hellas*, 2016 May–June

Hellas showed weak, sporadic local dust activity during late May to early June: see Figure 6 (top panel). Valimberti's animations of May 27–30 and subsequent images by Foster and Kumamori show well the variable, light dust haze over the basin; a variable core to the NW; and some dust spilling over the E. and W. edges. On Jun 3, a small streak projected over the W. edge. On Jun 6 there was a slight core in NW *Hellas*, which next day had spilled out of the basin as a weak plume to the WNW, changing form slightly on Jun 8. Next day, the activity apparently finished. However, a reddish streak found in RGB images over several days from Jun 11 (and described under 'Violet holes' in Part II) marked part of the trajectory of the aforementioned dust.

On some dates there was also white cloud activity mixed with the dust streaking away from the W. edge of the basin, noted in the discussion of *Hellas* in Part II. *Hellas* became frost-free on Jun 7.

Airborne dust streaking out to the west over the mountains on the W. border of *Hellas* has been observed in the past, *e.g.*, at the start of the Encircling storm of 1924 December.

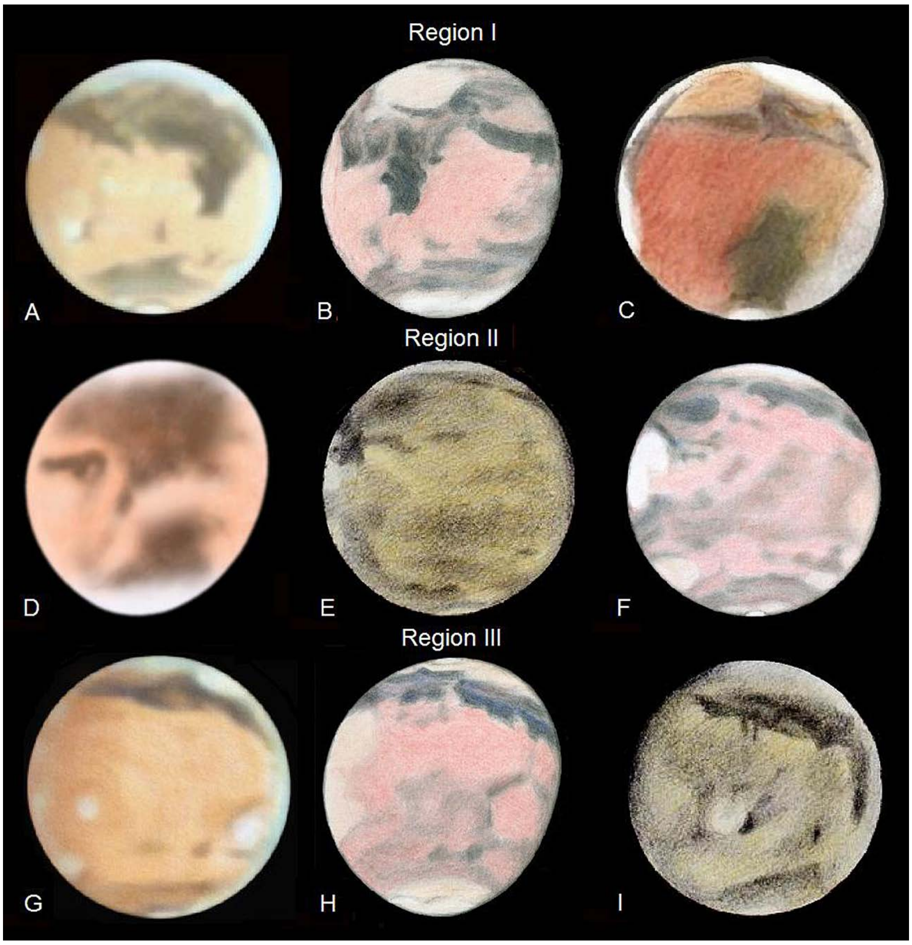

Figure 4. Drawings of Regions I (A–C), II (D–F) and III (G–I).

(A) 2016 May 15, 01:10 UT, CM = 256°, 415mm DK, ×270, 365. *Elysium Mons*; *Olympia*. *(Gray)*

(B) 2016 Jul 17, 19:30 UT, CM = 318°, 407mm refl., ×540, 700. *(Biver)*

(C) 2016 Apr 14, 22:02 UT, CM = 349°, 178mm MKT, ×236. *Pandorae Fretum* not yet visible. *(Ebdon)*

(D) 2016 Aug 30, 03:40 UT, CM = 029°, 305mm OG, ×208. NPH. *(Abel)*

(E) 2016 Jun 18, 11:30 UT, CM = 107°, 310mm refl., ×450, 600. *(Adachi)*

(F) 2016 May 27, 23:30 UT, CM =117°, 407mm refl., ×540. Fine details in *Tithonius Lacus*; *Gallinaria Silva*. *(Biver)*

(G) 2016 May 24, 00:20 UT, CM = 165°, 415mm DK, ×365. Orographics. *(Gray)*

(H) 2016 Jul 29, 19:00 UT, CM = 198°, 407mm refl., ×700. *(Biver)*

(I) 2016 May 1, 16:00 UT, CM = 238°, 310mm refl., ×400, 800. *(Adachi)*

Local storm at *Valles Marineris*, 2016 June

According to images by Morales and Peach a local storm arose on Jun 9 over southern *Margaritifer Sinus*, being absent the previous day. Development was slow, but Morales found mild expansion on Jun 13, which became more obvious to several observers on Jun 15: an e-mail alert was issued by the author on the next day. From Jun 14 a secondary core was also seen over *Valles Marineris*. This core, like the larger event discovered by E. C. Slipher on 1922 Jul 9,[27] had dispersed within a few days of Jun 18. The event was also recorded by Flanagan, Hanson, Hernandez, Jolly, Maxson, Melillo, Morales, Phillips and Walker. See Figure 6 (lower part).

Posted at the ALPO Japan website can be found an image by A. Soares, taken on Jun 14 (CM longitude = 335°), showing that the W. extremity of the storm's secondary core, south of *Aurorae Sinus*, was high enough to have projected slightly over the a.m. terminator.

Table 2. Observers of Mars, 2016 (Cont'd from p.229)

Name	*Location*	*Instrument(s)*
T. Kumamori	Osaka, Japan	355mm SCT
G. Lewis	Bunwell, Norfolk	254mm SCT
M. R. Lewis	St. Albans, Herts.	444mm refl.
P. Lyon **V**	Birmingham	203mm SCT
T. McCague **V**	Chicago, IL, USA	333mm refl.
R. J. McKim **V**	Upper Benefield, Northants.	410mm DK Cass.
	Mnichovo Hradiště, Czech Republic	70mm OG
S. Macsymowicz	Ecquevilly, France	100mm & 127mm OGs, 180mm & 200mm MKT
S. Massey	Hervey Bay, Queensland, Australia	305mm refl.
P. W. Maxson	Surprise, AZ, USA	250mm & 315mm DK Cass., 355mm SCT
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.	102mm OG
C. Nuttall **V**	Bishopthorpe, Yorks.	300mm refl.
T. Olivetti	Bangkok, Thailand	410mm DK Cass.
A. Pace	Malta	355mm SCT
D. A. Peach	Barbados, West Indies	355mm SCT
C. E. Pellier	Paris, France	250mm Gregorian
J. H. Phillips	Charleston, SC, USA	254mm MKT
J-J. Poupeau	Pecqueuse, France	350mm & 410mm Cass.
M. Radice	Salisbury, Wilts.	150mm MKT & 279 mm SCT
R. Schulz	Vienna, Austria	203mm SCT
	Hakos, Namibia	505mm RCT
M. Smrekar	Ljubljana, Slovenia	300mm refl.
J. Sussenbach	Houten, Netherlands	355mm SCT
R. Tatum	Henrico, VA, USA	305mm SCT
	Bon Air, VA, USA	178mm OG
D. B. V. Tyler	Flackwell Heath, Bucks.	178mm OG
M. P. Valimberti	Melbourne, Australia	355mm SCT
A. G. Vargas & S. Calizaya	Cochabamba, Bolivia	203mm refl. & 152 mm SCT
D. Vidican **V**	Bacău, Romania	150mm refl.
G. Walker	Macon, GA, USA	254mm OG
J. Warell	Skivarp, Sweden	220mm refl.
A. Wesley	Rubyvale, Queensland, Australia	406mm refl.
K. Yunoki	Osaka, Japan	260mm refl.
D. Weldrake	Bungendore, NSW, Australia	130mm OG

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

Johnson supplied images of the conjunction of Venus, Mars and Jupiter, 2015 October. Delcroix sent images from other Pic du Midi observers. Macsymowicz sent images by the Carvalhos.

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

Local dust clouds around *Mare Sirenum*, 2016 June–July

On Jun 14 & 18, three or four small, bright dust-plumes S*f. Mare Sirenum* (near $\lambda = 180°$) were imaged by Foster and Olivetti, appearing bright in red and green light, but faint in blue. Foster's next really good image on Jun 22 recorded further changes in form, after which there were no further sightings: see Figure 7 (top panel).

On Jul 9, Hanson (Figure 7, bottom panel), Maxson (Part II, Figure 16) and Morales all caught a new bright yellow local dust cloud cutting across the central longitudes of *Mare Sirenum* from W. *Memnonia*. The cloud was brightest in red and green light, but was also bright in blue, suggesting a water ice component. It had not been observed by anyone on Jul 8, and little trace remained on Jul 10 or later, but it may be significant that the largest 'front' seen moving south from the N. polar region (also illustrated in Figure 7) occurred at the same time (see Part II). Dust cutting across this area outside of an Encircling storm is very rare.

Regional storm in *Nilokeras* to *Valles Marineris*, 2016 August

On 2016 Aug 20, Morales caught some small yellow dust clouds at the *Chryse Planitia–Nilokeras* border. A larger yellow cloud in N. *Chryse–Xanthe* was captured by Maxson on Aug 22, which decayed until Aug 28 into a small remnant at its E. edge. During Aug 23–27 the focus of activity had moved to the south, when dust was recorded in the E. part of *Valles Marineris* by Chappel, Flanagan, Maxson, Melillo, Morales and Tatum (Figure 8).

The Director had issued an alert to observers in the USA on Aug 22: this received a good response, though the activity quickly died away. Abel, during a visit to the Griffith Observatory, found no trace of the event remaining on Aug 30 (Figure 4D). However, a few days later, fresh activity would begin near *Hellas*, while an area just to the east of the Aug 20 dust clouds would also be active again in September.

Regional storm in *Hellas* & environs, 2016 September

On 2016 Sep 2, Regional dust activity lasting around ten days commenced as a small dust cloud north of the N. border of *Hellas*. Nothing had been visible on Sep 1. The event was imaged in detail by MRO, and its start recorded by a fine red image by Morales. According to MRO, next day there was a second dust cloud over mid-*Deucalionis Regio* and another over *Mare Serpentis*, which would expand further.

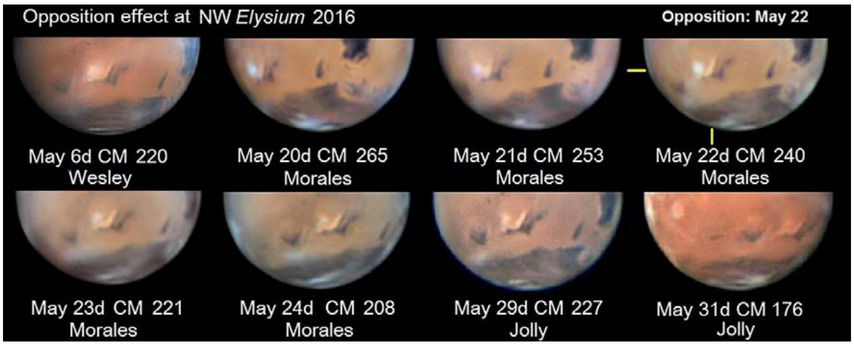

Figure 5. Opposition brightening at the yellow patch northwest of *Elysium* (indicated for May 22), according to RGB images by Jolly (ASI 120MM camera), Morales (Flea 3) and Wesley (GS3-U3-32S4M-C). *Note*: The bright white *Elysium Mons* orographic cloud does not show any opposition effect; it is merely brighter in late afternoon. A 'banner cloud' is visible off the NPC outlier *Olympia* in several images.

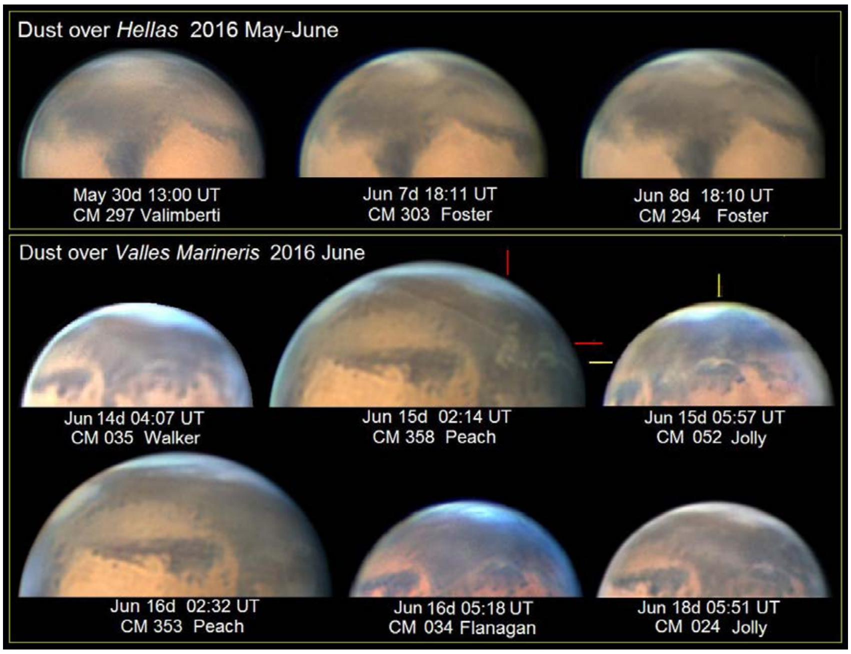

Figure 6. ***Top row*****:** Small-scale local dust activity over *Hellas*, 2016 May to June, according to Foster (ASI 224MC camera) and Valimberti (ASI 224MC). ***Bottom row*****:** Dust storm activity at *Valles Marineris* and southern *Margaritifer Sinus*, 2016 June (indicated for Jun 15), according to Flanagan (PGR GS3-U3-32S4M-C), Jolly (ASI 290MM), Peach (ASI 120MM-S) and Walker (ASI 174MM).

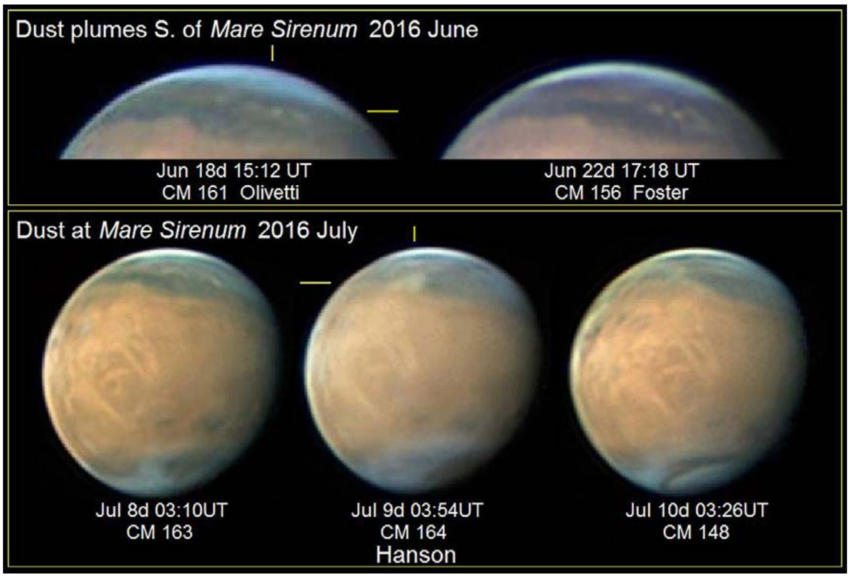

Figure 7. ***Top row*****:** Dust plumes south of *Mare Sirenum*, 2016 June, according to Foster (ASI 224MC camera) and Olivetti (Blackfly ICX692). ***Bottom row*****:** Images of dust activity over central *Mare Sirenum*, 2016 July (indicated for Jul 9), according to Hanson (ZWO 174MM camera).

Dust spread over N. *Hellespontus* to the west, and must have excavated dust from eastern *Noachis*. On Sep 8 *Yaonis Fretum* had darkened, as had *Noachis*, resulting in a broadening of *Hellespontus–Mare Serpentis*. Dust fallout was evident in *Argyre* to the west, which had become strikingly bright and yellow upon Foster's images from Sep 11 onwards and to the Director visually from Sep 20. The fallout would fade only slightly during October. Dust also spread slightly beyond *Hellas* to the east: on Sep 5 the Director noticed that dust had reached *Ausonia*. Figure 9 illustrates the event, and some MRO images were published by Minami (2016).[28] According to MRO-MARCI data, the storm had entered its final decay phase by Sep 12, terminating all active dust-lifting.

The broadening of *Mare Serpentis* is a normal result of such storms. In September, *Pandorae Fretum* began to appear as a weak albedo marking, and as the *Noachis* dust settled the following month, it was seen to have darkened into a conspicuous belt. This further effect of the storm is also illustrated in Figure 9.

Local storm at *Niliacus Lacus*, 2016 September

Following closely on the heels of the August event, a short-lived and localised yellow cloud appeared over the E. end of *Niliacus Lacus* on Foster's images of Sep 13. Its rapid decay was seen during the next two days: see Figure 8. This was an unusual location, and with the benefit of hindsight we note that it was close to where the 2018 global storm would commence.

Regional storm in SW *Arcadia*, 2016 September

According to spacecraft images,[29] a Regional storm developed in SW *Arcadia* or *Diacria* (+35°, 174°) on 2016 Sep 24. This event was independently recognised upon amateur images from Japan during Sep 25–28. Images by Iwamasa are shown in Figure 10.

Dr Jim Shirley (Jet Propulsion Laboratory) notified us by e-mail that,[30] on Sep 26 (according to MRO-MARCI imaging), the storm had merged with additional activity in *Amazonis* to cover latitudes 0 to +49° and longitudes 163–210°.

This was a highly unusual Regional event, unique in location for a telescopic storm.[31]

S. polar dust, 2017 January

A diffuse yellowish streak near the SPC was witnessed by Morales on 2017 Jan 9, its W. end located at $\lambda \sim 90°$. It almost certainly represented a local dust storm, as the MRO-MARCI weather reports cite a number of transient storms at the SPC N. edge at that time.

Two Regional storms, 2017 February–March

The seasonally joint latest-known Encircling storm arose in 1924 at *Ls* = 311°.[26] In MY 33 this *Ls* value corresponds to 2017 Feb 3. The Director, in BAA *e-Bulletin* No. 956 (2017 Jan 16),[32] encouraged observers to continue active monitoring. On 2017 Feb 20, and again by Mar 6 onwards, spacecraft images showed two successive Regional storms which began in the northern hemisphere but which propagated to (and expanded in) the south.[33–34] (An online movie for the period Feb 18 – Mar 6 was particularly useful.) The combined event failed to become Encircling.

We obtained several images of these late Regional storms (Figure 11), but given the patchiness of our late coverage, the exact course of events was only established by reference to the weekly MRO-MARCI 'weather reports'. Extracts with ground-based comparisons follow:

2017 Feb 20–26

The *Acidalia* (telescopic *Mare Acidalium*) region had already produced some small-scale local storms according to MRO, but these were below the limits of telescopic resolution.

Two local dust storms, first observed south of *Niliacus Lacus* and near *Idaeus Fons* on Feb 20, propagated along the *Acidalia* storm track and merged to form a Regional storm, which by Feb 21 reached from *Lunae Planum (Lunae Lacus)* to *Xanthe* and *Aurorae Sinus*, and impinged upon western *Arabia*, with *Valles Marineris* also starting to be affected.

The image by Morales for Feb 22 (Figure 11) shows the dust in *Chryse–Xanthe*, while MRO's coverage of longitudes to the west showed dust continuing to spread over *Valles Marineris* and to expand south over W. *Mare Erythraeum*. On Feb 23, a fresh dust core

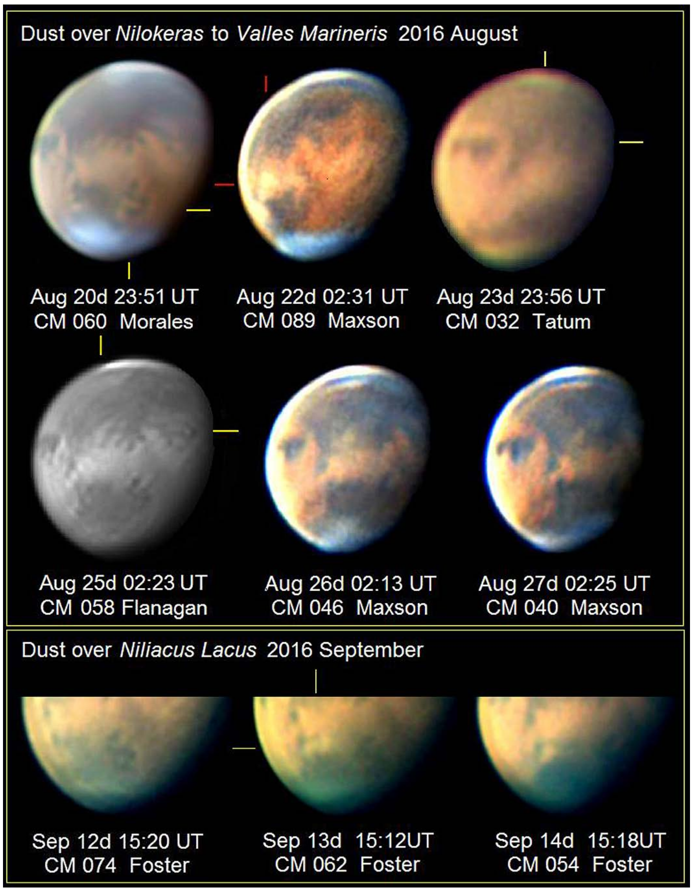

Figure 8. Dust storm activity at *Chryse Planitia–Nilokeras*, extending into *Valles Marineris*, 2016 August (top two rows) and over *Niliacus Lacus* in September (bottom row), according to Flanagan (PGR GS3-U3-32S4M-C camera), Foster (ASI 224MC), Maxson (ASI 290MM), Morales (Flea 3) and Tatum (178mm OG, ASI 224MC).

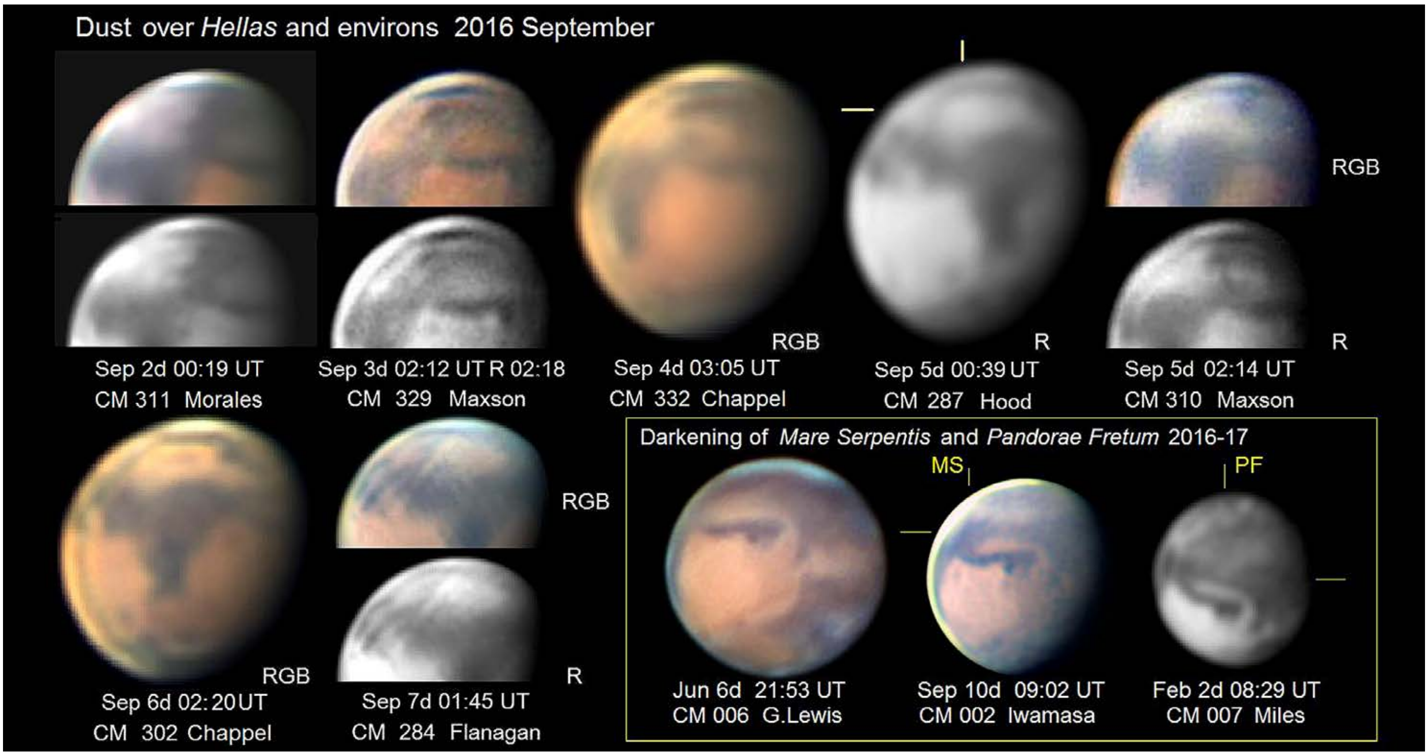

Figure 9. Regional dust storm from *Hellas* to eastern *Noachis*, 2016 September (indicated for Sep 5), illustrated by RGB composite and red (R) images by E. Chappel (ASI 224MC camera), W. D. Flanagan (PGR GS3-U3-32S4M-C), M. Hood (ASI 290MM), P. W. Maxson (ASI 290MM) and E. Morales (Flea 3). Times are for RGB images; R times given if significantly different. The darkening of *Mare Serpentis* and *Pandorae Fretum* from September onwards is illustrated in images by R. Iwamasa (ASI 290MM), G. Lewis (DBK21AU04.AS) and P. Miles (Grasshopper3 GS3-U3-32S4M).

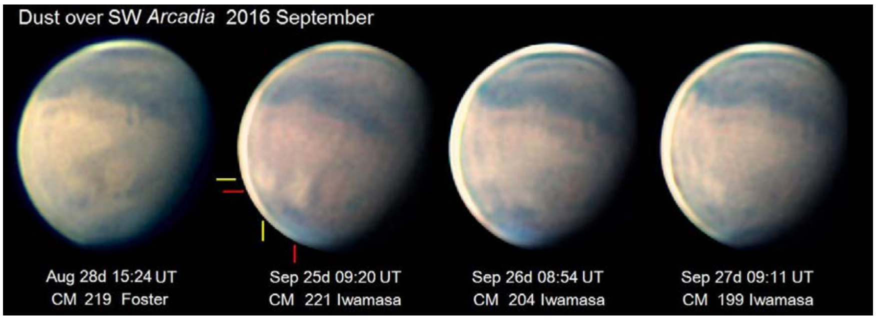

Figure 10. Regional dust storm at SW *Arcadia,* 2016 September, imaged by Foster (ASI 224MC camera) and Iwamasa (ASI 290MM).

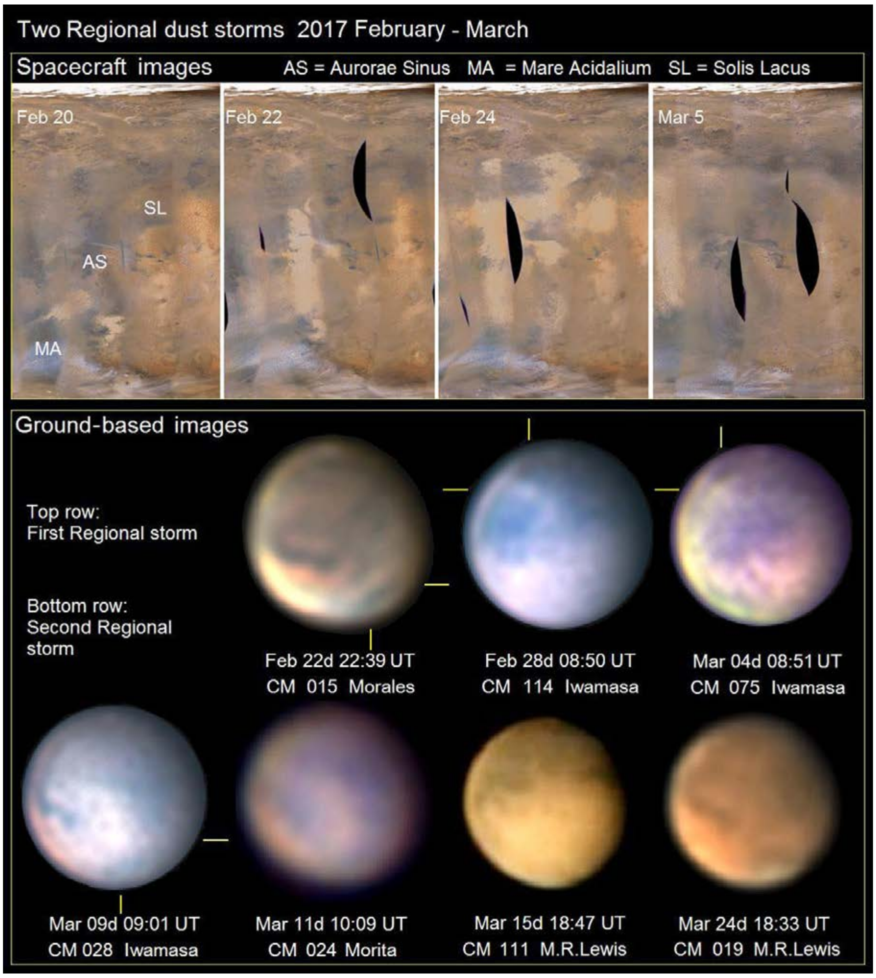

Figure 11. Two large, nearly concurrent Regional dust storms, 2017 February to March. Imaged by MRO-MARCI (top), and from the Earth (below) by Iwamasa (ASI 290MM camera), M. R. Lewis (ASI 224MC), Morales (Flea 3) and Morita (Flea 3). Selected MRO daily images show the longitudes of *Margaritifer Sinus* to *Daedalia*, captured from the weekly videos posted online.[33] Black areas represent an absence of data.

was evident over *Margaritifer Sinus*. Next day, a Regional-scale storm arose over *Solis Planum (Solis Lacus) – Sinai*. This merged with the other event and propagated SW over *Aonia (Aonius Sinus)* and E. *Daedalia*, affecting *Argyre* and western *Noachis* to the east by the end of the week. McKim, with CM = 291°, observed no obscuration upon the planet on Feb 24, as did Adamoli (CM = 260°) the next day.

2017 Feb 27 – Mar 5

At the start of the week, this Regional storm was abating. It had reached as far east as S. *Cimmeria (Mare Cimmerium)*. The image by Iwamasa for Feb 28 (Figure 11) shows dust remaining south and southwest of *Solis Lacus*, while on Mar 4 he imaged residual dust over *Argyre*.

By Mar 5, a second dust storm that had propagated along the *Acidalia* storm track had become Regional in size over *Xanthe Terra (Xanthe)*. This later activity raised the atmospheric opacity at the *Opportunity* rover site, with *Margaritifer Sinus* beginning to be freshly obscured on Mar 3.

2017 Mar 6–12

The second Regional storm now lay just west of *Opportunity*, and extended from *Chryse Planitia* to NW *Noachis*. *Margaritifer Sinus* was covered by bright dust clouds throughout this week, as we see from images by Iwamasa and Morita for Mar 9 & 11 (Figure 11). Dusty haze from the previous event remained in the south.

2017 Mar 13–19

The second Regional storm began to dissipate in the last three days of this period, dust having reached NW *Hellas* by the end of the week *via Noachis*. Hillebrecht caught *Solis Lacus* at the evening limb on Mar 10, and M. R. Lewis showed this feature and its surroundings completely normal on Mar 14, with *Margaritifer* partly recovered on Mar 24 (Figure 11).

The *Opportunity* rover at first had its solar cells cleaned by the winds associated with the event, but subsequently suffered from dust fallout. No major dust activity was recorded by MRO in April.

General discussion

In summary, no Encircling storm occurred in MY 33. The last was in 2007 (MY 28), and the next would occur in 2018 (MY 34). In MY 32 (2014–'15), a southern Regional event had begun on 2015 Mar 13 at Ls = 307°.[2] In the presently discussed apparition a large, seasonally late event – comprising two consecutive Regional storms – occurred in 2017 February–March, beginning on Feb 20 (Ls = 320°). Both storms originated north of the equator but expanded in the south. It is unusual for two successive large Regional storms to occur so close together in time, but the season was too late for an Encircling event. It may be significant that the planet-encircling event of 2018 would begin in the northern hemisphere.[35]

In 2016, several minor northern events occurred in locations rarely or never previously active telescopically: in particular, the local storms around *Mare Sirenum* in June–July and the Regional one in SW *Arcadia* in September. The ongoing obliteration of certain northern albedo features supports the net accumulation of dust in that hemisphere.

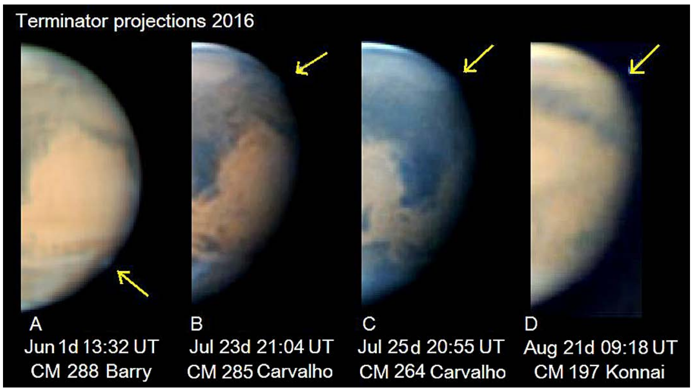

Figure 12. Terminator projections in 2016.

(A) A very small object at the N*f.* terminator above W. *Cydonia* on Jun 1. PGR GS3-U3-32S4M-C camera. *(Barry)*

(B) A broad projection at the S*f.* terminator located over SW *Noachis* on Jul 23. QHY5L-II mono camera. *(F.& G. Carvalho)*

(C) A subtle terminator bulge over *Argyre* on Jul 25. QHY5L-II mono camera. *(F.& G. Carvalho)*

(D) Low projection at the SW terminator on Aug 21. ASI 224MC camera. *(Konnai)*

Predictions of future planet-encircling dust storms

By modelling the change of angular momentum in the solar system, and armed with a partial data set of historical Encircling storms, Dr Jim Shirley tentatively predicted a global storm for MY 33.[36] As we have seen, in reality there were two nearly concurrent large Regional events just beyond the historically latest possible seasonal moment. In 2019, Shirley and the author cooperated to add considerably more historical data to his model, which has enabled improved predictions for the following three Martian years.[37]

Terminator projections

Compared with the remarkable high-altitude terminator projections of 2012,[1] the 2016 phenomena were all low-level. See Figure 12.

On 2016 Jun 1, under CM = 288°, Barry recorded a very small projection, visible in blue light (and in the RGB composite image) at the N*f.* terminator above W. *Cydonia*. This was therefore white cloud.

We have already mentioned a projection seen on Jun 14 that was associated with a southern dust storm at *Valles Marineris*.

On Jul 23, under CM = 293°, G. and F. Carvalho recorded a broad, low projection at the S*f.* terminator, located over SW *Noachis*. The projection was still just traceable in their Jul 25 image under CM = 264°, over W. *Hellas*. On both dates the projection lay at the western end of a band of dull white cloud running from *Ausonia* to *Noachis*.

Morales on Jul 25 (CM = 321°) showed a subtle terminator bulge over *Argyre*, again probably white cloud, at a latitude close to the foregoing. On Aug 21, Konnai (CM = 197°) imaged a dull bulge on the SW terminator.

Formulae for calculating the height of a terminator projection are available.[38]

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