The opposition of Mars, 2012: Part I

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A team of 110 observers contributed nearly 6,000 observations at this aphelic opposition. Part I discusses albedo features and dust storms, as well as some highly unusual terminator events. Following the 2007 global dust storm, a number of albedo markings were still returning to their customary shapes. *Solis Lacus* had not yet recovered its 2005 form, but E. *Noachis* and many other features had returned to normal. There was a succession of minor dust storms over and around the N. polar cap in 2012 January–April, while it was just possible to detect the aftermath of a regional storm centred upon *Hellas* that had been imaged from martian orbit in 2012 November. By far the most intriguing telescopic phenomenon was a series of large projections over the morning terminator during March and April, attaining an exceptional height of at least 200km. The largest such feature was brightest at shorter visual wavelengths and was centred at a latitude of about –44° over *Electris*, a region within the planet's crustal magnetic field anomaly. The data favour an auroral origin, with one or more solar Coronal Mass Ejections providing the impetus. Significant projections over the terminator and limb at *Electris–Eridania* in 1933 & 1950 are discussed in connection with the 2012 data. Appendix I provides a simple method of calculating the height of a terminator projection. Part II will discuss seasonal white cloud activity and the behaviour of the polar regions, with the N. polar cap recession being quantitatively compared with previous years.

Introduction

In this report we adopt the convention of numbering Martian Years (MY), beginning at the 1955–'56–'57 apparition at the dawn of the Space Age. Each year begins at Northern Spring Equinox, at Ls (areocentric longitude)= 0°. Table 1, from Meeus (1983),[1] lists the first 32 Martian Years.

Third in the present series of aphelic encounters, Mars was undergoing late northern spring at opposition on 2012 Mar 3 at Ls= 78°, when it was very close to aphelion (Ls= 70°). The planet lay in Leo with a relatively favourable declination for European observers of +10° that did not unduly disadvantage our Australian contributors. The latitude of the sub-Earth point (or disk centre), D_e, varied from –20° in 2011 mid-May, falling to zero in late July and rising to nearly +24° in December. It remained high at +22° at opposition, rising further to +26° in 2012 June and decreasing to zero in November.

Mars was closest on 2012 Mar 5, at 101 million km, with a disk diameter (D) of 13.9″; almost the least possible at opposition, and the smallest of the current cycle. D remained above 6″ from 2011 Nov 3 till 2012 Jul 20. Key seasonal dates are given in Table 2.

Observing conditions in the UK were typical, but the weather deteriorated considerably after opposition. 110 contributors sent 5,226 images and 724 drawings; 5,950 observations covering 2011 May 12 (Ls= 291°, D= 4.1″ (Akutsu image)) to 2013 Feb 14 (Ls= 264°, D= 4.0″ (Adamoli drawing)). Days per month logged (actual/possible) were: 2011 May, 2/31; June, 3/30; July, 12/31; August, 24/31; September, 28/30; October, 25/31; November, 23/30; December, 27/31; 2012 January, 29/31; February, 29/29; March, 31/31; April, 30/30; May, 31/31; June, 22/30; July, 20/31; August, 10/31; September, 2/30; 2012 October, 0/31; November, 0/30; December, 0/31; 2013 January, 2/31 and 2013 February, 4/28. We covered 92% of the span of a martian year (albeit fragmentary 2012 post-September), during MY 30–31.

Akutsu, Maxson, Morales Rivera, Morita, Peach and Willems each took more than 150 images, with Maxson securing 647 on 156 dates (including much early morning work), and Willems (a new contributor) sending 678. I. D. Sharp obtained images from Barbados during 2011 December. Abel, Adachi, Adamoli, Bailey, Beish, Konnai, McKim, Macsymowicz and Niechoy each made more than 30 drawings.

The most successful colour imaging was done by compositing individual red (R), green (G) and blue (B) filter images. Some observers display individual channels separated from a one-shot colour image, but 'blue' channel separations are misleading and useless as they encompass a much wider waveband than any 'blue' filter.

The 2011–'12 apparition (Ls= 78° at opposition) was seasonally similar to the following post-1890 approaches: 1997 (Ls= 92°),[2] 1995 (58°),[3] 1980 (71°),[4] 1965 (84°),[5] 1948 (63°),[6] 1933 (76°),[7] 1918 (90°),[8] 1916 (56°),[9] & 1901 (69°).[10] 1933, 1965 & 1980 were close matches.

Several accounts of how to observe Mars were published.[11–13] The author contributed two interim reports,[14,15] and a note about the large terminator projections of 2012 March–April.[16]

Images were archived on the websites of the Association of Lunar & Planetary Observers (ALPO),[17] ALPO Japan,[18] Oriental Astronomical Association (OAA),[19] International Marswatch,[20] and Société Astronomique de France (SAF).[21] These databases have much overlap, but exclude many BAA contributors who do not post online.

Table 1. Martian Years (MY)

Year number	*Start date (Ls= 0°)*	*Year number*	*Start date (Ls= 0°)*
1	1955 Apr 11	17	1985 May 15
2	1957 Feb 26	18	1987 Apr 1
3	1959 Jan 14	19	1989 Feb 16
4	1960 Dec 1	20	1991 Jan 4
5	1962 Oct 19	21	1992 Nov 21
6	1964 Sep 5	22	1994 Oct 9
7	1966 Jul 24	23	1996 Aug 26
8	1968 Jun 10	24	1998 Jul 14
9	1970 Apr 28	25	2000 May 31
10	1972 Mar 15	26	2002 Apr 18
11	1974 Jan 31	27	2004 Mar 5
12	1975 Dec 19	28	2006 Jan 21
13	1977 Nov 5	29	2007 Dec 9
14	1979 Sep 23	30	2009 Oct 26
15	1981 Aug 10	31	2011 Sep 13
16	1983 Jun 28	32	2013 Jul 31

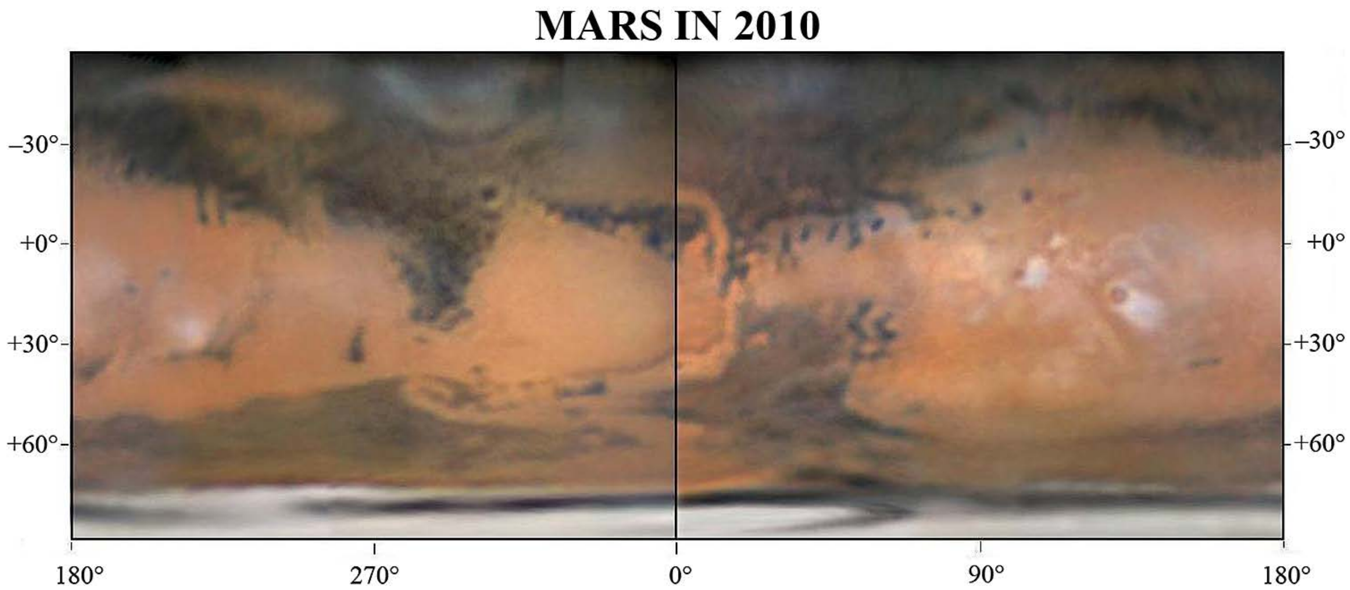

Figure 1. Map made by Damian Peach from his own images with a SKYnyx 2-0M camera, 2012 Mar 1–30. *Note*: Unless stated otherwise, south is uppermost in Part I figures.

The opposition was marked by the unsuccessful *Phobos-Grunt* mission, which had been designed to return samples from Phobos.[14] The *NASA* lander-rover mission *Mars Science Laboratory* (MSL, or *Curiosity*), was launched in 2011 October,[22] and landed on 2012 Aug 6. Stooke (2015) has published an atlas of the MER missions.[23] Here we only cite recent professional literature relevant to our programme: for example, a recent study by Wang (2016) concerning the evolution of large dust storms.[24] The author discussed the early results from *Curiosity*,[25] and the Mars work of past Section member Walter F. Gale,[26] after whom Gale crater is named. Meanwhile, NASA's *Mars Reconnaissance Orbiter* (MRO), in martian orbit since 2006, continued to send back superb images.

This is one of the most complex reports that the author ever had to compile, which largely accounts for the delay in publication. On the other hand, this makes it possible to refer to later professional papers concerning the remarkable terminator phenomena, to be described. This report continues from that of the 2010 opposition.[27]

Surface features

General

Whole-planet maps were compiled by Peach (Figure 1) and M. R. Lewis. Absolute relative intensities cannot be guaranteed unless every single image is close enough to opposition to avoid the phase effect. In Peach's 2010 map,[27] the longitudes of *Syrtis Major* and some distance to the east look faded, because that part was only imaged weeks after opposition and was influenced by morning cloud. This problem was not encountered in 2012 because all mapping images were close to opposition. The aforementioned longitudes look darker, but fine details appear the same. Combining the work of several observers only highlights differences between cameras, filters and processing routines.

Comparison of the 2012 chart with that of 2010 reveals few changes in the albedo features. The most surprising change concerned *Solis Lacus*. Returning to near-normal in 2009–'10 following the 2007 global dust storm, its central western part actually faded over conjunction due to dust activity that could not have been witnessed by us. In our last report we discussed markings that are prominent at high phase angle; similar observations were made this time.

This opposition, D_e & D_s (the latitude of the subsolar point) were briefly equal on 2012 Feb 3 (at latitude +22.8°) & May 9 (+23.8°), but there were no reports of 'flares' or 'flashes' from the surface.

We have not described apparent martian colours, leaving the illustrations to speak for themselves. As usual it is often convenient to refer to the telescopic nomenclature of Ebisawa.[27,28]

Region I: long. 250–010°

See in particular Figures 1 & 2 (and Part II, Figure 15). There were few significant changes.

The blunt-ended *Syrtis Major* revealed much interior detail to the CCD camera. The *Huygens* crater in *Iapigia* was still easily identifiable as a light ring with a dark patch in its centre. The absence of

Table 2. Physical details of the 2012 apparition

	Ls (°)	*Date*
Solar conjunction	230	2011 Feb 4
Perihelion	250	2011 Mar 9
N. winter solstice/ S. summer solstice	270	2011 Apr 9
N. spring equinox/ S. autumn equinox	0	2011 Sep 13
(MY 31 commences)		
Aphelion	70	2012 Feb 15
Opposition	78	2012 Mar 3
N. summer solstice/ S. winter solstice	90	2012 Mar 30
N. autumn equinox/ S. spring equinox	180	2012 Sep 30
Perihelion	250	2013 Jan 24
N. winter solstice/ S. summer solstice	270	2013 Feb 24
Solar conjunction	303	2013 Apr 18

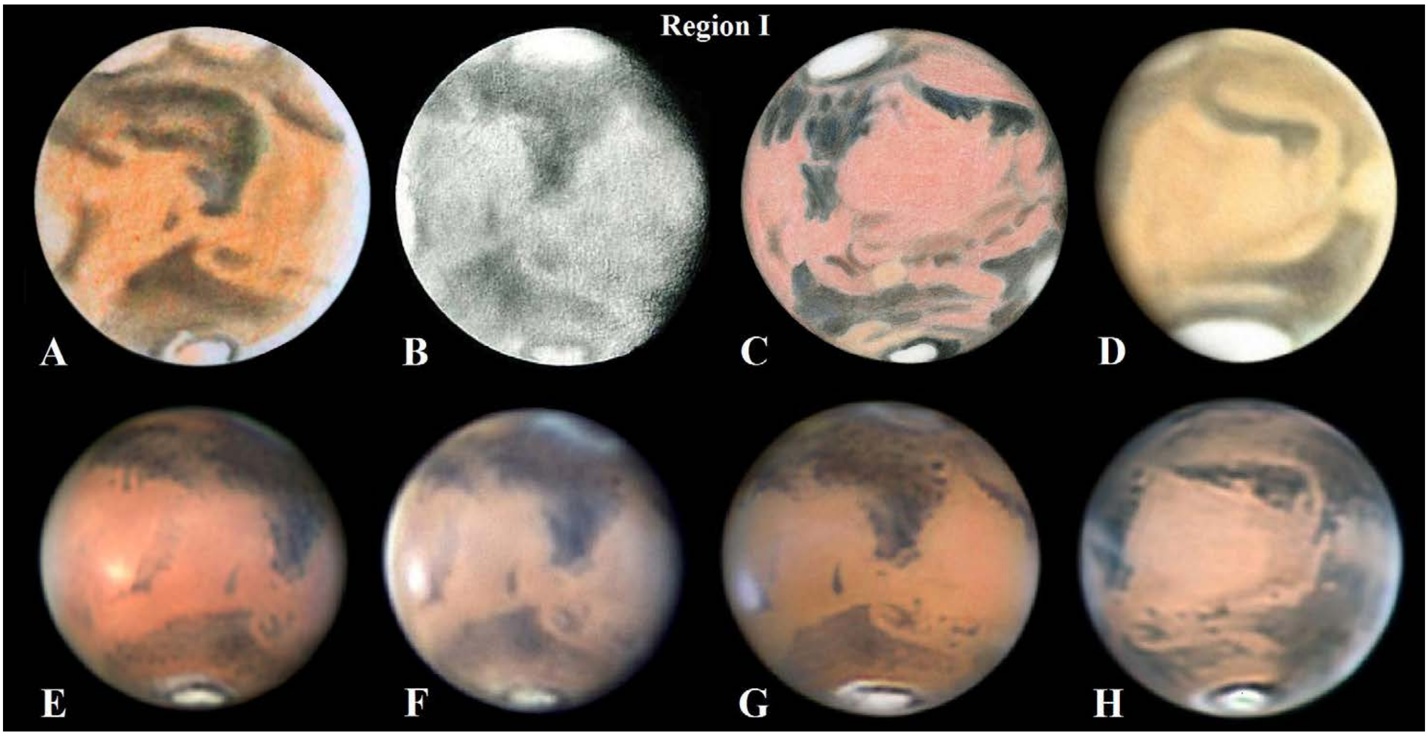

Figure 2. Drawings (*top row*) and images of *Region I*, λ= 250–010°.

(A) 2012 Mar 2d 01:20 UT, CM= 280°, 203mm refl., ×400; *P. G. Abel*. *Olympia* is detached from the NPC in (A) & (E)–(H).
(B) 2012 Apr 28d 12:05 UT, CM= 290°, ×750; *R. Konnai*. *Hellas* now frosted.
(C) 2012 Mar 28d 19:40 UT, CM= 323°, 407mm refl., ×700 ; *N. D. Biver*.
(D) 2011 Nov 7d 05:10 UT, CM= 331°, 415mm DK Cass., ×535; *D. Gray*. Large spring NPC.
(E) 2012 Mar 16d 07:28 UT, CM= 250°, 356mm SCT, SKYnyx 2-0M camera, RGB image; *G .Jolly*. *Elysium Mons* and *Syrtis* Blue Cloud.
(F) 2012 Mar 25d 14:36 UT, CM= 275°, 356mm SCT, DMK 21AU 04 camera, LRGB image; *T. Akutsu*. Cloud in N. *Hellas*. *Huygens* crater dark central spot visible in (C) and (F)–(H).
(G) 2012 Mar 1d 00:48 UT, CM= 283°, SKYnyx 2-0M camera, RGB image, *D. A. Peach*. *Olympia* shows a 'tail' to the west.
(H) 2012 Mar 1d 05:00 UT, CM= 344°, 356mm SCT, DMK 21AU 618.AS camera, RGB image; *D. C. Parker*. Bright white cloud bisects the evening *Syrtis Major*. *Chasma Boreale* crosses the NPC.

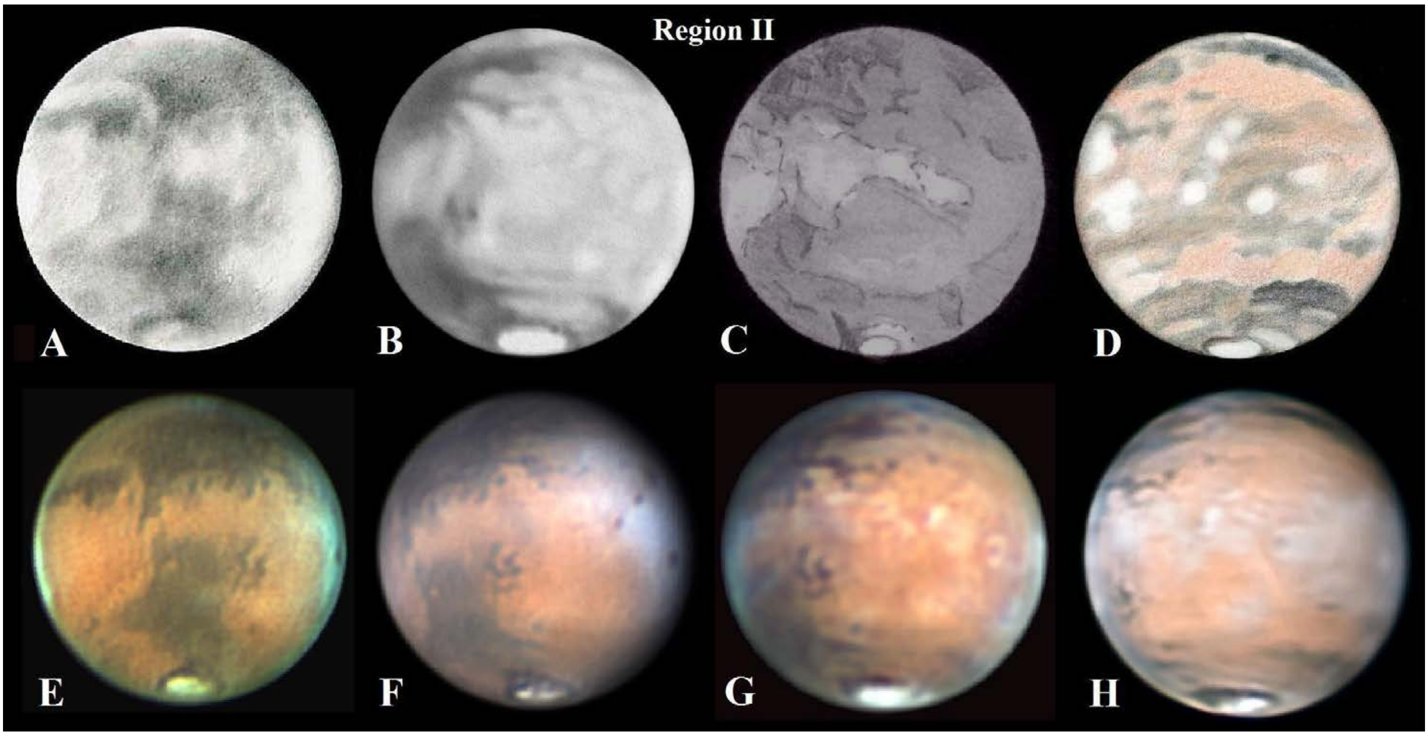

Figure 3. Drawings (*top row*) and images of *Region II*, λ= 010–130°.

(A) 2012 Mar 15d 15:10 UT, CM= 029°, ×600; *R. Konnai*. Note the third fork of *Sinus Sabaeus* and tiny details in S. *Chryse*.
(B) 2012 Feb 14d 02:30 UT, CM= 088°, ×365; *D. Gray*. *Solis Lacus* shows fine details.
(C) 2012 Mar 19d 23:07 UT, CM= 093°, 254mm refl., ×400; *K. N. L. Bailey*. Drawing made with the assistance of a Pan TZ20 LCD camera.
(D) 2012 Mar 12d 21:30 UT, CM= 130°, ×700; *N. D. Biver*. All three *Tharsis Montes* seen.
(E) 2012 Mar 12d 13:41 UT, CM= 033°, PGR Flea3 camera, RGB image; *T. Barry*.
(F) 2012 Mar 28d 02:39 UT, CM= 074°, PGR Flea3 camera, RGB image; *W. Jaeschke*. *Olympus Mons* and *Tharsis Montes* as dark spots amidst morning cloud in (E) and (F).
(G) 2012 Feb 21d 06:43 UT, CM= 088°, PGR Flea3 camera, RGB image; *E. Morales Rivera*. *Ascraeus Mons* is already showing its orographic cloud.
(H) 2012 Mar 24d 03:30 UT, CM= 122°, 356mm SCT, DMK 21AU 618.AS camera, RGB image; *D. C. Parker*. *Ascraeus Mons* and *Pavonis Mons* orographics.

Nepenthes continued. Cloud activity over *Hellas* was seasonally normal, but was followed in more detail than in the past: in Part II we describe the transition from diurnal cloud to surface frost during 2012 March–April.

Mare Serpentis looked paler in 2012 and no longer invaded E. *Noachis*, reverting to its pre-2007 form. *Pandorae Fretum* was still invisible. *Yaonis Fretum* formed a thin dark W. border to *Hellas*. The fading of a third supplementary 'prong' of *Meridiani Sinus* – which lies between the normal W. component and the narrow *Brangaena* (Ebisawa) – was noticeable in the best 2012 images.

Region II: long. 010–130°

See in particular Figures 1 & 3 (and Part II, Figure 15).

In 2010 *Solis Lacus* was returning to its old form, prior to the global storm of 2007. Surprisingly, the 2012 images revealed a fresh fading of its central western part, due to dust storm activity around conjunction that we could not have witnessed from Earth. In 2010 the *Bathys* 'canal' had reappeared between *Solis Lacus* and *Aonius Sinus*. This remained visible, and now showed a more marked darkening and broadening in its centre. *Aonius Sinus* too appeared larger and darker than in 2010. The *Phasis* streak was barely evident, but the diminutive *Gallinaria Silva* remained obvious. To the south, the *Argyre* basin was rarely conspicuous. The seasonal activity of the *Tharsis Montes* clouds is discussed in Part II.

The northern 'coastline' of the dark southern continent between *Margaritifer Sinus* and *Aurorae Sinus* – namely *Aurorae Fretum* (Ebisawa) – was slightly broken in 2010, but looked continuous in 2012. The SE corner of *Margaritifer Sinus* had become rounded and closer to the historical norm compared with 2010.

Region III: long. 130–250°

See in particular Figures 1 & 4 (and Part II, Figure 15).

Cerberus and *Trivium Charontis* were both still only tiny dark spots, now long-effaced by dust deposition. The small yellowish streak of dust fallout in western *Elysium* was still present, and was recovered by Jaeschke as early as 2011 Sep 13: it remained visible in 2016–'17. The western border of *Elysium* appeared as in 2010, with the *Aetheria* secular darkening having persisted since the late 1970s; however, the *Aethiopis–Amenthes* canal-like dark streaks of 2007–'10 had become fainter. *Castorius Lacus* remained small and thin north-south, and *Propontis* retained its truncated and distorted appearance. The southern markings looked the same as in 2010.

For seasonal activity of the *Elysium Mons* and *Olympus Mons* orographic clouds, see Part II.

Dust storms

Introduction

As in 2009–'10, the season for observation favoured the detection of smaller northern hemisphere events associated with north polar hood activity, or with the retreat of the NPC. Compared with the larger of the polar dust storms of early 2010,[27] the 2012 events covered a smaller area, but in both instances dust crossed the cap and was deposited both upon and outside it. If it seems there was more activity in 2012 compared with, say, the epoch of the 1990s, it is simply a matter of the higher resolution now available. Indeed, activity was detectable only upon the best images.

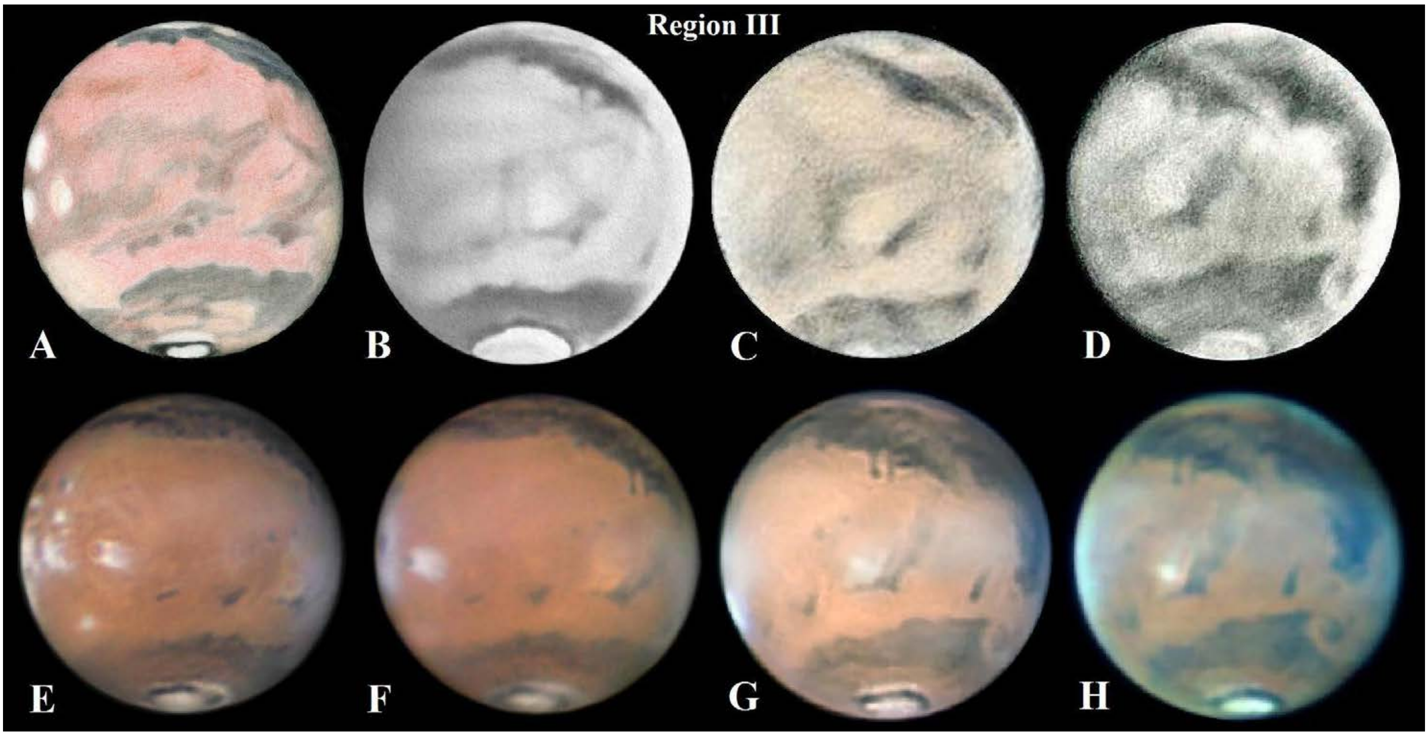

Figure 4. Drawings (*top row*) and images of *Region III*, λ= 130–250°.

(A) 2012 Apr 12d 20:03 UT, CM= 194°, ×700; *N. D. Biver*. Note *Olympia* in (A) and (D)–(H).
(B) 2012 Feb 3d 00:10 UT, CM= 206°, ×365; *D. Gray*. *Olympia* is not yet detached. In (B), (D), (G) & (H) faint streaks cross *Aethiopis* N–S.
(C) 2012 Mar 27d 12:05 UT, CM= 221°, 310mm refl., ×526; *M. Adachi*.
(D) 2012 Feb 19d 16:00 UT, CM= 241°, ×500; *R. Konnai*.
(E) 2012 Mar 11d 23:19 UT, CM= 166°, SKYnyx 2-0M camera, RGB image; *D. A. Peach*. The *Arsia Mons* orographic cloud is extremely tiny.
(F) 2012 Mar 8d 22:49 UT, CM= 184°, SKYnyx 2-0M camera, RGB image; *D. A. Peach*. *Castorius Lacus p. Propontis* is very small and thin.
(G) 2012 Mar 14d 04:36 UT, CM= 226°, 356mm SCT, DMK 21AU 618.AS camera, RGB image; *D. C. Parker*. *Elysium Mons* and the *Syrtis* Blue Cloud in (G) & (H).
(H) 2012 Mar 20d 09:29 UT, CM= 244°, DMK 21AU 618.AS camera, RGB image; *F. Willems*. Yellow dust fallout streak at NW of *Elysium*.

Wang (2015) has reviewed spacecraft data for the period in question.[24]

Early observations, 2011 May–August

Akutsu's very early images of 2011 May 12 – Jun 26 (starting at Ls= 291° in S. summer, with D= 4.1″) showed only the coarse albedo features expected, so there was clearly no event as large as an encircling storm in progress then. Melka described his Aug 4 image (D= 4.4″) as showing dust in *Hellas*,[29] but the author disagrees, as do MRO data.

Activity E. of Olympia, 2012 January–February

The seasonal separation of *Olympia* from the N. polar cap (see Part II) was a period of dust activity at more than one point upon the cap's periphery. *Olympia* is bounded on the E. side by the dark patch *Deucalidonius Lacus* (λ~ 160°) upon Antoniadi's N. polar chart.

Flanagan and Maxson recorded a bright spot (brightest in red (R) and green (G) light) at the edge of the cap from Jan 15–19 (λ~ 115°). At higher resolution on Jan 19, under CM (central meridian) ~150°, Willems showed a dark orange streak upon the *p.* side of the cap located west of *Chasma Boreale*. Johnson (Australia) on Jan 27, and Buda on Jan 28 saw there what we take to have been a large, dusty outflow from the cap: Buda recorded a long streak that was dark against the cap but light beyond its periphery. Barry on Feb 3 (CM= 045°) and Sussenbach on Feb 8 (CM= 092°) imaged what seem to have been dusty outflows leaving the cap at the morning side.

On Feb 9–11 Morales and S. Walker imaged what had become a complex polar dust storm under CM~ 170°, when a wide dark-orange dust cloud close to the CM stretched NW from the edge of the cap to reach at least the annular rift, and a lighter yellowish dust streak was orientated in a SE direction from the edge of the cap. The nearly separated *Olympia* formed the only bright part of the cap. From Europe the activity was seen at the morning limb on Feb 11 by Poupeau and Sussenbach, when that side of the cap was strongly yellow; on the next day Peach caught the same yellow streak moving off the cap on the morning side.

Near the CM on Feb 12, Morales found an E–W streak of dust outside the cap parallel to its edge in addition to the dark-orange streak across the cap. Parker imaged the complex area near the CM on Feb 15, when the streak across the cap had contracted to a small dark patch and dust moved SE off the cap edge at CM ~ 130°, while another dust streak stretched SW *f.* the CM. Morales imaged the dark area upon the cap at low resolution on Feb 16 and he, Jaeschke and Parker saw it again on Feb 19–22 – still changing – on the morning side. Akutsu saw it upon the evening side on Feb 18.

On Feb 23–27, as the longitude of *Deucalidonius Lacus* was presented to Barry, Buda, Kumamori and Willems, the dusky-orange streak that had cut deeply into the cap continued to create an anomalous appearance, but activity was now less widespread. At high resolution on Feb 24 Willems continued to find a streak leaving the cap in a S*p*. direction at λ~ 120°. Flanagan on Feb 26 saw this activity at the morning limb. On Feb 29 to Kumamori the area was nearly normal, though the dusty colour remained.

The foregoing activity is shown in Figure 5A, with an index map in Figure 5C.

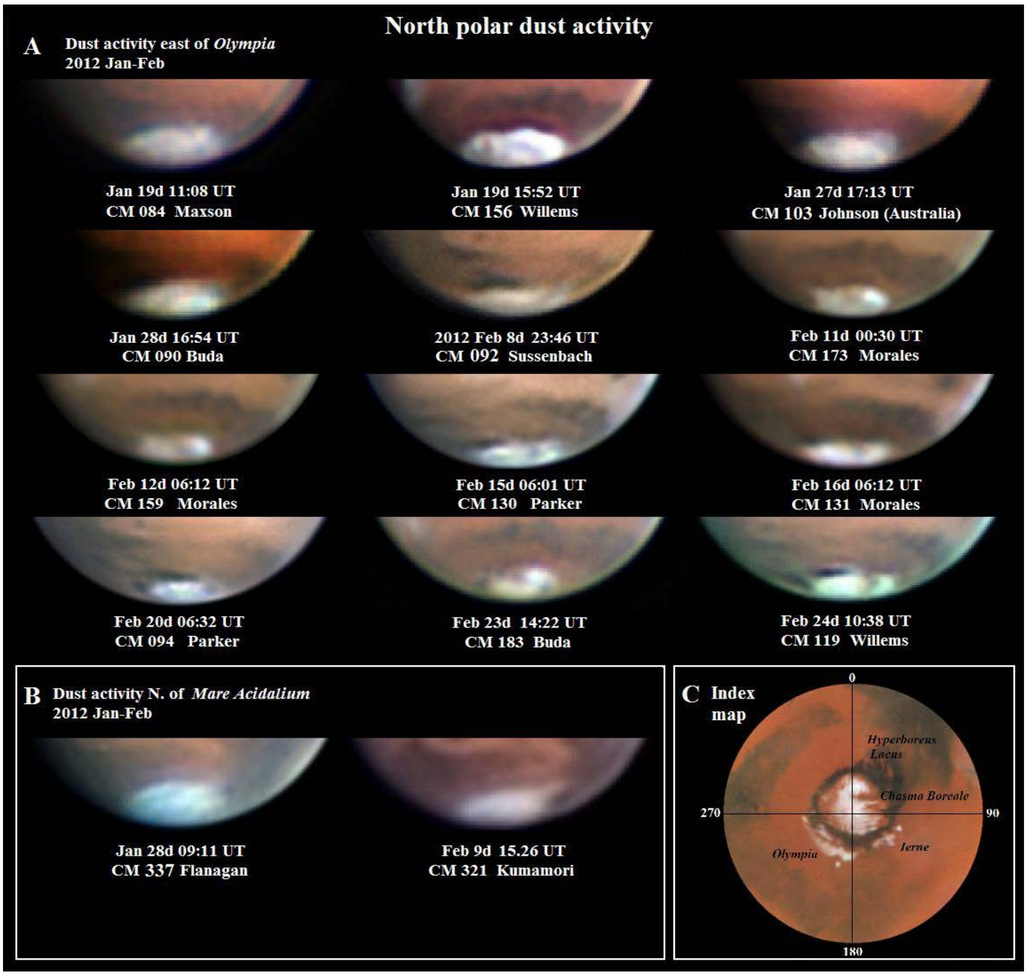

Figure 5. Dust activity in the N. polar region. **(A)** Dust activity east of *Olympia*, 2012 Jan–Feb. **(B)** Dust activity N. of *Mare Acidalium*, 2012 Jan–Feb. **(C)** Name index upon an HST 1997 March N. polar projection map. © *Space Science Institute & NASA.*

Activity N. of Mare Acidalium, 2012 January–February

On the opposite hemisphere during Jan 28–30 (CM~ 330°), Flanagan showed a dusty outflow (which originated N. of the annular rift) W. of the CM, moving southwest. This outflow had been caught in the morning by Peach the previous day. On Feb 9–11 Kumamori, Massey and Morita observed a small, strongly yellowish streak leaving the NPC in a S*f.* direction at λ~ 010°, north of *Mare Acidalium* and close to the outflow seen by Flanagan.

The above activity is shown in Figure 5B, with an index map in Figure 5C.

Activity around Chasma Boreale, 2012 February–April

Further activity was seen around the broad, dark *Chasma Boreale* rift. On Feb 21–26 Flanagan, Jolly, Morales, Parker, S. Walker and Peach showed it cutting well into the cap, but its mouth looked faint, obscured by variable airborne dust (light in R & G but not in B), as was part of *Hyperboreus Lacus*. The dust seemed to reach NW *Mare Acidalium*, confirmed by spacecraft data. A little variable dust over the tail of *Acidalium* seemed to last several days longer. *Chasma Boreale* looked extended towards the pole beyond its fixed northern limit, by the presence of a dust streak on some days.

On Mar 6–12 under CM= 024–107°, Barry and Go showed the side of the cap west of *Chasma Boreale* and the W. part of *Hyperboreus Lacus* yellowed by fallout, while the mouth of the rift still looked obscured. On Mar 22–24, Jaeschke and Peach found a temporary dust streak extending partly across the cap W. of *Chasma Boreale*. Furthermore, on Mar 24 a small bright orange patch was seen by Peach (under CM= 044°) on the opposite side of the cap to *Chasma Boreale*. For a time this made it look as if *Chasma Boreale* extended nearly all the way across the cap. (For its normal appearance, see the post-storm image of May 6, and Figure 5C.) Akutsu imaged the other side of the cap at high resolution on Mar 25–30 and was able to catch the small, fading, orange patch at the edge of the NPC at λ~ 270°. (It was visible in R & G only.) Peach found dust still affecting the dark cap border there on Mar 29 – Apr 1, but the activity had nearly died out. From then onwards, *Chasma Boreale* displayed its normal darkness. Further comments about this rift are made in Part II under ‘NPC fragmentation’.

See Figure 6 for selected images of this dust activity. (See also the index map in Figure 5C.)

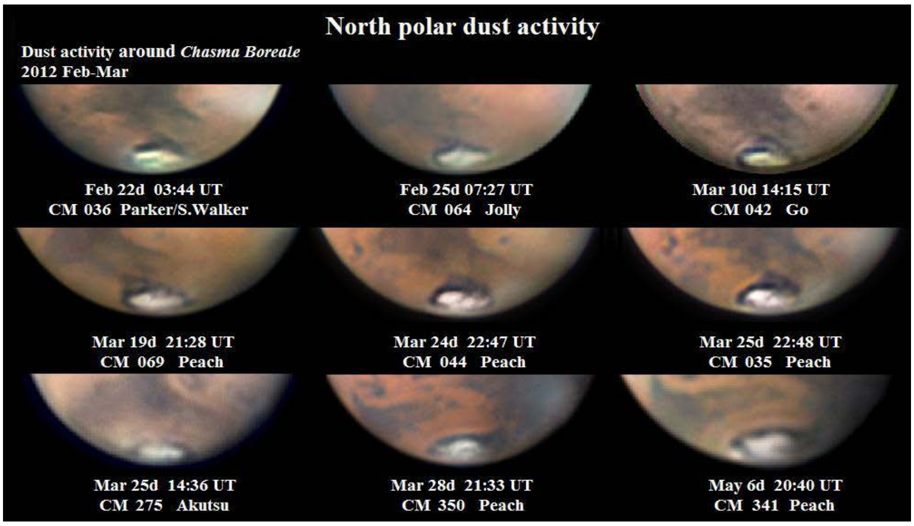

Figure 6. Dust activity in the N. polar region around *Chasma Boreale*, 2012 Feb–Mar. The final image of May 6 was added as a post-storm comparison. See Figure 5C for an index map.

Miscellaneous observations, 2012 February–April

As already indicated, some dust from these polar events dispersed to the south. For example, during Mar 2–20 the best images of Barry, Jaeschke, Jolly, Morales and S. Walker showed a number of small, light dust patches – probably now surface deposits – causing northern *Copais Palus–Cecropia* (NW of *Utopia*) to appear patchy.

During the polar dust activity a temporary violet hole (in other words, a darker patch seen in blue/violet light) over *Hyperboreus Lacus* and NW *Mare Acidalium* was visible on Feb 24 & Mar 23–26. The implied local reduction in the water vapour content of the overlying atmosphere was probably due to warming by suspended dust. Another violet hole, over NW *Acidalium*, was imaged by Akutsu on Apr 18–21, correlating with the cessation of the early April activity at *Chasma Boreale*.

An ephemeral and extremely narrow dust streak crossed one component of *Sinus Meridiani* in Parker’s 2012 Apr 4 image, while on Apr 6 Parker (Figure 12) recorded a small near-equatorial terminator projection. The latter was probably a local dust storm, but it is included in the following section dealing with other terminator phenomena for convenience.

2012 July–August & the landing of Curiosity

On 2012 Aug 6, *Curiosity* landed at Gale crater.[22,23,25] With D below 6″, detailed BAA coverage was impossible. A local dust storm began in *Hellas* on Jul 31,[30] but became inactive on Aug 2. The Aug 4 (Ls= 150°) MRO whole-planet map shows dust still constrained within *Hellas*,[30] in addition to a separate event over S. *Margaritifer Sinus* and along part of *Valles Marineris*.

Up to at least Jul 23, our work had shown bright frost in *Hellas* (see Part II). No BAA observations of *Hellas* are available for the critical period, though Willems on Aug 6 and Morita on Aug 16 found *Hellas* much less white than it had earlier been – confirming that dust obscuration must have endured – while on Aug 27 Adamoli showed it bright again.

For the separate event, on Jul 28 Willems recorded no obvious dust along *Valles Marineris*, but Konnai’s drawing of Aug 5 suggests lighter cloud *p. Aurorae Sinus*: perhaps dust. Adamoli found the latter area normal, though at very low resolution, on Aug 14.

Very late observations, 2012 September – 2013 February

Adamoli followed the planet visually until 2012 Sep 11 (Ls= 170°, D= 5.0″), with a break till 2013 Jan 18. On the latter date (Ls= 247°, D= 4.1″) his 235mm SCT showed low contrast: *Syrtis Major* at the CM looked suspiciously faint and the boundaries of *Hellas* were ill-defined, yet *Mare Tyrrhenum* was more obvious. Adamoli considered that dust must have been deposited from a storm. Reference to the MRO archive shows that a regional storm had begun on Nov 10 (Ls= 204°), ultimately stretching from W. *Eridania* across *Hellas* to W. *Noachis* by Nov 18,[31] while S. *Mare Cimmerium*, most of *Mare Tyrrhenum* and *Iapigia* were effaced by bright dust clouds. Partial MRO mosaics for Nov 18 & 25 are shown in Figure 7. The storm lasted into December, and MRO instruments recorded a temperature increase of 25°C at 25km altitude.[31]

To Adamoli on Jan 26 *Mare Cimmerium* was definitely seen but still pale, while on Feb 4 & 9 all features looked normal for diameter and seeing. On Feb 14 (Ls= 265°), dark and sharply defined markings were seen (including S. *Mare Acidalium*) under CM= 030°.

Spacecraft images are shown in Figure 7. Further spacecraft data show that there was no planet-encircling storm in 2012–’13 (MY 31).

A remarkable series of terminator projections, 2012 March–April

Introduction

Historically, terminator projections have been classified as dust storms or white clouds. Although the exact nature of the 2012 March–April events to be described remains unclear to this day, it is certain that with the exception of a small, near-equatorial projection, they were *not* primarily dust storms.

Object A, 2012 March

From Mar 12 onwards, a projection was seen over the S*f.* terminator. The first sighting was by Delcroix, who measured its position at –45°, 194°. At first appearance the projection was small, but its size and latitudinal extent soon increased considerably, and it persisted for eleven consecutive nights during Ls= 82–87°.[15,16] On Mar 19/20 the projection had grown considerably in both latitude and longitude; this night and that which followed marked its maximum development. An image of it by Parker on Mar 21 features in Figure 8A. The author now issued a BAA *e-Bulletin*.[32] Projections tend to be visible only at the terminator and not at the limb: it is a matter of viewing geometry coupled with the faintness of the projecting feature compared to the brightness of the sunlit disk.

The 2012 projection not only lay beyond the terminator; on some nights it even extended beyond the *limb*. Projection beyond the limb implies tremendous height. The author's measurement of Parker's image of Mar 21 gave an altitude of about 149km (see Appendix I), placing it in the martian ionosphere and exosphere. No dust storms occur above 60km, nor are clouds of water ice or carbon dioxide found above 100km.

In terms of latitude, longitude and seasonal occurrence, the 2012 event immediately reminded the author of a projection witnessed by E.–M. Antoniadi on 1933 Apr 14 at 19:30 UT (Ls= 96°):[33] see Figure 8B. At the south, this projection was connected to the morning terminator, and its altitude was 35km (see Appendix I). Its lack of brightness and its connection with the surface are consistent with a small dust storm. In 1933 April the phase was 0.94 and the maximum phase defect was in the S*f.* quadrant, 102° from the N. pole. In 2012 March the phase was much higher, 0.99; with the maximum phase defect ~106° from the N. pole. On 1929 Mar 16 Antoniadi had previously found a very large and completely detached morning terminator projection over *Zephyria*, but it was not very high (30km).[34]

In terms of its great height, the 2012 phenomenon recalled a pre-opposition observation by T. Saheki on 1950 Jan 15 at 19:30 UT (Ls= 67°),[35] when a dull yellowish-grey cloud centred near λ= 202° and latitude –58° appeared to extend about 0.16 arcsec above the S. limb (D= 8.7″): see Figure 8C. It was not very bright, so irradiation was not the cause. Saheki himself considered a volcanic origin likely.

An exhaustive search of our database was undertaken, and images from other databases were checked online, though the latter added little. The following are the limits of CM longitudes (adjusted where necessary to the BAA ephemeris) of positive sightings on successive nights: double dates are necessary for clarity.

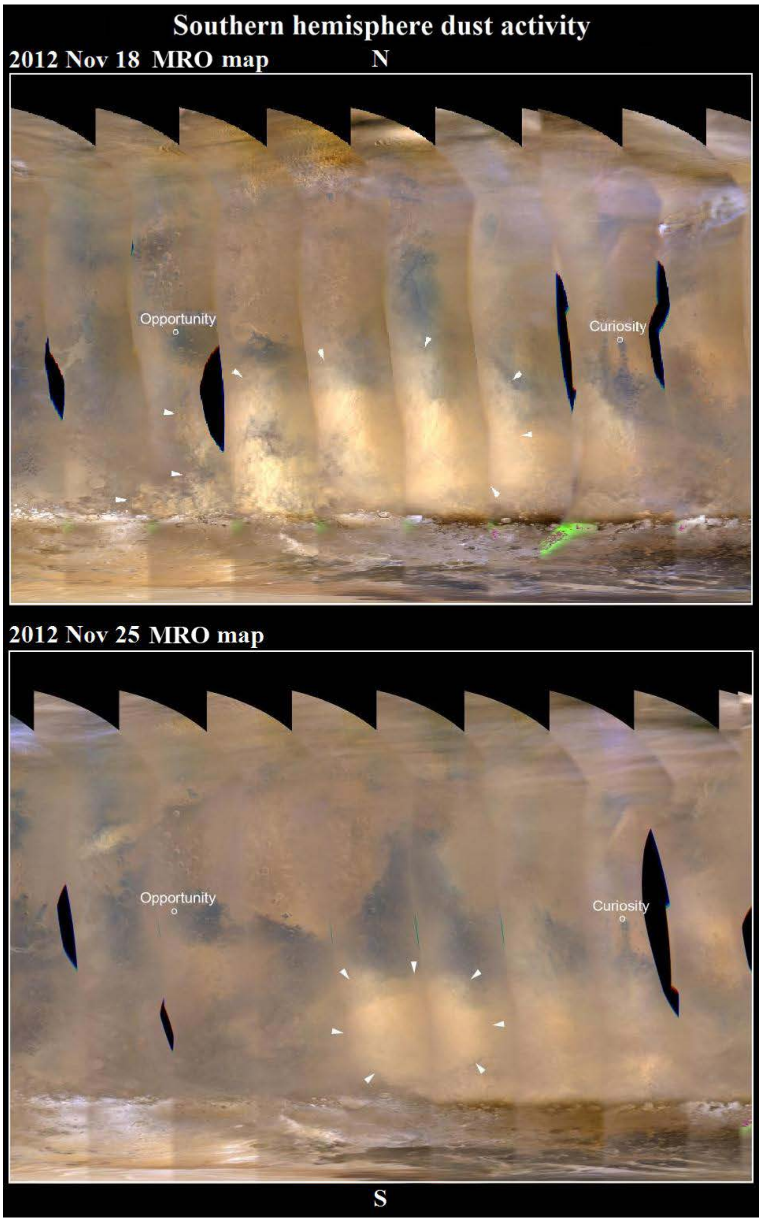

Figure 7. Spacecraft images of the 2012 November, S. hemisphere regional dust storm. MRO partial mosaics from Nov 18 & 25, with dust indicated by chevrons. North is uppermost in this figure. © *NASA/JPL-Caltech/MSSS.*

Dates	*CM (°)*	*Comments*
Mar 12/13	152.6–155.5	
Mar 13/14	Not observed	*Note 1*
Mar 14/15	141.6–151.8	
Mar 15/16	142.9 – ?	(Not visible at 138.1° or 158.7°)
Mar 16/17	Not observed	*Note 2*
Mar 17/18	149.2 – ?	(Not visible at 153.5–156.1°)
Mar 18/19	146.8–165.6	
Mar 19/20	135.5–156.0	
Mar 20/21	135.9–153.0	
Mar 21/22	140.5–161.7	
Mar 22/23	145.9–159.4	

Limits: 135.5–161.7°.

Note 1. Not visible at144.8–149.0°, but no data available for higher longitudes.
Note 2. Relevant longitudes were not observed.

Observers: Delcroix, Jaeschke, Jolly, Kivits, Majewski, Maxson, Melillo, Morales Rivera, Parker, Peach, J. H. Phillips, N. G. Phillips, Poupeau, G. Walker & Willinghan.

Data for Mar 11/12 covered the area fairly well over CM= 141–178°, so Mar 12/13 marked its first appearance. There is definite

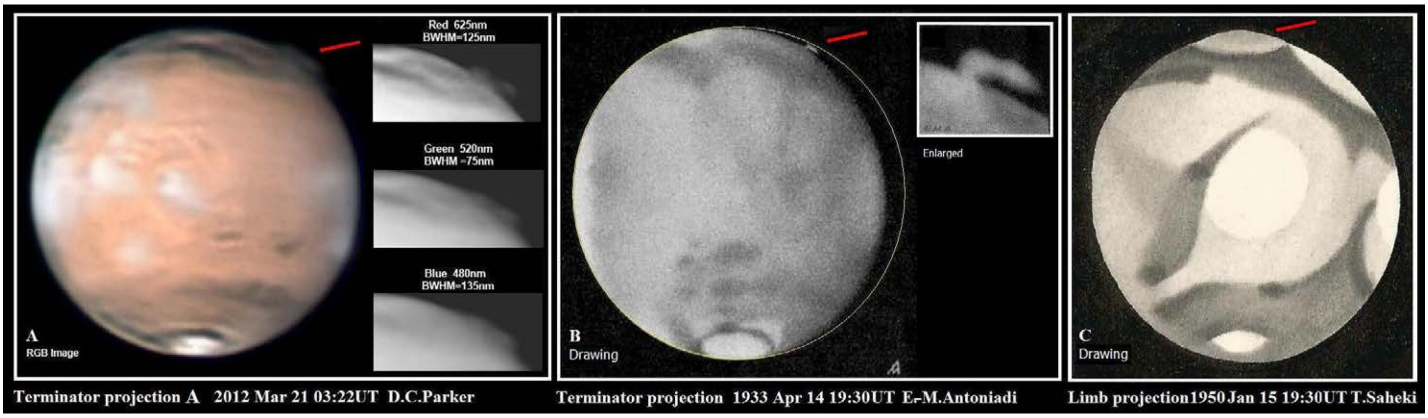

Figure 8. (A) The major terminator projection (arrowed) imaged by D. C. Parker with 356mm SCT and DMK 21AU 618.AS camera, on 2012 Mar 21d, 03:22 UT, CM= 146°. **(B)** Drawing by E.–M. Antoniadi with 830mm OG, ×450, on 1933 Apr 14d, 19:30 UT, CM= 182°, showing a small terminator projection (arrowed) over *Eridania*.[33] The disk has been outlined by the author with a light circle; the inset gives an enlargement. Comparing (A) with (B) to the same scale shows that the 2012 event was similar in position, but much larger in latitudinal extent and at higher altitude. **(C)** Drawing by T. Saheki on 1950 Jan 15d, 19:30 UT, CM= 200°; with 203mm refl., ×400, showing a dull yellowish-grey cloud (arrowed) apparently projecting beyond the south limb over *Eridania–Electris*.

variability in nightly CM limits. It is reasonable to assume that the phenomenon occurred each night from Mar 12–22. We cannot say for certain when it ended, as observations of the critical longitudes are sparse after Mar 23. However, it was definitely absent under CM= 137.6–146.4° on Apr 1 (images by Willems). It was seen again during Apr 9–25: we consider this to be a reappearance, not a continuation.

Figure 9 shows selected daily images and enlargements (to uniform scale). The variation in both size and position is evident. Certain images resemble the 1933 projection,[33] being anchored at one end. Some show two such anchor points. On Mar 21 at 02:51 UT the feature was even resolved into a series of vertical auroral-like spikes, while on other occasions its top seemed ill-defined.

The projection was imaged through broadband filters on several nights. Visible from red to blue wavelengths, it was brightest in green and blue. Dust would be brighter at longer wavelengths and crystal clouds at shorter ones. Dust can arise at any martian season,[34] but enduring dust storms are never observed so close to the southern winter solstice (Ls= 90°, 2012 Mar 30).

Some of the better nightly sequences, especially one by Jaeschke on Mar 19/20 (Figure 9) shows the projection appearing from behind the dark limb, growing by rotation, reaching a maximum apparent height, then shrinking at the illuminated disk. Past projections, 2012 included, have proved invisible at the evening limb. We have not made precise height measurements (other than that stated) as they have been performed by Sánchez-Lavega *et al.* (2015),[36] who derived maxima of 200 ± 50km for Mar 20 and 260 ± 50km for Mar 21.

Peach measured the projection's precise location upon the image by Jaeschke on Mar 19 02:55.8 UT (CM= 157.2°) using *WinJUPOS*: –43.7°, 190.5°. This image was taken at the point at which the projection had impinged upon the terminator (33.3° *f.* the CM). The extreme range in observed CM translates to terminator longitudes of 169–195°. Measurements from Mar 20/21 images give a latitude range from –39 to –50°,[36] or a span of 460km.

Object B, 2012 March

We recorded another terminator projection in late March at a lower longitude, but at similar latitude (–48°), above the S*f.* terminator. The feature again showed slight variability:

Date	*CM (°)*	*Comments*
Mar 27	77.9	(Not visible at 71.0 or 79.8°)
Mar 28	72.7	(Not visible at 70.7 or 73.7°)
Mar 31	77.0	

Limits: 72.7–77.9°.
Observers: Jaeschke, Jolly, G. Walker.

It was not as pronounced as the earlier feature, and showed a narrow range of visibility (see Figure 10). It was, for instance, not visible upon good images before Mar 27, nor on Mar 29 at CM 76.7° or Mar 30 at 70.2°.

Object C, 2012 April

Another projection over the S*f.* terminator (near latitude –42°) resembled Object A more closely, but occurred within a slightly higher longitude band:

Dates	*CM (°)*	*Comments*
Apr 9/10	183.7	*Note 3*
Apr 11/12	157.0–168.2	*Note 3*
Apr 12/13	158.5–162.7	
Apr 13/14	183.0–184.4	(Not visible, for example, at 177.4 or 189.3°)
Apr 16/17	167.3–181.9	
Apr 19/20	188.4–189.9	
Apr 24/25	177.2–181.8	

Limits: 158.5–189.9°.
Note 3. These sightings from Eastern Europe were found online at ALPO Japan.[18]
Observers: Flanagan, Kardasis, Kivits, Peach, Sussenbach.

This object (Figure 11) was as impressive as the first projection, though it was less well observed. It varied in longitude, was best seen at shorter wavelengths and again fell within the southern magnetic anomaly region. There are clear negative observations earlier, during and later: for example on Apr 4 an excellent series by Barry over CM= 138.3–160.7° did not reveal anything, and on Apr 15 McKim (Figure 20) did not see it at CM= 170.3–175.2°. We feel that the object was not visible before Apr 9. However, on several dates during Apr 10–24 the relevant longitudes were not monitored intensely. We assume it was of the same nature as Object A.

In mid-May, under CM= 185–220°, Kivits made a special study of the terminator on several nights, but obtained no further positive sightings.

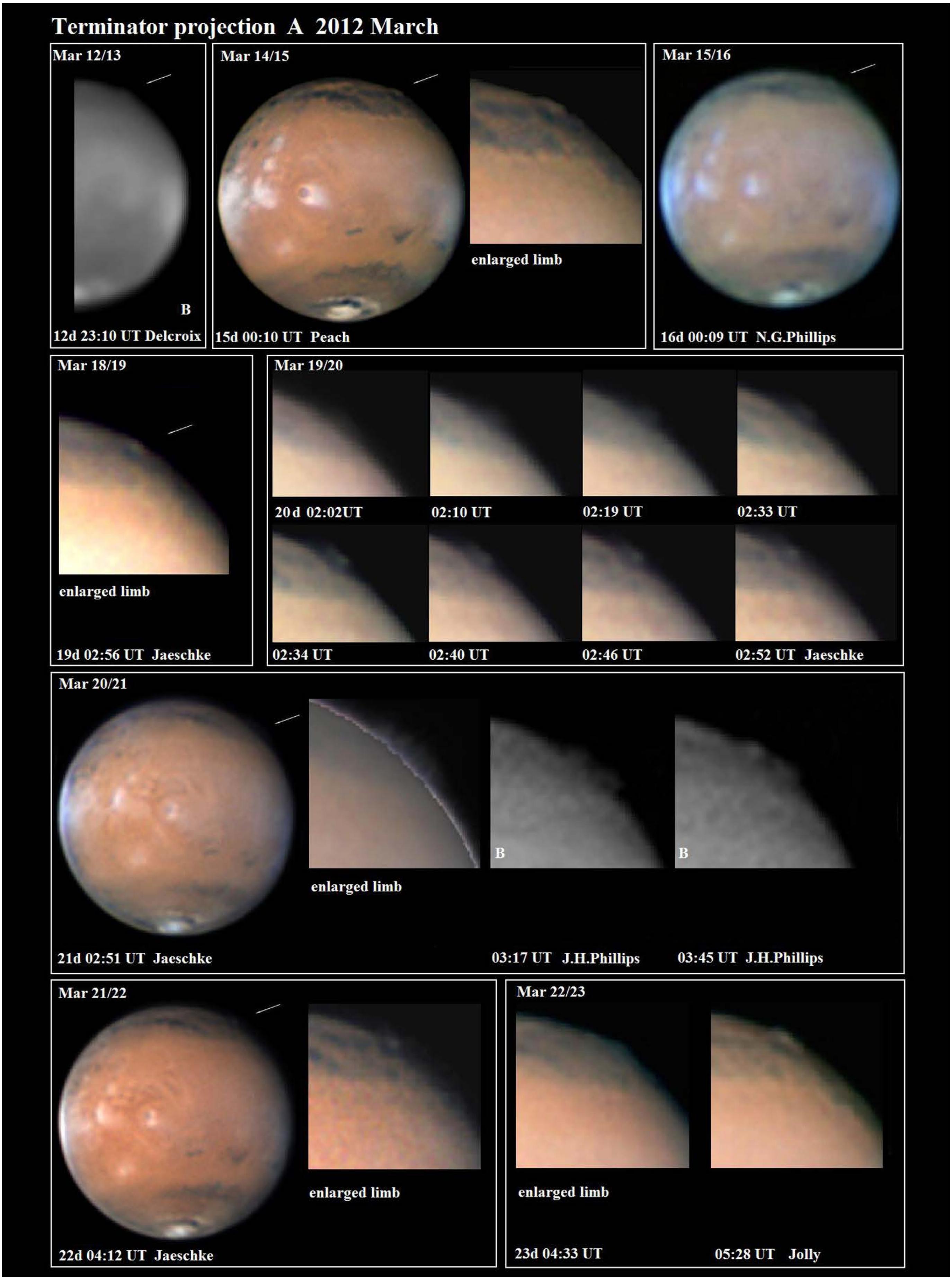

Figure 9. Terminator projection A, 2012 March. Selected nightly images and sequences (reproduced to the same scale) showing its remarkable size and its changing behaviour from night to night.

Object D, 2012 April

Finally, a very small event over SW *Xanthe* was imaged by Parker on Apr 6 (Ls= 93°), at 02:39–02:42 UT under CM= 353.3–354.1°. It was visible in R, but best seen in G & B. (Not seen by Grafton at 03:17 UT, nor under the same CML on the neighbouring days.) See Figure 12. The author measured it to be only 29km high, and white cloud perhaps mixed with some dust would be a reasonable assumption given its low altitude, near-equatorial location (at latitude +13°), and seasonal timing.

General discussion

Of the above phenomena, Objects A & C were the most remarkable. Could these events have been auroral in nature?

The discovery observation of martian aurorae by *Mars Global Surveyor* was made above this part of the planet,[37] although this early example was seen only to emit UV radiation. Aurorae registered by *Mars Express* averaged 137 ± 27km in altitude.[38] Minami (2012) has suggested a direct link with the major Coronal Mass Ejection (CME) events that had occurred only days before the 2012 March projections.[39] Major CME events were rare in 2012; CME data and space weather predictions may be obtained online.[40] CME velocities are highly variable: transit time to the Earth is 3.5 days on average, or 5.3 days to Mars.[41]

NASA's MAVEN orbiter has been studying the planet's atmosphere since 2014. The auroral activity was concentrated over the crustal magnetic anomaly region in the S. hemisphere (Figure 13).[38,42] Up till that point, the most energetic event had been recorded in 2015 March, following a CME event on Mar 11.[43] In 2015 the accumulated data showed that energetic martian aurorae could be visible to the naked eye from the surface of the planet, with blue light predominating, but with green and red also emitted.[44]

In 2017 September, the MAVEN Imaging Ultraviolet Spectrograph recorded a UV auroral event 25 times more intense than the previous brightest event of 2015 March, despite generally low solar activity. This followed a CME event on Sep 11. Increased radiation levels were detected upon the surface by the *Curiosity* rover.[45]

The 2012 March activity occurred directly above the southern magnetic anomaly. As Sánchez-Lavega *et al.* note,[36] this anomaly 'can drive the precipitation of solar wind particles in the atmosphere.' On the IAU albedo map the relevant area lies in *Electris*, SE of *Mare Cimmerium* (*Cimmeria Terra*). Antoniadi's 1933 projection lay over adjacent *Eridania*, and in the 1950s a number of observations of other apparently high clouds were recorded by Japanese observers, of which Saheki's (Figure 8C) was one of the most striking. The position of that 1950 cloud, again located at the border of *Electris* and *Eridania*, can hardly be ignored.

Sánchez-Lavega *et al.* also identified a high altitude terminator projection on 1997 May 17 (MY 23) HST images.[36] The only large recent terminator projection in our telescopic survey that was not associated with an ongoing dust storm dates from 2003 November (MY 26).[46–48] Another well-observed projection in the following month merely marked the highest point of the regional storm then covering *Hellas* and *Noachis*.[46] Minami noticed that the 2003 November event was also preceded by exceptionally fast solar wind.[39,48] The author's dust storm *Memoir* lists the most important terminator projections up to 1993.[34]

The brightness of the 2012 event was said to have been much higher than expected if only auroral processes had been involved.[36] The author noticed in the available rotational sequences that the projection brightened as it rotated into sunlight, then faded. This behaviour suggests the presence of at least some fine particulate matter. Sánchez-Lavega *et al.* did consider that 0.1μm particles of CO_2 or H_2O ice (as found in terrestrial mesospheric clouds) might constitute an alternative to aurorae,[36] provided they could be raised to that altitude, and the Director wonders whether the event's height coupled with its brightness may require the presence of both particulate matter and auroral processes.

MRO does not observe the martian terminator, so was unable to record the projection. This alone demonstrates the value of continued telescopic work. Meanwhile, a recent analysis of spacecraft plasma data tentatively supports the contribution of large CME events to the 2012 March–April & 1997 May phenomena.[49]

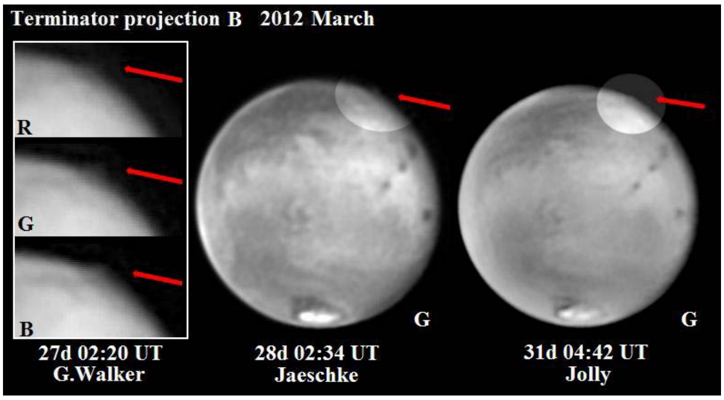

Figure 10. Terminator projection B, 2012 March. Selected nightly images.

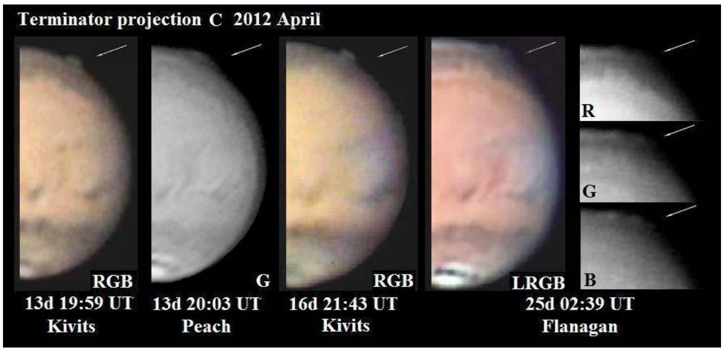

Figure 11. Terminator projection C, 2012 April. Selected nightly images.

Figure 12. Terminator projection D; the equatorial event of 2012 Apr 6.

Conclusions

A remarkable suite of large terminator projections was studied during 2012 March–April. Object A was located at altitudes up to 250km. Its high altitude – and its location above a region of residual crustal magnetic field – forces us to consider an aurora, though its brightness may suggest the presence of fine particulate matter. It is possible that some other interesting and previously unexplained ground-based observations of the same longitude region, such as that of Saheki in 1950, may have had the same origin. Since 2012 it has been demonstrated that martian aurorae, though they can occur planetwide and radiate primarily in the UV, are likely to be more intense in the region of the southern magnetic anomaly, and moreover will have a visible component.

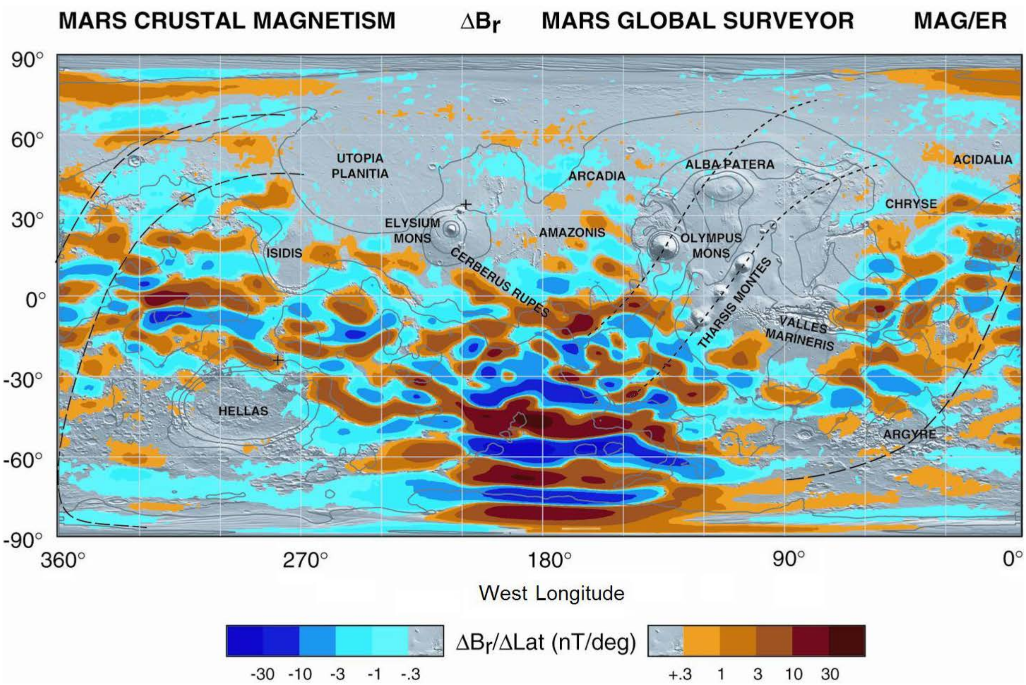

Figure 13. A chart of the residual crustal magnetism of Mars, showing the presence of closed magnetic field loops. Adapted from an online illustration,[42] plotting longitude west rather than east to accord with telescopic maps. B_r represents the magnetic field strength, and $\Delta B_r / \Delta Lat$ is the rate of change of field with latitude. In this figure, north is uppermost.

Height calculations

In Appendix I the author describes a simple way to calculate the height of a terminator projection, as no method has ever been published in the *Journal*.

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References & notes

1 Meeus J., *Astronomical Tables of the Sun, Moon and Planets*, Willmann-Bell Inc., 1983, pp 7–66 to 7–67
2 McKim R. J., *J. Brit. Astron. Assoc*., **116**, 169–186 (2006)
3 McKim R. J., *ibid*., **115**, 313–333 (2005)
4 McKim R. J., *ibid*., **94**, 197–210 (1984)
5 Collinson E. H., *ibid*., **77**, 202–207 (1967)
6 McKim R. J., *ibid*., **94**(5), front cover (1984)
7 Waterfield R. L., *ibid*., **43**, 240–242 (1933)
8 Thomson H., *Mem. Brit. Astron. Assoc*., **26**(1) (1924)
9 Antoniadi E.–M., *ibid*., **21**(4) (1920)
10 Antoniadi E.–M., *ibid*., **11**(3) (1903)
11 McKim R. J., *J. Brit. Astron. Assoc*., **121**, 258–259 (2011)
12 Venable R., *Sky & Telesc*., **122**(5), 50–51 (2011)
13 MacRobert A., *ibid*., **123**(4), 50–51 (2012)
14 McKim R. J., *J. Brit. Astron. Assoc*., **122**, 75 (2012)
15 McKim R. J., *ibid*., **123**, 6–7 (2013)
16 McKim R. J., '*Nature* Letter reports a remarkable terminator projection on Mars, 2012 March–April', *ibid*., **125**, 74 (2015)
17 The ALPO website: **http://www.alpo-astronomy.org/marsblog/** For short notes on the ALPO observations: Venable R., *J. Assoc. Lunar Planet Obs*., **54**(1), 8–10; (2), 10–11 & (3), 11–12 (2012)
18 ALPO Japan (JALPON) website: **http://alpo-j.asahikawa-med.ac.jp/Latest/index.html**
19 OAA website: **http://www.mars.dti.ne.jp/~cmo/ISMO.html** The OAA continued to publish its bulletin *Communications in Mars Observations* (the issues from 2011–'13 – lately online only – are relevant).
20 At the time of writing, the International Marswatch 2012 website is defunct.
21 **http://www.astrosurf.com/planetessaf/mars/index.htm**
22 MSL website: **http://mars.jpl.nasa.gov/msl/**
23 Stooke P. J., *International Atlas of Mars Exploration: From Spirit to Curiosity; Volume 2: 2004 to 2014*, Cambridge University Press, 2016
24 For a discussion of the evolution of large dust storms during 1999–2011, see Wang H. & Richardson M. I., *Icarus*, **251**, 112–127 (2015).
25 McKim R. J., ''Curiosity' at Gale crater', *J. Brit. Astron. Assoc*., **122**, 255–256 (2012)
26 McKim R. J., '*Curiosity*, Gale crater and BAA observer Walter F. Gale', *ibid*., **122**, 202–203 (2012)
27 McKim R. J., 'The opposition of Mars, 2010: Part I', *ibid*., **128**(3), 157–167 (2018)
28 Ebisawa S., *Contr. Kwasan Obs. Kyoto*, No. 89 (1960). See also the BAA Mars Section website: **http://www.britastro.org/mars**.
29 Venable R., *J. Assoc. Lunar Planet. Obs*., **54**(1), 8–10 (2012)
30 **https://www.nasa.gov/mission_pages/msl/multimedia/pia15968.html**
31 **https://www.nasa.gov/mission_pages/mars/multimedia/pia16450.html**. See also: **https://phys.org/news/2012-11-mars-reconnaissance-orbiter-storm.html**.
32 BAA *e-Bulletin* No. 661 (2012 Mar 12)
33 Antoniadi E.–M., *Bull. Soc. Astron. France*, **47**, 345–361 (1933)
34 McKim R. J., *Mem. Brit. Astron. Assoc*., **44**, 66 (1999)
35 See Ryves P. M., 'Cloud Formation on Mars', *J. Brit. Astron. Assoc*., **60**, 146 (1950). Saheki's drawing appears in this *Journal* (as Figure 8C) for the first time (*Mars Section Archives*); see also V. A. Firsoff, *The World of Mars*, Oliver and Boyd, 1969. From *J. Assoc. Lunar Planet. Obs*., **4**(2), 11; (3), 1; & 10–11 (1950) we learn that Saheki's projecting cloud was confirmed by two other Japanese on Jan 15 at 16:30 UT with the 30cm OG at Kwasan Observatory. R.J.McKim, *J. Brit. Astron. Assoc.,* **124**, 4–5 (2014) gives some details of Saheki's life and work. Japanese observers made other significant observations of limb and terminator projections and 'flashes' in 1950 & 1951–'52. One of the 'flash' observations (at *Tithonius Lacus* on 1951 Dec 8, again by Saheki) caused a sensation in the popular press, in connection with the atomic weapons testing of the time.
36 Sánchez-Lavega A. *et al*., *Nature*, **518**, 525–528 (2015)
37 Bertaux J.–L. *et al*., 'Discovery of an aurora on Mars', *ibid.*, **435**, 790–794 (2005)
38 For the *Mars Express* UV aurorae chart, 2004–'14, see: **http://www.esa.int/var/esa/storage/images/esa_multimedia/images/2015/11/mars_night-time_aurora/15667783-1-eng-GB/Mars_night-time_aurora.jpg**.
39 Minami M., *Communications in Mars Observations*, No. 396 (2012); see also Minami M. & Murakami M., 'The dawn protrusions observed in 2012 compared with those in 2003', *ibid*., No. 400 (2012).
40 **http://www.spaceweatherlive.com**. See also: **https://iswa.gsfc.nasa.gov/**.
41 **https://www.swpc.noaa.gov/phenomena/coronal-mass-ejections**
42 The magnetic contour map from *Mars Global Surveyor* was published by Connerney J. E. *et al*., *Proc. Nat. Acad. Science USA*, **102**, No. 42, 14970–14975 (2005); also see: **https://www.nasa.gov/centers/goddard/news/topstory/2005/mgs_plates.html**).
43 Schneider N. M. *et al*., 'Discovery of diffuse aurora on Mars', *Science*, **350**, No. 6261, 2015 Nov 6, aad0313; **DOI: 10.1126/science.aad0313**
44 Lilensten J. *et al*., 'Prediction of blue, red and green aurorae at Mars', *Planetary and Space Science*, 2015 May, PII: S0032–0633(15)00130-0, **DOI: 10.1016/j.pss.2015.04.015**; also see: **https://www.nasa.gov/langley/feature/blue-aurorae-in-mars-sky-visible-to-the-naked-eye**
45 **https://www.nasa.gov/feature/jpl/large-solar-storm-sparks-global-aurora-and-doubles-radiation-levels-on-the-martian-surface**
46 McKim R. J., *J. Brit. Astron. Assoc*., 120, 280–295 (2010)
47 **http://homepage2.nifty.com/~cmomn2/283OAA/index.htm**

Table 3. Observers of Mars, 2011–'12

Name	*Location*	*Instrument(s)*
P. G. Abel **V**	Leicester	203mm refl.
	Leicester University Obsy.	508mm DK Cass.
	Selsey, W. Sussex	381mm refl.
M. Adachi **V**	Dynic Observatory, Shiga, Japan	600mm Cass.
G. Adamoli	Verona, Italy	235mm SCT
L. Aerts	Heist-op-den Berg, Belgium	355mm SCT
T. Akutsu	Cebu, Philippines	355mm SCT
J. Albert **V**	Lake Worth, FL, USA	279mm SCT
W. Anthony	High Bridge, NJ, USA	203mm & 305mm SCT
(with V. Alexandrov & M. Revalski)	NJAA Edwin Aldrin Obsy.	660mm Cass.
D. L. Arditti **V**	Edgware, Middlesex	355mm SCT
F. Badalotti	Cremona, Italy	250mm MKT
K. N. L. Bailey	Swindon, Wilts.	152mm OG & 254mm refl.
T. Barry	Broken Hill, Australia	406mm refl.
D. R. Bates	Houston, TX, USA	254mm refl.
J. D. Beish **V**	Lake Placid, FL, USA	318mm & 406mm refls.
N. D. Biver **V**	Paris, France	407mm refl.
G. Boots & K. Peters	Worthing AS	279mm SCT
R. Bosman	Enschede, Netherlands	279mm SCT
J. Boudreau	Saugus, MA, USA	279mm SCT
S. Buda	Melbourne, Australia	405mm DK Cass.
P. Casquinha	Palmela, Portugal	355mm SCT
M. Cole	Keighley, Yorks.	279mm SCT
E. Colombo **V**	Gambarana, Italy	150mm refl.
M. Delcroix	Tournefeuille, France	254mm SCT
P. Edwards	Horsham, W. Sussex	279mm SCT
C. Fattinnanzi	Montecassiano, Italy	360mm refl.
W. D. Flanagan	Houston, TX, USA	355mm SCT
M. Foulkes	Henlow, Beds.	279mm SCT
S. Gale **V**	Landing, NJ, USA	254mm refl.
S. Ghomizadeh	Tehran, Iran	279mm SCT
J. Gionis	Breckland AS, Norfolk	235mm SCT
M. Giuntoli **V**	Montecatini Terme, Italy	203mm SCT
C. Go	Cebu, Philippines	355mm SCT
E. Grafton	Houston, TX, USA	355mm SCT
D. L. Graham **V**	Barton, Richmond, N. Yorks.	150mm MKT
D.Gray **V**	Kirk Merrington, Co. Durham	415mm DK Cass.
P. T. Grego **V**	St. Dennis, Cornwall	100mm OG & 203mm SCT
R. Haddon **V**	Coventry, Warwicks.	152mm OG
P. Haese	Blackwood, S. Australia	355mm SCT
C. Hastorf **V**	Fountain Hills, AZ, USA	127mm SCT
A. W. Heath **V**	Long Eaton, Notts.,	203mm SCT & 254mm refl.
C. Henshaw	Tabuk, Saudi Arabia	80mm OG
R. Hill	Tucson, AZ, USA	203mm MKT & 355mm SCT
M. Högberg	Örebro, Sweden	254mm refl.
D. A. Holt **V**	Kelling Heath, Norfolk	254mm refl.
K. C. Howlett	Cwmbran, Gwent	350mm refl.
	Wroughton, Wilts.	203mm SCT
T. Ikemura	Nagoya, Japan	380mm refl.
W. Jaeschke	West Chester, PA, USA	355mm SCT
P. Jennings **V**	Malton, N. Yorks	203mm SCT
R. Johnson	Liverpool AS	355mm SCT
R. Johnson	Pooraka, S. Australia	300mm refl.
R. W. Johnson	Ewell, Surrey	300mm SCT
G. Jolly	Gilbert, AZ, USA	355mm SCT
M. Kardasis	Athens, Greece	279mm SCT
A. S. Kidd	Welwyn, Herts.	355mm SCT
W. Kivits	Siebengewald, Netherlands	355mm SCT
R. Konnai	Fukushima, Japan	305mm SCT
S. Kowollik	Ludwigsburg, Germany	203mm refl.
T. Kumamori	Osaka, Japan	279mm SCT
P. Lawrence	Selsey, W. Sussex	355mm SCT
W. J. Leatherbarrow	Sheffield	235mm SCT
M. R. Lewis	St. Albans, Herts.	222mm refl.
R. N. B. Lewis	Cardiff	254mm SCT
P. Lyon **V**	Birmingham	203mm SCT
T. McCague **V**	Chicago, IL, USA	333mm refl.
R. J. McKim **V**	Upper Benefield, Northants.	410mm DK Cass.

48 Nakagawa T. & Minami M., 37th COSPAR Scientific Assembly, Montreal, Canada 2008; paper B02-0038-08

49 Andrews D. J. *et al.*, 'Plasma observations during the Mars atmospheric 'plume' event of March–April 2012', *J. Geophys. Res.*, 121, 3139-3154(2016), **DOI: 10.1002/2015JA022023**

50 Lowell P., *Mars as the Abode of Life*, MacMillan, 1908. Appendix 13, pp 256–265 reproduces the solution given in *Lowell Observatory Bulletin* No. 1, 1903 Jun 9. The 1900 & 1903 projections are further described in Lowell's *Mars and its Canals*, MacMillan, 1906, pp 100–104.

51 Antoniadi E.–M., *Mem. Brit. Astron. Assoc.*, **20**(4), 121–122 (1916). This semi-graphical solution is repeated in *La Planète Mars* (1930). His formula is correct but it is not stated that the result must be multiplied by the radius of the planet.

52 Flammarion C., *La Planète Mars*, **I**, Paris, 1892, p. 85

53 **https://pds-rings.seti.org/work/ephem_mar_37012.tab**

Table 3. Observers of Mars, 2011–'12 (*Cont'd*)

Name	*Location*	*Instrument(s)*
S. Macsymowicz	Ecquevilly, France	150mm MKT, 203mm & 305mm Cass.
R. Majewski	Las Vegas, Nevada, USA	203mm SCT
S. Massey	Hervey Bay, Queensland, Australia	305mm refl.
P. W. Maxson	Surprise, AZ, USA	254mm refl.
F. J. Melillo	Holtsville, NY, USA	254mm SCT
J. Melka	Chesterfield, MO, USA	305mm & 457mm refls.
L. E. Mercer	Malta	279mm SCT
M. Minami **V**	Fukui City Observatory, Japan	200mm OG
M. P. Mobberley	Bury St. Edmunds, Suffolk	300mm refl.
E. Morales Rivera	Aguadilla, Puerto Rico	310mm SCT
M. Morgan-Taylor	Leicester	355mm SCT
Y. Morita	Hiroshima, Japan	254mm refl.
P. U. Neville **V**	Maidenhead, Berks.	127mm MKT
D. Niechoy **V**	Göttingen, Germany	203mm SCT
S. Norrie	Coningsby, Lincs.	235mm SCT
T. Olivetti	Soiano del Lago, Italy	410mm DK Cass.
D. C. Parker	Miami, FL, USA	355mm SCT & 410mm refl.
D. A. Peach	Selsey, W. Sussex	355mm SCT
C. Pellier	Paris, France	250mm Gregorian
N. G. Phillips	Great Notley, Essex	245mm refl.
J. H. Phillips	Charleston, SC, USA	254mm OG
J.–J. Poupeau	Pecqueuse, France	350mm Cass.
A. R. Pratt	Leeds	203mm MKT
D. Put	Brielle, Netherlands	235mm SCT
A. H. Robinson	Dawlish, Devon	279mm SCT
R. W. Schmude	Barnesville, GA, USA	90mm MKT
I. D. Sharp	Ham, W. Sussex & Barbados, West Indies	279mm SCT
I. Sharp	Carlisle, Cumbria	254mm SCT
K. Smet **V**	Bornem, Belgium	305mm refl.
J. Sussenbach	Houten, Netherlands	279mm SCT
A. Tasselli	Lincoln	250mm refl.
T. Thibault	Blackstone, MA, USA	203mm SCT
D. B. V. Tyler	Flackwell Heath, Bucks.	355mm SCT
R. Vandebergh*	Wittem, Netherlands	254mm refl.
J. Vetterlein	Rousay, Orkney	100mm OG
D. Vidican **V**	Bacau, Romania	150mm refl.
G. Walker	Macon, GA, USA	254mm OG & 355mm SCT
S. Walker	Manchester, NH, USA	317mm refl.
J. Warell	Skivarp, Sweden	220mm refl.
A. Wesley	Murrumbateman, NSW, Australia	369mm refl.
F. Willems	Waipahu, Hawaii	355mm SCT
J. Willinghan	Elkridge, Maryland, USA	305mm SCT
K. Yunoki	Osaka, Japan	260mm refl.

*Vandebergh did not image Mars, but provided images of *Phobos-Grunt* whilst it was in Earth orbit.[14]

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

Abbreviations: Cass.= Cassegrain; DK= Dall-Kirkham; MKT= Maksutov-Cassegrain and SCT= Schmidt-Cassegrain (Telescope).

Appendix I

Calculating the altitude of a terminator projection

The calculation of the height of a projection at or beyond the morning or evening terminator is straightforward provided the problem is properly visualised. Percival Lowell demonstrated his mathematical ability in calculating the heights of terminator projections seen at his observatory in 1900 & 1903.[50] E.–M. Antoniadi offered a semi-graphical solution in the 1911 *Memoir* and in his book,[51] but his derivation is somewhat hard to visualise. Camille Flammarion described (without a diagram) a simple specimen geometrical solution in *La Planète Mars*.[52]

When representing a projection on a sketch there is often a tendency to exaggerate its size, and so to overestimate its height. No such problem exists with images, unless they are highly processed, which makes the phase appear smaller and the projection appear higher. It is necessary to brighten images so that the terminator is correctly exposed.

In Figure 14, C is the north pole of Mars and the arc of the large circle is the planet's perimeter. The direction of illumination chosen corresponds to the situation at the post-opposition morning terminator, TC. A projection, whose relative height has been exaggerated, is shown in the three positions 1, 2 & 3 as it rotates towards TC. In Position 1 it is completely in shadow. In the second position its top starts to catch the sunlight by virtue of its elevation, and begins to be seen from Earth (which lies in the direction PP′), while at Position 3 more of the feature is illuminated.

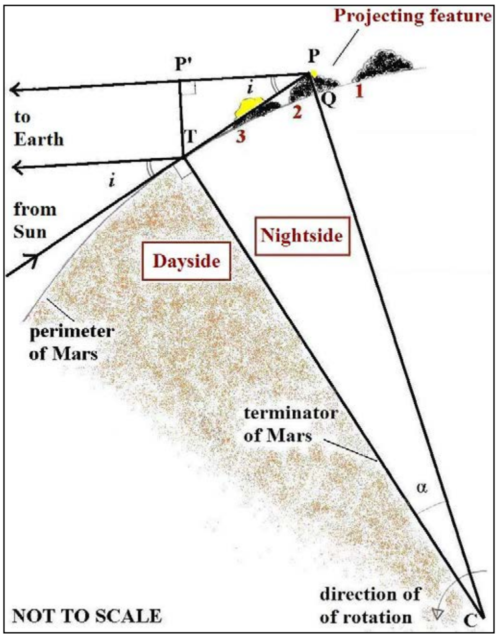

Figure 14. The geometry of terminator projections. *R. J. McKim*

Let PQ be the true height of the projection as its top first catches sunlight. In Position 2, it lies at an actual distance PT from the terminator. From Earth however it appears to lie at a distance P′T from the terminator, due to foreshortening. In Figure 14, angle i is the phase angle: the angular separation of the Sun and Earth as seen from Mars. If necessary, the fractional phase F (tabulated in the BAA *Handbook*) can be converted to the phase angle i by the formula:

$$F = \tfrac{1}{2}(1+\cos i)$$

Hence:

$$\cos i = 2F - 1$$

If we consider the plane of the Sun–Earth–projection, and if the distance P′T is measured from the image (or drawing), we can find PT from:

$$PT = P'T/\sin i$$
$$= P'T \operatorname{cosec} i$$

Now the problem is considered in the Sun-projection-Mars plane. In the right-angle triangle TPC, CT & CQ equal the radius of Mars, and PQ is the true height of the projection. First we find the angular distance α of the projection from the terminator, from:

$$\tan \alpha = (PT/CT)$$

Then, knowing α, we can derive the true height PQ:

$$CT = (CT+PQ)\cos\alpha \qquad \text{hence}$$

$$CT + PQ = CT / \cos\alpha \qquad \text{and}$$

$$PQ = CT\,((1/\cos\alpha) - 1)$$
$$= CT\,(\sec\alpha - 1)$$

In the above, all quantities must be consistently measured in millimetres or pixels. PQ, the true height of the projection, is now scaled to kilometres using the planet's equatorial radius of 3,397km. The distance from the top of the projection to the terminator *must* be measured in a direction perpendicular to the line of the cusps, and not radially towards the disk centre, except in the special case when it lies midway between the cusps. The formulae are independent of latitude and longitude of the projection, or of the values of D_e and D_s.

It is convenient to rotate the image using a programme such as *Registax* in order to give the greatest defect of illumination a position angle of 90 or 270° before carrying out measurements involving pixel-counting. The diameter of the image can be measured easily N–S; the distance of the projection beyond the terminator is then measured precisely in an E–W direction.

For Parker's 2012 Mar 21 image in Figure 8, the ephemeris gives i= 14.1°. On an enlarged copy, the radius (CT) is 302 pixels (px) and the highest part of the projection lies some 22px beyond the terminator, measured at right angles to the line of the cusps. This gives PT= 22 cosec 14.1 = 90px. Thus $\alpha = \tan^{-1}(90/302) = 16.6°$. Hence PQ= 3397 (sec 16.6 – 1) = 149km. At the time of this image the projection had rotated closer to the terminator, and its lower parts had become more illuminated. With an error of a single pixel in the distance of this projection from the terminator, an error of *ca.* ± 15km is easily introduced. The formulae are also extremely sensitive to phase angle.

For Antoniadi's published drawing in Figure 8, an online ephemeris gives i= 29.3°,[53] and the author obtained a height of around 23km from it. However, Antoniadi would have measured his *original* drawing to have derived the stated 35km.

For Parker's 2012 Apr 6 image in Figure 12, the ephemeris gives i= 24.2°. On an enlarged copy, the radius is 279px and the highest part of the projection is some 15px beyond the terminator, measured at right angles to the line of the cusps. This gives a much more modest height of 29km.

As a projection nears the terminator, some vertical structure may become visible as the lower parts become sunlit; for example, it may be shown to rise from a column at one end. It is assumed that the height measurement will be made at the moment the feature's summit is first illuminated. If measurement is made after the point of first detection, once it has moved towards the terminator, the calculated height will be too low.

If a very high projection is imaged at the moment it appears at the *limb*, then its height can be calculated directly in proportion to the planet's diameter.

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