The opposition of Mars, 2001: Part I

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

The highlight of this opposition was the outbreak of a planet-encircling dust storm in 2001 June, almost as obscuring and long-lasting as that of 1971, which set a new record as the seasonally earliest such event. Visual, imaging and polarimetric data demonstrate the presence of airborne dust for around 159 successive days. Atypically, the N. polar hood did not disappear during the storm, and instead showed considerable activity. Viewed before the storm, the albedo features showed little or no changes from 1999, but during and following the storm at least a dozen changes took place. These changes included the following: *Syrtis Major* became narrower to the NW, *Moeris Lacus* developed, NW *Mare Sirenum* and *Pandorae Fretum* darkened, *Phasis* reappeared, *Claritas–Daedalia* darkened and *Solis Lacus* became smaller with an altered orientation. Dust fallout brightened *E. Syria* and *Ausonia Borealis*, thinning *Mare Tyrrhenum* to the north of the latter. The Equatorial Cloud Band and the orographic clouds over *Olympus Mons* and the *Tharsis Montes* were followed from 2000 December till 2001 April and June respectively. Seasonal white cloud activity resumed from 2001 October as the dust storm subsided. Part II describes short-lived 'flashes' located in *Edom* recorded on 2001 June 7 and 8, when the sub-Earth and subsolar latitudes coincided, due to specular reflection from near-horizontal ground ice/hydrated mineral deposit or other smooth surfaces. These events had been predicted from seasonally similar observations made in 1954. A further flash on June 16 was located further south near *Hellespontus Montes*, another region found to have an historical precursor for such an event. The North and South polar regions are also described in Part II.

Introduction

Mars was under surveillance by NASA's *Mars Global Surveyor* (MGS)[1] before, during and after the period covered by our ground-based data. MGS in its polar orbit imaged N–S swathes of the disk at 2 pm local time. Atmospheric temperature data acquired by MGS and its Thermal Emission Spectrometer (TES) were relevant to the discussion of the great dust storm described in the present report.[1] Cantor has given a full account of the great storm,[2] and Strausberg *et al*.[3] have also described the event in great detail from several sources, whilst Smith *et al*.[4] have succinctly described MGS visual waveband and thermal imagery of its early history. Gurwell *et al*.[5] used submillimetre wavelength data to study the storm. Benson *et al*.[6] used MGS data to study water ice clouds, and James & Cantor[7] studied the NPC retreat in 2000 from MGS images. Smith has also carried out a longer-term review of TES data from 1999–2003.[8] On 2001 Oct 24 NASA's *Mars Odyssey* (launched 2001 April) reached the Red Planet,[9] and carried out thermal infrared imaging. Professional studies of the SPC in 2001 are of interest here.[10] The avalanche of new data has led to several reference books, such as those by Hartmann, Read & Lewis, and Barlow.[11]

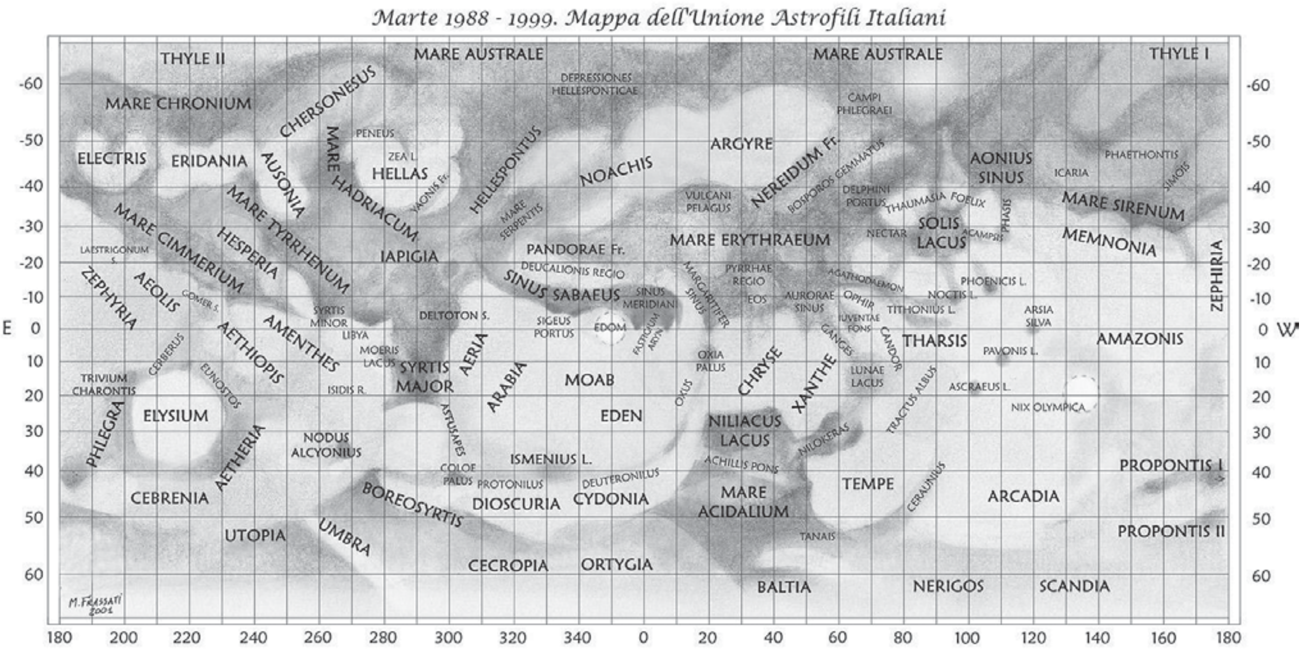

Figure 1. General UAI albedo map 1988–1999 drawn by Mario Frassati, lettered by Paolo Tanga. (See: M. Frassati & P. Tanga, 'Marte 1988–1999: la mappa dell'Unione Astrofili Italiani', *Astronomia UAI*, No. 4, 2001.) This map resembles the actual appearance of pre-opposition Mars in 2001.

Mars was in opposition in southern Ophiuchus on 2001 June 13 (diameter 20".4, appearing as a blazing red star at magnitude –2.3), at areocentric longitude (Ls) 177°, just before the start of southern martian spring. Falling within 90° of perihelion (Ls= 250°), the opposition heralded a new series of perihelic approaches. The planet was closest to Earth eight days after opposition, at 67.3 million km distant, diameter 20".8. The declination at opposition was –26.5°. Other details follow:

Physical data for the 2001 opposition

Solar conjunction	2000 Jul 01	Ls= 15°
Aphelion	2000 Oct 31	Ls= 70°
S. winter solstice/ N. summer solstice	2000 Dec 16	Ls= 90°
Opposition	2001 Jun 13	Ls= 177°
S. spring equinox/ N. autumnal equinox	2001 Jun 17	Ls= 180°
Perihelion	2001 Oct 11	Ls= 250°
S. summer solstice/ N. winter solstice	2001 Nov 11	Ls= 270°
S. autumnal equinox/ N. spring equinox	2002 Apr 18	Ls= 0°
Solar conjunction	2002 Aug 10	Ls= 53°

The latitude of the disk centre as viewed from Earth (D_e) was +3° at opposition. From 2000 October D_e (+25° at the start of the observing campaign) decreased to zero in early 2001 April, and reached –2° in early May. D_e then changed signs to reach +7° by early July, decreasing again to zero in September, reaching –26° by the close of the year, and decreasing steadily to around zero at the close of the apparition.

A total of 80 contributors (Table 1) followed Mars from 2000 Sep 15 (Gray, Ls = 50°) throughout 2001, till 2002 May 13 (Frassati and Minami, Ls = 12°): nearly 90% of a martian year. There were 3,634 observations: 2,810 CCD images, 775 drawings and 49 photographs (digital). Days observed per month (actual/possible) were: 2000 Sep 1/30; Oct 1/31; Nov 3/30; Dec 9/31; 2001 Jan 12/31; Feb 13/28; Mar 19/31; Apr 27/30; May 30/31; Jun 30/30; Jul 31/31; Aug 31/31; Sep 28/30; Oct 30/31; Nov 30/30; Dec 29/31; 2002 Jan 25/31; Feb 17/31; Mar 15/28; Apr 2/30; May 3/31.

Despite the generous disk diameter (>10 arcsec from 2001 late Mar till mid-Oct), 2001 was an exceptionally poor year for UK observers. Seasonally similar oppositions of 1907 (opposition Ls = 199°), 1922 (Ls = 175°), 1939 (Ls = 215°), 1954 (Ls=188°), 1969 (Ls=166°) and 1986 (Ls=202°) were all followed by the BAA. At opposition, Mars culminated at only 11° altitude from London, its declination remaining southward of –25° from mid-May until early October. Around opposition the few UK stalwarts could watch Mars only for a few hours either side of the meridian. The declination was more favourable many months either side. To offset atmospheric dispersion, some employed a narrow-angle prism; a deep red filter also helped. Large apertures had no advantage in bad seeing: the writer often preferred to use an 18cm off-axis stop with his large reflector. Other than the Director's efforts (2001 May 12 to 2002 March 29 for 71 drawings) there were no long UK series of visual observations. Fortunately, significant visual contributions came from lower or southern latitudes, notably from Makoto Adachi, Gianluigi Adamoli, Jeff Beish, Nicholas Biver, Walter Haas, Masatsugu Minami, Richard Schmude and Kamil Schumann.

Traditional photography has now been displaced by electronic imaging. Leading exponents of the new technology included Tomio Akutsu who sent over 400 images, Antonio Cidadão, Ed Grafton, Toshihiko Ikemura (300+), Teruaki Kumamori, David Moore, Yukio Morita, Don Parker (700+ images; hereinafter, 'Parker'), and Wei–Leong Tan. From Melbourne, Australia, where Mars was very high around opposition, Stefan Buda, Maurice Valimberti and colleagues made over 200 images between them. Using a telescope loaned by Robert Schulz, Herbert Csadek did some successful imaging from Namibia, but no British observer travelled south.[12] At the end of the apparition Damian Peach took high resolution images from the UK, something he would regularly achieve at later oppositions. From the south coast, Chris Proctor obtained small but useful images.

The Director issued observing tips,[13] BAA *Circulars* 777 and 779,[14,15] and one Section *Circular.*[16] He described the results at an Ordinary Meeting and during the 2002 Winchester Weekend Course,[17] and published two interim reports.[18,19] Notes were also given in a Report of Council.[20] Mars was regularly monitored by other groups. The OAA (Japan) bulletins and website[21] were always of interest, the ALPO issued *Circulars* and notes,[22] but no major amateur group has produced a final report. Schmude made polarimetric measurements.[23] Many observers contributed images to the Pro-Am *Marswatch* website, and many Hubble Space Telescope (HST) images were released onto the internet.[24] Dr Ebisawa summarised his polarimetric work.[25,26] A contemporary review of amateur planetary observing was published by Jean Dragesco.[27]

Observations

Figure 1 is the general map published by the Unione Astrofili Italiani (UAI). Figure 2 is a selection of the Director's drawings covering the whole apparition. We refer to the Ebisawa map[28] for matters of detailed nomenclature. The present Section Report continues from our account of the last opposition, 1999.[29]

Surface features

Generalities

At the beginning of the apparition there had been no obvious albedo changes since 1999. However, we could observe the more southerly features better. Estimates of intensities of albedo features could only be made prior to the global storm: afterwards, Mars was too distant. The amount of good data obtained was therefore not large, so we publish only a special study within the 'dust storm' section. The Director previously reported estimates for the ten oppositions from 1980 to 1999. This is now a field for electronic imagers to take up quantitatively.

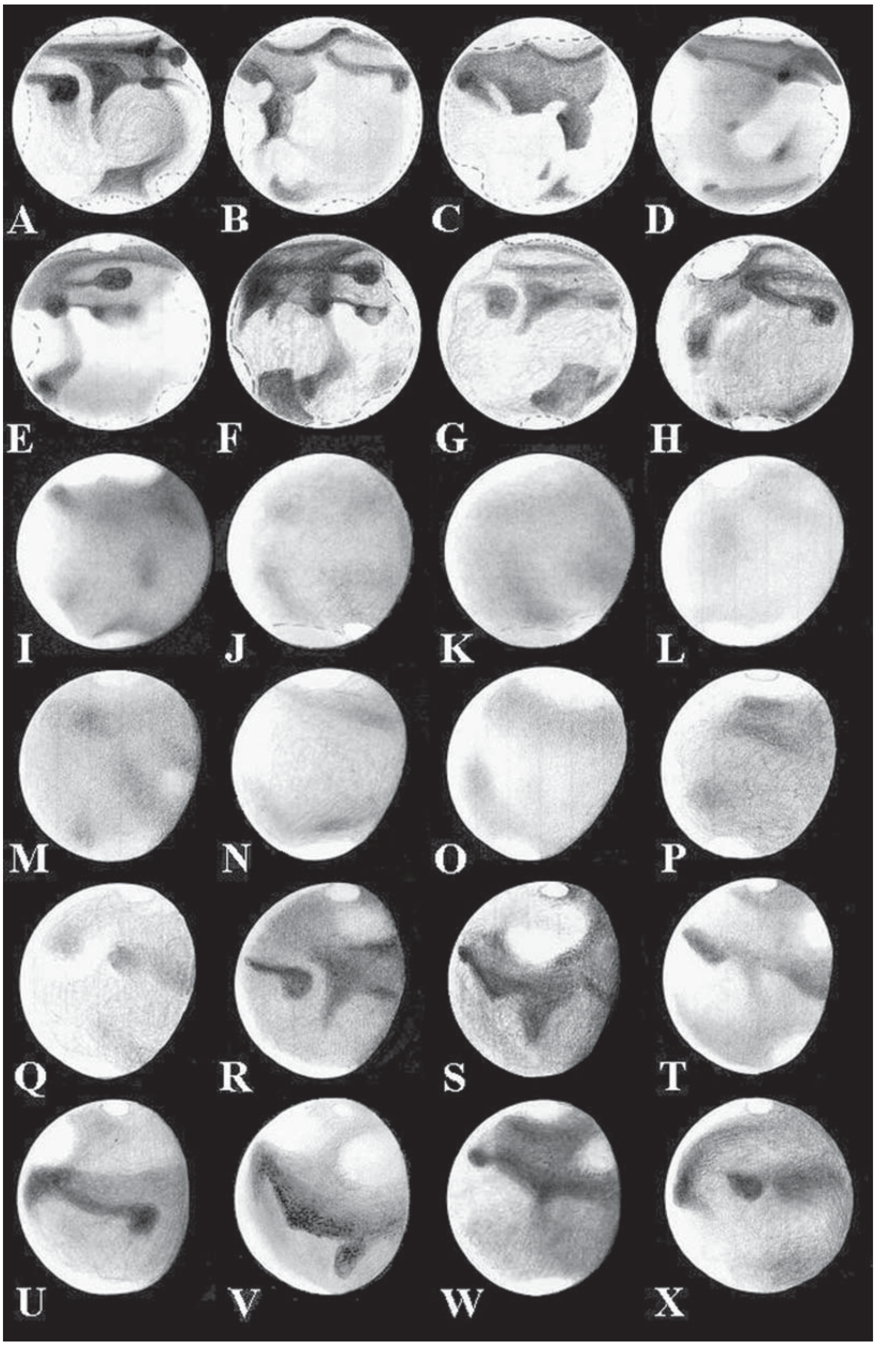

Figure 2. Drawings by the Director. All with 410mm Dall–Kirkham Cass., ×256, ×410, in white light, or with W15/W25 filters, except where stated.
Top row, left to right:
A 2001 May 22d 01h 00m, 300mm refl., ×141, ×353, CML= 31°. Brightness in *Argyre* within SPH.
B 2001 May 30d 00h 25m, CML= 310°
C 2001 Jun 4d 00h 20m, CML= 265°. SPH. *Nodus Alcyonius*.
D 2001 Jun 9d 00h 10m, CML= 218°. SPH, brighter on *p.* side. Pale surroundings of *Elysium*.
Second row, left to right:
E 2001 Jun 21d 23h 05m, CML= 87°. SPC, foreshortened and concave to N. pole in E and F; *Solis Lacus* region details; diurnal clouds.
F 2001 Jun 22d 22h 40m, CML= 72°. Weak or absent NPH.
G 2001 Jun 28d 22h 20m, CML= 14°. Evening limb yellowish and dusty.
H 2001 Jul 3d 21h 25m, CML= 316°. *Hellas* yellowish and oval. Albedo detail weak near *p.* limb. NPH larger, and bluish white.
Third row, left to right:
I 2001 Jul 6d 19h 50m, 200mm OG (Prague), ×200, CML= 266°. Major obscurations.
J 2001 Jul 29d 20h 40m, CML= 69°. Large NPH with bright patch in a.m. *Mare Acidalium* hardly visible. *Syria–Daedalia* dusky.
K 2001 Jul 31d 20h 30m, CML= 48°
L 2001 Aug 10d 20h 00m, CML= 302°. Ghostly *Syrtis Major* with bright *Hellas*.
Fourth row, left to right:
M 2001 Aug 13d 20h 10m, CML= 282°
N 2001 Aug 20d 19h 30m, CML= 219°. Darker patches in the north.
O 2001 Sep 25d 18h 40m, CML= 210°
P 2001 Sep 29d 18h 30m, CML= 169°. SPC easy, but border not seen. Markings darkening in the south, with classical W. end of *Mare Sirenum* restored and E. part still obscured. Faintly dusky *Olympus Mons* on *p.* side.
Fifth row, left to right:
Q 2001 Oct 6d 18h 15m, CML= 98°. Bright surface dust between *Aurorae Sinus* and *Solis Lacus*. *Claritas–Daedalia* dusky.
R 2001 Nov 19d 17h 40m, CML= 19°. Markings normal. *Argyre* light.
S 2001 Nov 26d 17h 30m, CML= 308°. N. *Hellas* still dusty and light.
T 2001 Dec 8d 16h 55m, CML= 181°. Obvious diurnal clouds.
Bottom row, left to right:
U 2001 Dec 29d 17h 10m, CML= 336°
V 2002 Jan 2d 17h 15m, CML= 298°. No dust in *Hellas*.
W 2002 Jan 19d 17h 05m, CML= 126°. *Claritas–Daedalia* darkening. (D = 5.7")
X 2002 Feb 28d 18h 00m, CML= 104°. Tilted *Solis Lacus* with the new secular darkening following. (D = 4.8")

Much space was given to martian apparent colours in our 1999 report,[29] but there were fewer descriptions this time, and the images must speak for themselves. Biver often found the principal maria dark blue-grey. Specific remarks are included below. Drawings of the planet are given in Figures 2–3, and CCD images illustrating the unobscured surface features in Figures 4–6.

Region I: long. 250–010°

Before the dust storm

Refer to Figures 2–4. *Syrtis Major* was broad and blunt-ended, as in many past apparitions, the continuing darkened aspect of *Astusapis Sinus* at the NW corner (perhaps a bit darker than in the 1990s) being responsible for the straight north edge. Grafton's June 11 image probably shows the most internal detail of all the images to hand. *Nili Sinus* was a tiny NE protrusion. *Osiridis Promontorium* was a tiny protrusion to the east side, and there was then a tiny gap and a very tiny spot marking *Moeris Lacus*. All these details were like the 1990s aspect. The *Syrtis* had a dark bluish tint to several observers and in many images, the hue being enhanced by diurnal cloud from *Isidis Regio–Libya* near the limb or terminator. *Nepenthes* was not seen. The dark spot inside *Huygens* was visible, though as in the last few apparitions the basin interior was continuous with the desert to the west. *Deltoton Sinus* was invisible, with just *Nymphaeum Promontorium* protruding from the SW of the *Syrtis* to indicate its place.

To the north, *Nodus Alcyonius* maintained its isolated triangular shape, and *Utopia* was dark. The details of

Table 1. Observers of Mars in 2001

Name	*Location*	*Instrument(s)*
M. Adachi	Otsu, Japan	310mm refl.
G–L. Adamoli	Verona, Italy	108mm OG
T. Akutsu*	Tochigi, Japan	320mm refl.
	Okinawa, Japan	400mm refl.
D. Bates**	Houston, Texas, USA	254mm refl.
S. Beaumont	Kendall, Cumbria	203mm SCT
J. D. Beish	Lake Placid, Florida, USA	320mm refl.
N. Biver	Meudon Observatory, France	320mm OG
	Versailles, France	256mm refl.
	Noordwijk, Holland	203mm refl.
J. N. Brown	Warmington, Northants.	254mm refl.
S. Buda*, B. Curcic* & M. Justice*	Melbourne, Australia	250mm DK Cass.
T. R. Cave	Long Beach, California, USA	325mm refl.
A. Cidadão*	Oeiras, Lisbon, Portugal	254mm SCT
E. Colombo	Milan, Italy	150mm refl.
B. A. Colville*	Cambray, Ontario, Canada	300mm SCT
E. Y. Crandall	Winston-Salem, N. Carolina	75mm OG
H. Csadek*	Hakos, Namibia, SW Africa	203mm SCT
K. De Groff**	Kwajalein, Marshall Is., South Pacific	254mm refl.
P. Devadas	Madras, India	355mm refl.
T. M. Dobbins* et al.§	Florida Keys, USA	152mm refl.
		300mm SCT
C. Ebdon*	Fordham Heath, Essex	254mm refl.
N. Falsarella*	São Jose do Rio Preto, São Paolo, Brazil	200mm refl.
M. Frassati	Crescentino, Italy	203mm SCT
C. M. Gaskell	Lincoln, Nebraska, USA	203mm SCT
		406mm Cass.
E. Grafton*	Houston, Texas, USA	356mm SCT
D. Gray	Kirk Merrington, Spennymoor, Co. Durham	415mm DK Cass.
W. H. Haas	Las Cruces, New Mexico, USA	320mm refl.
G. D. Hall*	Dallas, Texas, USA	203mm SCT
T. Haymes*	Reading, Berks.	305mm refl.
A. W. Heath	Long Eaton, Notts.	203mm SCT
M. J. Hendrie	Colchester, Essex	152mm OG
C. Hernandez	Miami, Florida, USA	203mm SCT
T. Ikemura*	Nagoya, Japan	310mm refl.
T. Kumamori*	Sakai City Observatory, Japan	600mm Cass.
E. Lo Savio	Catania, Italy	203mm SCT
R. J. McKim	Upper Benefield, Northants.	216mm refl.
		300mm refl.
		410mm DK Cass.
	Oundle, Northants.	102mm OG
	Petrín Observatory, Prague, Czech Republic	200mm OG
G. Marino	Catania, Italy	203mm SCT
S. Massey*	Siding Spring, Australia	600mm Cass.
F. J. Melillo*	Holtsville, New York, USA	203mm SCT
C. Meredith*	Manchester	203mm SCT
M. Minami	Fukui City Observatory, Japan	200mm OG
	Naha, Okinawa, Japan	250mm refl.
		400mm refl.
D. M. Moore*	Phoenix, Arizona, USA	362mm Cass.
S. L. Moore	Fleet, Hants.	222mm refl.
Y. Morita*	Hiroshima, Japan	250mm refl.
E. Ng*	Hong Kong	356mm SCT
D. Niechoy	Göttingen & Kirchheim, Germany	203mm SCT
		102mm OG
B. Pace*	Sydenham, Victoria, Australia	152mm Mak–Cass.
M. Palermiti*	Jupiter, Florida, USA	254mm refl.
P. W. Parish	Rainham, Kent	102mm OG
D. C. Parker*	Coral Gables, Miami, Florida, USA	410mm refl.
T. J. Parker*	Los Angeles, California, USA	318mm Cass.
D. A. Peach*	King's Lynn, Norfolk	305mm SCT
I. S. Phelps	Warrington, Cheshire	114mm refl.
		215mm refl.
T. C. Platt*	Binfield, Berks.	250mm refl.
		320mm refl.
C. J. Proctor*	Torquay, Devon	500mm refl.
T. J. Richards*	Melbourne, Australia	180mm OG
F. Salvaggio	Catania, Italy	203mm SCT
R. W. Schmude	Barnesville, Georgia, USA	102mm OG
	Villa Rica, Georgia, USA	510mm refl.
R. Schulz*	Vienna, Austria	300mm OG
		203mm SCT
K. Schumann	Mt Stromlo Observatory Canberra, Australia	229mm OG
M. Di Sciullo*	Coconut Creek, Florida, USA	254mm refl.
W. P. Sheehan	Willmar, Minnesota, USA	300mm SCT
	Union Observatory, Johannesburg, S. Africa	673mm OG
I. Stellas	Athens, Greece	102mm OG
		130mm OG
D. Strange*	Worth Matravers, Swanage, Dorset	500mm refl.
Wei–Leong Tan*	Singapore	279mm SCT
P. Tanga	St André de la Roche, Nice, France	150mm refl.
G. Teichert	Hattstatt, France	279mm SCT
D. M. Troiani	Schaumberg, Illinois, USA	444mm refl.
M. Valimberti*	Melbourne, Australia	152mm OG
A. Gonzalo Vargas	Cochabamba, Bolivia	203mm refl.
		254mm refl.
C–K. Yan*	Hong Kong	250mm Mak–Cass.

* CCD observations submitted (some of these observers also sent drawings); ** photographs

§ A group representing *Sky & Telescope* and the ALPO observed from Florida Keys in early June, comprising P. & T. D'Auria, C. & M. Collins–Peterson, T. Dobbins, R. T. Fienberg, L. & S. Ireland, R. Itzenthaler, D. M. Moore, D. C. Parker, G. Seronik and D. M. Troiani. The successful results of their *Edom* 'flare campaign' (described in Part II) were reported to the BAA by Dobbins & Parker.

The work of Palermiti was sent by Carlos Hernandez. Images by Kumamori and Morita were sent by Masatsugu Minami (OAA Mars Coordinator). Drawings by Lo Savio, Marino and Salvaggio were sent by Paolo Tanga (UAI Mars Coordinator).

Boreosyrtis, *Protonilus*, *Ismenius Lacus* and *Deuteronilus* looked as they did in 1999, but at higher resolution. In particular, *Ismenius Lacus* continued to be much less prominent than in the 1980s decade. The far northern details were not favourably presented near opposition.

As has been the case for some time, northern *Ausonia* (*Ausonia Borealis*, or *Trinacria* [IAU]) was shaded, in contrast to the southern, brighter part. *Mare Tyrrhenum* was dark, especially at the north edge, and *Syrtis Minor* was just a small dark northward inflexion, as in 1999.

As will be related, the diurnal cloud over *Hellas* early in the apparition gave way to ground frost, and then to bare ground by 2001 May. *Hellas* exhibited scant floor details at this stage, but *Zea Lacus* was easy and *Peneus* weakly seen. The N. edge of the basin was very poorly outlined before the storm, but the dark belt of *Mare Australe* separated the S. part from the new spring cap. *Mare Hadriacum* was visible but less conspicuous before the storm. *Yaonis Fretum/Hellespontus* were as usual dark (the latter clearly divided by *Yaonis Regio*), and *Nerei Depressiones* was a dark patch on *Yaonis Fretum*. *Depressiones Hellesponticae* was a larger dark patch, visible even during the dust storm, and dark bluish to Minami on Jul 24.

Sinus Sabaeus was very dark, brownish to Minami in April, and only weakly connected with *Mare Serpentis* on the eastern side. The latter was very dark, and extended to the SW as a dark belt (or arch) that crossed *Noachis* and joined E. *Mare*

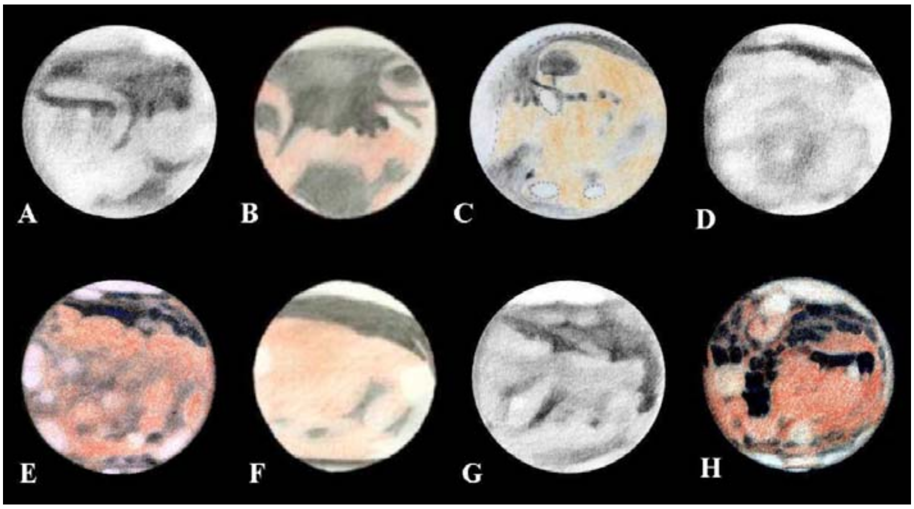

Figure 3. Pre-storm drawings.
A 2001 May 12d 17h 20m, 310mm refl., ×400, CML= 0°, *Adachi*. Dark arch across *Noachis*; sw *Edom*; SPH and vw *Argyre*.
B 2001 May 22d 02h 15m, 305mm SCT, ×406, W25, CML= 49°, *Peach*. Thin NPH. *Solis Lacus* and *Tithonius Lacus* prominent.
C 2001 Jun 3d 12h-13h, 229mm OG, ×300, ×625, W21A, CML= 84°, *Schumann*. *Solis Lacus* and surrounding details including *Geryon*. *Juventae Fons*. Several white clouds. SPH.
D 2001 Apr 27d 17h 40m, 310mm refl., ×400, CML= 141°, *Adachi*. Note sw orographics.
E 2001 Jun 15d 23h 54m, 256mm refl., ×333, CML= 152°, *Biver*. SPC. Orographic clouds. *Mare Sirenum* is the bluest marking visible.
F 2001 May 9d 03h 20–50m, 305mm SCT, ×406, CML= 186°, *Peach*. *Propontis*; *Elysium* with faint surroundings.
G 2001 May 25d 16h 40m, 310mm refl., ×400, CML= 233°, *Adachi*. Large SPC, *Aetheria* darkening.
H 2001 Jun 1d 02h 02m, 256mm refl., ×333, CML= 316°, *Biver*. Slight whitening of *Edom*, and patch of cloud in S. *Hellas* from SPH. *Huygens*.

Erythraeum. This aspect of a band crossing *Noachis* was very similar to 1986: it was too far south to have been taken for *Pandorae Fretum*, though there was some slight shading at the W. end of the classical location of the latter, merging gradually into the lighter *Deucalionis Regio*. *Sinus Sabaeus* and *Meridiani Sinus* (which showed both classical 'forks' as well as the third, narrower, *Brangaena*) showed the same aspects as in the last decade. The large equatorial deserts of this region were void of interesting markings: *Gehon* was weak and diffuse, and traces of *Typhon–Orontes* as a pale diffuse incomplete belt lay north of *Sinus Sabaeus*, as in several past apparitions. The phenomena exhibited by *Edom* are discussed separately, in Part II of this paper.

During and after the dust storm

Refer to Figures 2, 4, 7 and 9–11. *Syrtis Major* became narrower, thinning on the W. boundary and thus becoming more tapering to the north, as was apparent from Parker's Dec 8–9 images (Figure 4H) and the Director's drawings (Figure 2S). Ikemura also drew attention to the change. It is many years since the *Syrtis* changed shape; however, the change did not persist into the next apparition. There are earlier instances of a narrowing following a large storm, for example in 1973, but the change is certainly not the seasonal event that it was once believed to have been.[30]

Nepenthes did not reappear, but from December it was clear that *Moeris Lacus* had become considerably enlarged and extended to the east. In fact, Parker's images of Dec 8–9 (Figure 4H) partly recall its aspect in 1909,[30] also just after an encircling storm. Also in early December, *Deltoton Sinus* (largely invisible since 1975) partly recovered its classical form on the W. of *Iapigia*, but this change too would prove to be short-lived. *Ausonia Borealis* (*Trinacria*) had become lighter, now appearing continuous with the southern part, *Ausonia*

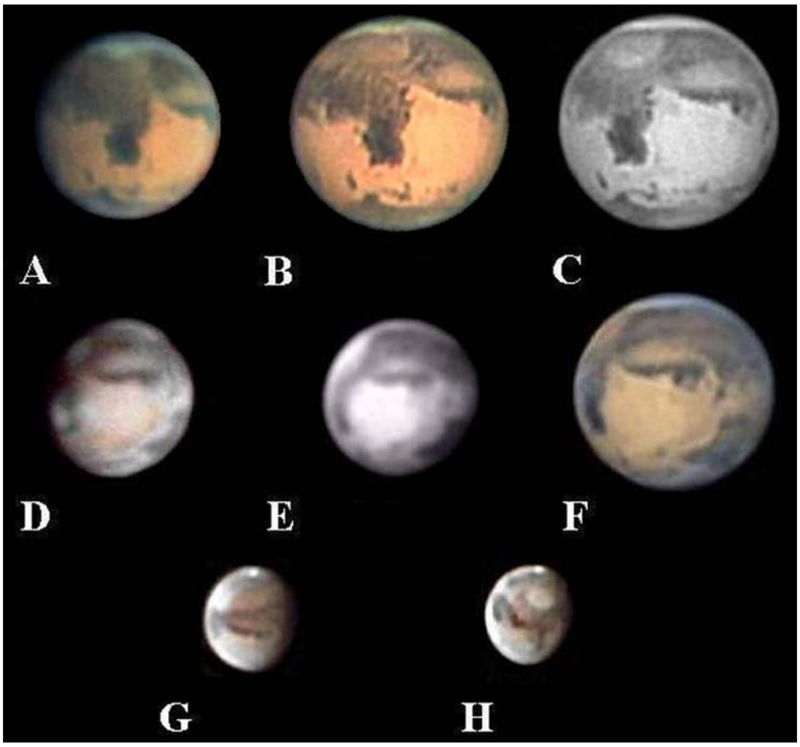

Figure 4. ***Region I.***
***A–F** pre-storm and early storm*
A 2001 May 13d 13h 16m, 254mm DK Cass., CML= 292°, *Buda & Curcic*. SPH protrudes into S. *Hellas*.
B 2001 Jun 11d 07h 03m, 356mm SCT, CML= 301°, *Grafton*. Many *Syrtis Major* fine details including *Huygens*. *Hellas* dull. Albedo detail in southern SPC.
C 2001 Jun 17d 11h 36m, red light image, 254mm DK Cass., CML= 314°, *Buda*. Exceptionally fine details, *e.g.*, in *Protonilus–Deuteronilus* with small *Ismenius Lacus* (faded on E. side). Albedo detail in southern SPC.
D 2001 Mar 26d 09h 50m, 410mm refl., CML= 330°, *Parker*. Bluish p.m. *Syrtis* cloud; faint ECB; *Hellas* bright.
E 2001 Jul 5d 00h 08m, 254mm SCT, infrared image, *Cidadão*, CML= 347°. The still dust-free side of Mars, nine days into the global dust storm: only *Hellas* is dust-filled at the limb.
F 2001 Jun 21d 16h 30m, C11, CML= 359°, *Tan*. *Hellas* dull. Cloud activity low.
***G–H** post-storm*
G 2001 Nov 29d 22h 44m, 410mm refl., CML= 355°, *Parker*.
H 2001 Dec 9d 00h 05 m, 410mm refl., CML= 285°, *Parker*. Note enlarged *Moeris Lacus* and *Deltoton Sinus*; lighter N. *Ausonia*.

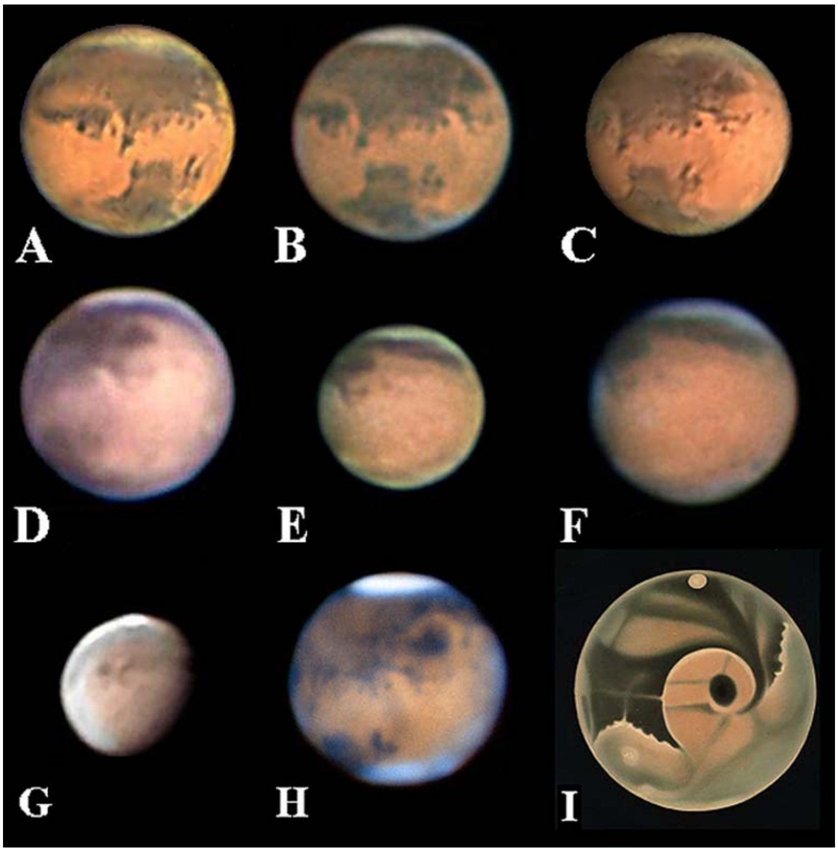

Figure 5. ***Region II. A–F, pre-storm***

A 2001 Jun 3d 07h 28m, 356mm SCT, CML= 18°, *Grafton*. Small details in S. *Chryse–Xanthe* as well as *Juventae Fons*, in **A–C**.
B 2001 Jun 10d 13h 06m, CML= 38°, *Buda & Curcic*.
C 2001 May 29d 06h 57m, 356mm SCT, CML= 55°, *Grafton*. *Tithonius Lacus* fine details.
D 2001 Jun 12d 17h 06m, 200mm DK Cass., CML= 79°, *Kumamori*. *Nix Olympica* in a.m.
E 2001 May 31d 12h 28m, CML= 118°, *Valimberti*. Weak clouds in *Tempe* and *Arcadia* (*Alba*) in **D–F**.
F 2001 May 31d 13h 05m, 254mm DK Cass., CML= 127°, *Buda & Curcic*.

G–H, comparisons including post-storm
G 2001 Oct 14d 00h 16m, 410mm refl., CML= 117°, *Parker*. Post-storm, *Phasis* present, *Tithonius Lacus* weak, *Claritas–Daedalia* darkening.
H 1986 Jul 15d 23h 07m, 1060mm Cass. (Pic du Midi Observatory), CML= 68°, TP2415 film, *J. Dragesco* (*assisted by R. J. McKim*). This R(G)B colour composite was prepared from original W29 red and W49 violet filter images by *J. Warell*: *Solis Lacus* is very large; *Phasis* and *Gallinaria Silva* following.
I 1877 Sep 3, drawing by *E.Trouvelot*.[32] Note the darkened *Phasis*, invisible *Nectar* and faded *Tithonius Lacus*.

Australis, a change which would persist into the next apparition. This settled dust impinged upon and slightly narrowed *Mare Tyrrhenum* north of *Ausonia Borealis*. *Hellas* exhibited floor detail again, in the shape of *Zea Lacus*. *Mare Hadriacum* was somewhat different in shape, and Parker described it as having a bluish cast in the morning on Dec 12 (owing to dull *Hellas* a.m. cloud). Minami found *Mare Tyrrhenum* visually greenish compared with *Mare Cimmerium* in November.

After the storm, *Pandorae Fretum* looked darkened and more classical in appearance (Figures 2U, 4G); *Mare Serpentis* remained dark.

Region II: long. 010–130°

Before the dust storm

Refer to Figures 2, 3 and 5. *Mare Acidalium* was as usual large and dark, and brownish to Minami (2001 Feb 19). Its separation from *Niliacus Lacus* was evident as usual, and, as in the 1990s, the latter showed several small projections from its S. side. This entire region including *Nilokeras*, the little dark spots *Idaeus Fons* and *Achilles Fons*, and the broad halftone *Ganges* appeared just as in 1999. As in *Region I,* details north of lat. +60°, including *Hyperboreus Lacus*, were too far north to be seen. *Tempe–Arcadia* and *Ascraeus Lacus* were again strongly reddish (when cloud-free) as noticed in several past oppositions (*e.g.*, Minami 2001 Feb 16 and later; Parker's Feb 8 image, etc.). *Uranius/Nilus* was very weak and diffuse and *Ceraunius* was invisible. *Olympus Mons* and the *Tharsis Montes* were apparent from their orographic clouds (2000 Dec–2001 Jun).

Mare Erythraeum, *Margaritifer Sinus/Oxia Palus*, *Chryse/Xanthe* (and the small dark spots at their S. boundary with *Aurorae Fretum/Aurorae Sinus*) were exactly as in 1999. *Aurorae Sinus* was as always conspicuously dark, appearing blue-black to Minami (Feb). *Juventae Fons* and *Baetis* were well seen in good seeing, and Cave even noticed that *Baetis* appeared as a twisted streak on May 29. *Tithonius Lacus* showed intricate small details, as it had done at the last opposition. *Tithonius Lacus* was not obviously connected to the dark spot *Phoenicus Lacus*, but the latter was joined to the weaker dark patch *Arsia Mons* by a pale band of shading.

Solis Lacus remained large and dark, its long axis running east-west. As in 1999 two small protrusions were visible on its S. edge, the *p.* one more evident, and beautifully shown on images by Grafton, Kumamori and Morita. Of the classical canali around the 'Eye of Mars', only *Geryon* was dark. *Nectar* was broad and dark. There was no sign of *Phasis*. *Gallinaria Silva* again appeared as a small spot, weaker than 1999, but the broad, faint E–W band of shading running W. from it appeared as in the last apparition. This shading ran across the *Daedalia* desert, cutting across the path of classical (but invisible) *Araxes*. It continued west into a faint band of shading north of *Mare Sirenum/Mare Cimmerium*, which has been noted in several previous apparitions. Compare the 2001 pre-storm appearance of *Solis Lacus* with a high resolution photograph by Prof J.Dragesco in 1986[31] at similar Ls. (Figure 5H) In 1986 notice the strong *Phasis* streak, terminated to the north by the conspicuously dark *Gallinaria Silva*.

In 2001 we could see a little more to the south. *Argyre* was a halftone, not distinguished from *Chalce* or *Noachis* except when frosted. The southern surroundings bordering the light *Thaumasia* appeared dark, from *Bosporos Gemmatus/Phrixi Regio*, through *Aonius Sinus* (a darker condensation) continued via the seasonally darkened *Icaria* to the E. end of *Mare Sirenum*. *Chrysokeras* did not appear light. *Mare Australe* was again a dark southern belt, marking the edge of the SPC.

In the 1986 BAA report[31] we illustrated the changes in *Solis Lacus* and environs over many years.

During and after the dust storm

Refer to Figures 2, 5, 7 and 9–11. Even in the early part of the storm it was easy to witness the development of a great new dark area in *Claritas–Daedalia* (whose W. end was near long. 130°) that extended eastward into *Syria*, north of *Solis Lacus*. This was adjacent to a region that constantly had lofted bright dust from early July onwards. On Jul 8 images by Ikemura and other Japanese observers showed the area had begun to darken. Adamoli drew attention to it on Jul 21. A series of complex dusky patches was drawn by Stellas on Jul 23; Biver on Jul 21 and 24 (Figure 9J) showed it fully developed with bright dust over *Thuamasia*. After the dust had settled, *Syria* regained its normal brightness, augmented by dust fallout, but the large dark patch in *Claritas–Daedalia* (shaped somewhat as in 1973–'75, and encroaching upon Region III) together with a newly darkened (and strongly curved) *Phasis* streak, and the dark spot *Gallinaria Silva* remained. *Phasis* had been imaged from early September onwards, when *Solis Lacus* itself was still mostly hidden by bright dust. *Solis Lacus* was seen to have a new, more circular shape, and was smaller with its long axis rotated clockwise so that it extended somewhat to the NW. It appeared brownish on Parker's 2002 Mar 13 image. *Solis Lacus* would recover its older form by the 2003 opposition, but the changes in *Phasis/Claritas–Daedalia* would persist longer. Meanwhile the 2001 aspect of *Solis Lacus/Phasis* calls to mind drawings from 1877, such as one by Trouvelot (Figure 5I).[32]

The region continued to change after the dust had settled. In November the centre of *Solis Lacus* was north of the 1999 position. More dust settled over the northern part of *Solis Lacus* and dust was lifted in the south so that its centroid gradually migrated south. However even at the end of the apparition it was still abnormal. CCD measures of latitude by Minami gave: 2001 Nov 20: 16–24° S (Parker); 2002 Jan 28: 20–27° S (Parker); 2002 Mar 1: 20–30° S (Peach).

Dust must also have settled out over *Nectar, Melas Lacus* (and *Tithonius Lacus* generally) and over central and western *Valles Marineris*: thus from 2001 late Sep and for many months a light gap ran from *Candor–Ophir* all the way to southern *Thaumasia*, with a persistent brighter patch in E. *Syria*. *Coprates* and *Tithonius Lacus* were faintly reappearing at the end of the opposition, but *Nectar* remained hidden by surface dust.

From Jul 5–Oct 24 *Olympus Mons* and the *Tharsis Montes* appeared as dark brownish spots. Dust therefore did not rise above their summits.

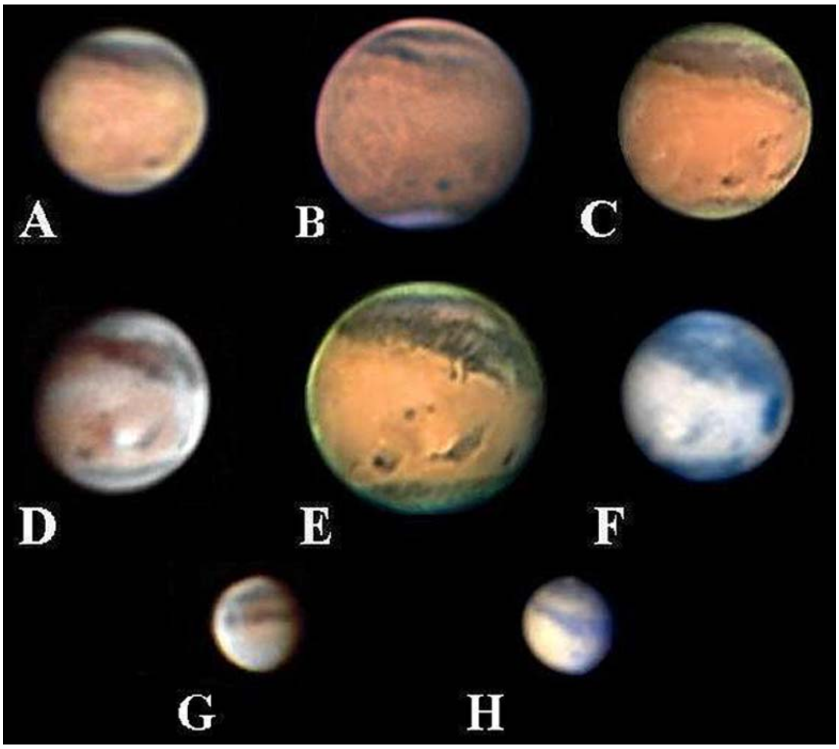

Figure 6. ***Region III. A–F, pre-storm and early storm***

A 2001 May 28d 12h 54m, 152mm OG, CML= 151°, *Valimberti*. Weak orographic evening clouds in **A–C**.
B 2001 Jul 2d 10h 34m, 254mm DK Cass., CML= 166°, *Buda & Justice*. Dust streak north of the SPC. Fine detail in equatorial deserts.
C 2001 May 19d 08h 32m, 356mm SCT, CML= 168°, *Grafton*. Small 'oasis' east of *Propontis* on **B** and **C**.
D 2001 Apr 6d 08h 40m, CML= 207°, *Parker*. Trace of partial ECB; *Elysium Mons*.
E 2001 Jun 20d 06h 10m, 356mm SCT, CML= 208°, *Grafton*. *Trivium Charontis–Phlegra* consist of two tiny dots. Fine structure between *Mare Cimmerium* and *Mare Tyrrhenum*.
F 2001 Jun 9d 01h 34m, 254mm SCT, RR(G)B image, CML=238°, *Cidadão*.

G–H, post-storm

G 2002 Jan 28d 23h 48m, 410mm refl., CML= 135°, *Parker*. (D = 5.5") *Claritas–Daedalia* dark.
H 2002 Feb 15d 17h 45m, 305mm SCT, CML= 229°, *Peach*. (D = 5.1") Small new dark patch in *Aethiopis* desert.

Region III: long. 130-250°

Before the dust storm

Refer to Figures 2, 3 and 6. *Cerberus* and *Trivium Charontis* were again nearly invisible: two tiny dark spots with pale shading between them again denoted this area, as imaged by Grafton, Parker and others. The *Aetheria* dark patch was again prominent, shaped exactly as in 1999, and *Phlegra* a halftone shading (brownish on Parker's 2001 Feb images). The SW side of *Elysium* had no border. *Elysium* itself often displayed the *Elysium Mons* orographic cloud. *Propontis* was isolated, slightly V-shaped, and again darker on the E.

side. The dusky shadings to the north of Region III were monotonous and did not differ from 1999.

Mare Cimmerium appeared precisely as in 1999, the W. end drawn out into a fine tip. The mare showed a hint of brown to Minami (2001 Feb 6); a comparison with the seasonally similar apparition of 1986[31] is also interesting, and the longer interval reveals small differences. In the latter year, *Gomer Sinus* was much more marked, and *Cerberus III* (as named on Ebisawa's map[28,30]) was a conspicuous marking observed to run across *Hesperia*. In 2001 there was a faint trace of *Cerberus III* in the best images.

As in 1986–'99, *Mare Sirenum* was a narrow dark belt, the classical NW end absent from long. *approx*.160°, and shading connected it with *Mare Cimmerium*. *Mare Sirenum* was an intensely blue feature on Biver's drawing of Jun 15 (Figure 3E). It was possible to see more southerly details: *Mare Chronium* was a very dark edge to the cap. When cloud-free, *Phaethontis* and *Electris* were shaded, with *Scamander* separating them from the light *Eridania*. *Xanthus* was a pale streak separating *Eridania* from *Ausonia*. *Caralis Fons* was a tiny dark spot just S. of *Mare Sirenum*, barely visible in Buda and Curcic's May 31 image (Figure 5F).

During and after the dust storm

Refer to Figures 2, 6, 7 and 9–11. *Cerberus III* had been faintly seen before the storm, but Minami found it conspicuous from Dec 8-9. The NW end of *Mare Sirenum* (long. 160-180°), faded since 1986, returned to visibility on Parker's images from Sep 3. Minami described *Mare Sirenum* as brownish (Nov 27). Two images by Peach (2002 Feb 15, 16) showed a small new dark spot in *Aethiopis* (at approx. +17°, 233°): it may correspond to an albedo drop at a nearby location on Smith's MGS summary map (Figure 7). This was destined to be short-lived, for it had vanished by 2003. However, a streak comprising several elongated spots was noticed at about the same position after the encircling storm of 2007,[33] and other secular dark markings have existed in the region since the time of Herschel and Schroeter and more recently in 1931–'33, and from 1958 till the late 1960s.[30]

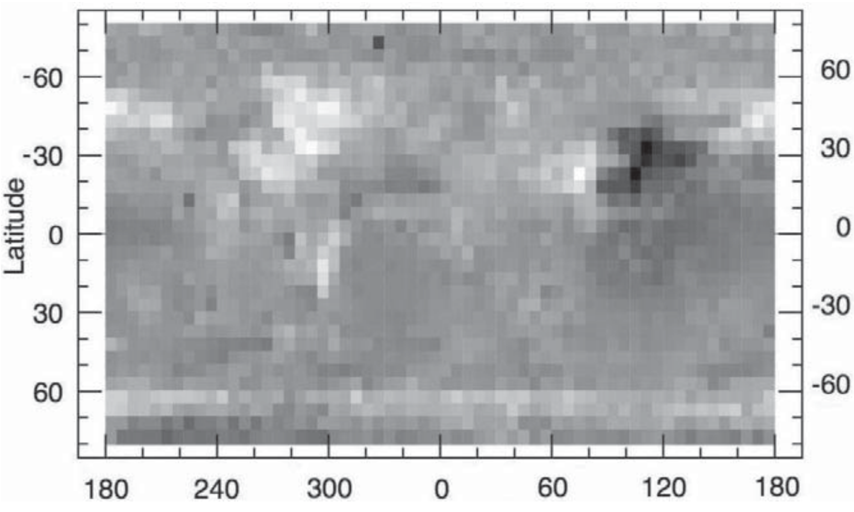

Figure 7. Post-storm albedo changes. Albedo difference map prepared from MGS data, reproduced by kind permission of M. D. Smith.[8] Bright areas represent dust fallout; dark areas show dust removal. The pixels represent data averaged over every 6° in longitude.

Spacecraft data

We reproduce a map by Smith (Figure 7) derived from MGS photometry[8] which neatly summarises albedo changes resulting from the great storm. The most extensive albedo decrease shown is in *Claritas–Daedalia*; the darkening of *Pandorae Fretum* and *Moeris Lacus* and the narrowing of the NW side of *Syrtis Major* (shown here as a brightening) are just visible, and the N. *Ausonia/ Mare Tyrrhenum* and NE *Syria* brightenings are confirmed, but some of the smaller changes we imaged are not shown at this resolution. Quoting Smith: 'The largest changes ... are concentrated in low-albedo regions such as *Syrtis Major*, *Terra Tyrrhena*, *Hesperia Planum*, and the area north and northwest of *Argyre*... Likewise, high albedo surfaces like *Tharsis* and *Arabia* that are already covered with dust and high northern latitude where relatively little dust fell ... show little change in albedo... The area near –30°, 120° was one of the larger centres of dust raising... The large albedo changes in that region suggest a redistribution of surface dust.' Cantor[2] has also analysed these changes in detail.

The martian atmosphere

White clouds

General

An Equatorial Cloud Band (ECB) was reported from about 2000 Dec 12 (Ls = 88°) till 2001 Apr 14 (145°). Many of the observations show it brighter on the evening side, but note that this side was observable to greater advantage pre-opposition. Typically the ECB is visible from *approx*. Ls= 50°; potentially earlier BAA sightings were defeated by the tiny disk (D< 4.7 arcsec before Dec 12). The orographic volcano clouds over *Olympus Mons* (*e.g.*, *Nix Olympica*) and the *Tharsis Montes* were viewed from 2000 Dec 22 (Ls= 93°) till Jun 24 (184°). Again, these features would surely have been visible much earlier given a larger disk. Their observed disappearance was apparently seasonally later than in 1995–'99, but in the latter apparitions we were unable to view the evening terminator, after opposition. In 2001 the orographic clouds disappeared before opposition, so they could be followed to the very final stage at the evening terminator. The extreme limits from 1995–2001, Ls = 41–184° accord very well with the MGS data analysed by Benson *et al*.,[6] which were discussed in our last report.[29] Multi-filter observations of ECB and orographics (as well as 'Blue Clearings') are collected in Figure 8.

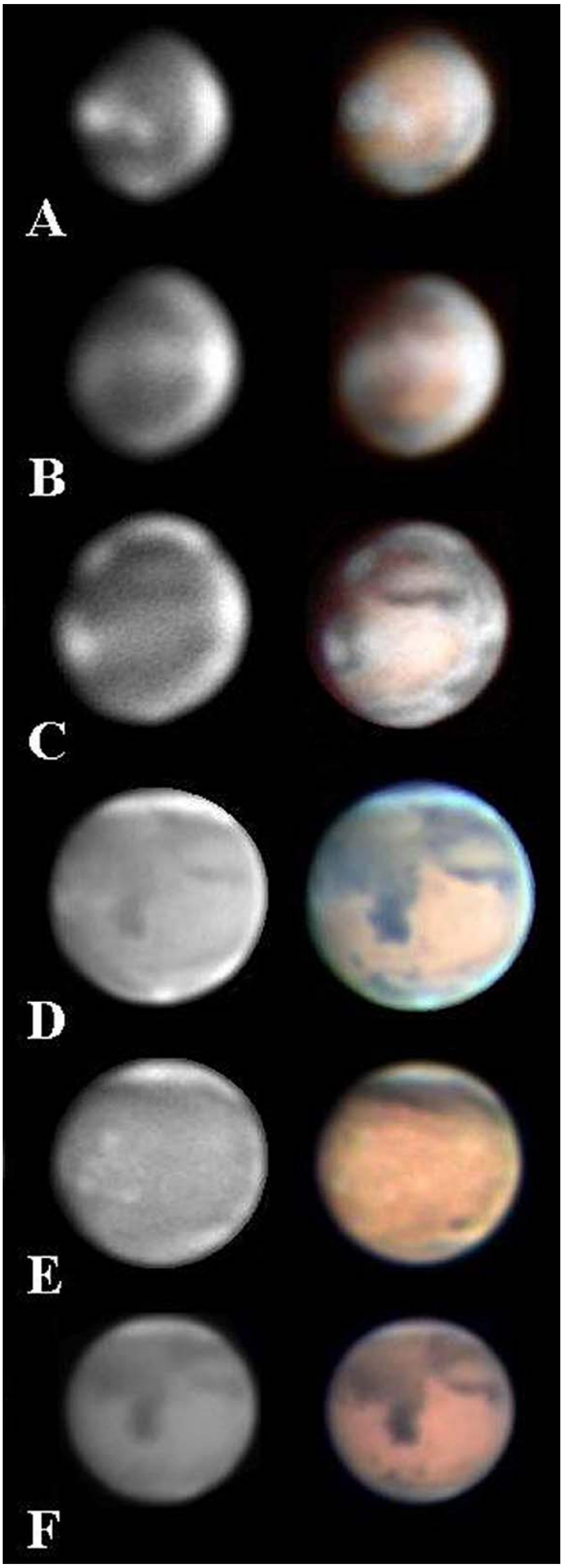

Figure 8. ECB, orographic clouds and Blue Clearing. Each row consists of a pair of a blue image *(left)* and an RGB or R(G)B composite *(right)*.
A 2001 Jan 31d 10h 58m, 410mm refl., CML= 139°, *Parker*. Orographics, including *Nix Olympica*.
B 2001 Feb 8d 11h 14m, 410mm refl., CML= 66°, *Parker*. Strong ECB from limb to limb.
C 2001 Mar 26d 09h 50m, 410mm refl., CML= 330°, *Parker*. *Syrtis* blue cloud; weak ECB; obvious BC.
D 2001 May 20d 18h 33m, 279mm SCT, CML= 305°, *Tan*. Obvious BC; evening cloud; SPH at maximum extent.
E 2001 May 28d 12h 51m , 152mm OG, CML= 151°, *Valimberti*. Orographics over *Tharsis Montes* at the *p.* limb forming part of the 'W' cloud; followed by *Nix Olympica*.
F 2001 Jun 7d 04h 37m, 254mm refl., CML= 301°, *Di Sciullo*. SPC; strong BC.

Date limits for ECB and orographic clouds, 1995–2001

Opposition	*ECB Ls (°)*	*Orographics Ls (°)*	*Ref.*
1995	62 onwards	41 onwards	34
1997	51 to 141	54 to 140 (+)	36
1999	50 to 145	47 to 150 (+)	29
2001	till 145	till 184	(this paper)

A feature of spacecraft data is the ability to repeat observations at the same season in successive years. Near opposition in 1999 BAA observers could follow the 'cyclonic' clouds imaged by HST over *Baltia/Mare Boreum* in N. spring.[29] At precisely the same season in 2001 Mar, though inaccessible at our level of resolution, the observations were repeated by MGS.[1]

In the following lists we give details of the bright areas frequently reported by observers in the morning or evening, as well as areas observed to be bright upon mid-disk. These were mostly interpreted from their wavelength-dependence to have been white cloud, though occasionally they represented frosted ground. Specific 'flashes' seen in *Edom* and elsewhere were surface phenomena, the subject of a separate section. The general level of white cloud fell in 2001 June, as the SPH was dissipating. No white cloud activity was seen during the storm; diurnal cloud returned in October. The disk diameter was above 6 arcsec from 2001 Jan till 2002 Jan. Outside that period observations were always low-res and often incomplete in longitudinal coverage.

2000 September–October

Ebisawa[25,26] reported that a S. pre-polar hood had formed by late Sep (D < 4"). This was also seen in October.

2000 November

a.m. limb: *Aeria, Chryse, Hellas* (slightly white (sw)), *Isidis Regio–Libya*, SW of *Noachis* and *Tharsis* (sw).

p.m. terminator: *Chryse* (sw), *Elysium* (sw).

mid-disk: *Elysium* was dull at the CM.
A partial S. polar hood covered *Ausonia–Electris–Eridania*.

2000 December

a.m. limb: *Aeria, Chryse–Xanthe, Hellas* and *Isidis Regio–Libya*.

p.m. terminator: *Aeria, Chryse–Xanthe, Elysium, Hellas, Libya–Isidis Regio* and *Tharsis*.

mid-disk: Peach (Dec 22) sketched orographic clouds from *Ascraeus Mons* to *Arsia Mons*: our first record of these at Ls = 93°. *Hellas* was bright. *Elysium* was again dull.

The *Isidis Regio–Libya* cloud joined with *Aeria* in the early morning and in the evening to veil the *Syrtis Major*.

Many southern 'deserts' showed an SPH, but *Phaethontis* did not.

Strong ECB was noticed, which seemed complete around the planet: Parker (Dec 12), weak, p.m. *Elysium* to a.m. *Aeria*;

Minami (Dec 19), definite at CML = 003°; Parker (Dec 28), definite, p.m. *Xanthe* to a.m. *Tharsis*, *etc*.

2001 January

a.m. limb: *Aeria, Cebrenia, Chryse–Xanthe, Elysium, Hellas* (very white (vw) by mid-Jan) and *Isidis Regio–Libya*.

p.m. terminator: *Aeria, Alba* (Minami, Jan 8 onwards), *Chryse–Xanthe, Elysium, Hellas* (vw), *Isidis Regio–Libya, Nix Olympica* (Parker, Jan 28 onwards (Figure 8)) and *Tharsis Montes* (Parker, Jan 31 (*Arsia Mons, Ascraeus Mons* and *Pavonis Mons*; also see Figure 8) and *Tharsis*.

mid-disk: *Chryse* (sw, forming part of the ECB on mid-disk), *Hellas* (vw) and *Nix Olympica* (Parker, Jan 31), *Elysium* was again dull.

Hellas was now also bright in red light, implying frost rather than cloud: a change from December.

An SPH was visible generally in the south, again excepting *Phaethontis*.
ECB remained conspicuously visible.

2001 February

a.m. limb: *Aeria, Arabia, Chryse–Xanthe, Elysium, Hellas* (vw), *Isidis Regio–Libya* (causing the '*Syrtis* Blue Cloud'), *Tempe* and *Tharsis*.

p.m. terminator: *Aeria, Alba, Arabia* (sw), *Argyre, Candor–Ophir, Cebrenia, Chryse–Xanthe, Eden* (sw), *Elysium*, *Hellas* (vw), *Isidis Regio–Libya, Nix Olympica, Tharsis Montes* and *Tharsis*.

mid-disk: *Hellas* (vw) and *Candor–Ophir*.

Hellas (again frosted; vw) inside a more general SPH (now longitudinally complete though still less prominent around *Phaethontis* in early Feb).

The ECB (Figure 8) remained prominently visible, as previously.[18]

2001 March

a.m. limb: *Aeria, Chryse–Xanthe, Elysium, Hellas* (vw), *Isidis Regio–Libya* (causing the '*Syrtis* Blue Cloud'), *Neith Regio, Nix Olympica* (vw to Peach, Mar 8), *Tempe* and *Tharsis*.

p.m. terminator: *Aeria, Alba, Cebrenia* (sw), *Chryse–Xanthe, Elysium* (especially *Elysium Mons* (Parker, Mar 1 onwards)), *Hellas* (vw), *Isidis Regio–Libya* (invading *Syrtis Major* near the terminator and causing the '*Syrtis* Blue Cloud'), *Nix Olympica, Tharsis Montes* and *Tharsis.*

mid-disk: *Alba, Cebrenia* (sw), *Elysium Mons, Hellas* (vw), *Isidis Regio–Libya*, and *Nix Olympica* (sw; Minami, Mar 18 onwards).

The *Elysium Mons* orographic cloud whitened around noon, and *Elysium* was covered by more general cloud in the afternoon and evening.

The SPH was large and not uniformly bright: by late Mar it deviated northward in the longitude of *Argyre* (*e.g.*, Ikemura, Mar 31, p.m. side). *Hellas* remained a bright patch within the hood.

ECB was again noted, *e.g.*, from the p.m. *Aeria* to the morning *Chryse*.

On 2001 Mar 2, MGS imaged swirling morning clouds (which exhibited a central hole) over *Baltia*, precisely as HST had done on 1999 Apr 27–30 at the same seasonal date.[29]

2001 April

a.m. limb: *Aeria, Baltia, Candor–Ophir, Chryse–Xanthe, Deucalionis Regio, Elysium, Hellas* (vw), *Isidis Regio–Libya, Neith Regio, Nix Olympica* (Parker, Apr 15), *Tempe* and *Thymiamata*.

p.m. terminator: *Aeolis* (sw), *Aeria, Alba, Amazonis–Memnonia, Arcadia* (sw), *Candor–Ophir, Cebrenia, Chryse–Xanthe, Eden, Elysium* (especially *Elysium Mons*), *Hellas* (vw), *Isidis Regio–Libya, Neith Regio, Nix Olympica* (weakening in late April), *Tempe* (sw), *Tharsis Montes, Tharsis* and *Zephyria* (sw).

mid-disk: *Aeria* (sw), *Chryse–Xanthe, Hellas* (vw), *Libya* (sw), *Nix Olympica* (sw) and *Tempe* (sw).

Bright cloud again extended across *Syrtis Major* from the neighbouring deserts at both the morning and evening sides. The Blue *Syrtis* cloud was often evident. *Elysium* behaved as in March.

The continuous SPH was larger than in March, grey to bluish-white. It exhibited large daily changes. It often contained bright patches, especially within *Ausonia* (Parker's Apr 5–10 red images suggesting surface frost) and in its northward incursions over *Argyre* (beautifully shown by Grafton, Apr 30) and *Solis Lacus/Claritas*. *Hellas* was now separated from the hood by *Hellespontus*.

ECB was visible but was no longer complete; the evening side was brighter. Early in April it ran from the evening *Elysium* to the morning *Aeria*, and the evening *Aeria* to the morning *Chryse–Xanthe* (*e.g.*, Adachi, Apr 9). On Apr 2 Adachi also showed it complete near CML = 60°. On Apr 5–6 Parker (Figure 6D) found it obvious only on the afternoon side, from *Amazonis–Memnonia* to *Zephyria*, and only the evening to mid-disk part features strongly on Adachi's drawings and Akutsu's images, Apr 11–14 with *Syrtis Major* central. Later sightings were sporadic.

2001 May

a.m. limb: N. *Mare Acidalium, Aeolis, Aethiopis, Candor–Ophir, Cebrenia, Chryse–Xanthe, Deucalionis Regio, Edom, Isidis Regio–Libya, Neith Regio, Nix Olympica* (*e.g.*, Cave, May 29), *Tempe and Tharsis. Elysium* was dull except in green (probable surface frost).

p.m. terminator: *Aeria, Alba, Amazonis, Amenthes, Arcadia, Candor–Ophir, Chryse–Xanthe* (partially veiling *Margaritifer Sinus*), E. *Dioscuria, Elysium* (especially *Elysium Mons*, but weakening this month), *Isidis Regio–Libya* (still veiling *Syrtis Major*), *Nix Olympica* (weakening, but still conspicuous in blue (*e.g.*, Akutsu, May 29), and with another such cloud *Sf.* it (Schumann, May 27 and upon several CCD images)), E. *Tempe* (De Groff, Schumann and Valimberti, May 31), *Tharsis Montes* (brighter than *Olympus Mons*) and *Tharsis* generally. *Hellas* was not bright.

mid-disk: *Alba* (sw, Valimberti, May 31), *Amazonis–Zephyria, Candor–Ophir, Chryse–Xanthe* (with a specific bright *Chryse Planitia* cloud to Minami, May 11), *Edom, Elysium Mons* (and ground frost?), *Libya* and *Nix Olympica* (vsw to Adachi, May 29). *Elysium* generally was dull.

There was a general fall in activity. *Hellas* was dull and frost-free throughout the day, except where the SPH sometimes invaded it in the far south. On May 19 Tan imaged a white streak (most visible in blue light) running from the SPH in a *Nf.* direction across the S. part of *Hellas*; it was fading next day. This feature can also be seen in a few other images.

SPH: Variable, bluish-white, having reached its seasonal maximum size in late Apr/early May, coming down to lat. 50°S in the blue images. *Argyre* was one of several bright areas (or lower latitude protrusions) within its midst, strikingly so (for instance) upon Ikemura's images May 11–12, and to the Director and Proctor on May 22–24. (Figure 2A) The SPC began to be visible.

ECB: A weak ECB was occasionally partially visible. Hernandez on May 12 (CML= 197°) and Stellas on May 17 (CML= 25°) saw it incomplete, and Parker on May 20 (under CML= 149–166°) merely suspected it. The last complete views date from April.

2001 June

a.m. limb: NW *Mare Acidalium–Baltia, Aeria, Alba* (sw; Morita, Jun 12), *Argyre* (*e.g.*, Massey and Minami, Jun 17, HST Jun 26), *Candor–Ophir, Chryse–Xanthe, Deucalionis Regio, Eden, Edom, Isidis Regio–Libya* (sometimes still seen to veil *Syrtis Major*), *Meroe, Nix Olympica* (sw, *e.g.*, to Kumamori and Morita, Jun 11–12), *Tempe*, *Tharsis*, SW *Thaumasia* and *Thymiamata*.

p.m. limb: N. *Mare Acidalium* (*e.g.*, De Groff, Jun 4), *Aeria, Alba, Candor–Ophir, Chryse–Xanthe* (partially veiling *Margaritifer Sinus* on several dates), *Cydonia, Elysium Mons* (cloud, and (being bright in green) apparently ground frost), *Hellas* (a white core twice seen by Minami), *Hesperia* and environs (De Groff, Jun 19; Massey, Jun 17), *Isidis Regio–Libya, Memnonia* (sw), *Nix Olympica* (weak even at the limb but still visible in late Jun (*e.g.*, Cave, Jun 26)), *Tempe, Tharsis Montes* (weak by late Jun but bright earlier, *e.g.*, to Akutsu, Jun 2), *Tharsis* and *Zephyria*.

mid-disk: *Aeria, Alba* (Schumann, Jun 3), *Candor-Ophir, Chryse–Xanthe, Edom* (cloud as well as the ground frost that led to the ‘flashes’: see later), *Elysium* (*Elysium Mons* only), *Libya, Tempe* (sw) and *Tharsis*.

Excepting *Elysium Mons, Elysium* and *Hellas* were free from cloud or frost.

The *Baltia* morning cloud was more southerly and formed a ribbon of twisting bright bluish cloud running diagonally from NE *Mare Acidalium* into the morning *Tempe*. On Jun 21, Tan’s image (Figure 16A) beautifully showed the E. portion of the ribbon starting to develop. It is fully developed and shown in detail on the HST image of Jun 26 (Figure 16C) and at lower resolution by Csadek (Figure 16B) on Jun 24. They were best seen on the a.m. side; thus on Jun 24 Biver did not see the ribbon cloud in the evening. Biver’s drawings of Jun 29 and 30 suggest something similar developed in the a.m. These recurrent clouds did not last the entire day, being similar to those seen over that region in the last few apparitions.

The SPH had mostly given way to the SPC, but in early Jun was still present over *Argyre* and *Ausonia*, with some invasion of S. *Hellas* (*e.g.*, Biver, Jun 1). Cidadão’s Jun 28 images show *Argyre* now hood-free.

The ECB was possibly seen incompletely by Stellas on Jun 8 (CML= 172°), but there was no confirmation.

2001 July–September

The same activity noted in June persisted at longitudes as yet unaffected by the dust storm till Jul 3. The limb brightening became more diffuse, fainter and yellow. White clouds did not return till early October.

2001 October

a.m. terminator: *Ausonia, Chryse* (sw), *Electris, Eridania and Hellas* (sw).

p.m. limb: *Candor–Ophir, Hellas* and E. *Thaumasia*.

mid-disk: *Candor–Ophir*.

White clouds were re-observed from Oct 3 (*Hellas*, a.m.).

2001 November

a.m. terminator: *Aeria, Ausonia, Eridania, Hellas, Isidis Regio–Libya* (again veiling *Syrtis Major*), S. and W. *Noachis*, E. *Thaumasia* (sw to Parker, Nov 25-27) and *Zephyria*.

p.m. limb: *Ausonia, Candor–Ophir, Hellas, Isidis Regio–Libya* and *Thymiamata*.

mid-disk: *Candor–Ophir*.

Hellas was bright at all wavelengths at the evening limb and contained both dust and diurnal cloud.

2001 December

a.m. terminator: *Ausonia, Elysium, Hellas* (sw) and *Isidis Regio–Libya*.

p.m. limb: *Ausonia, Chryse–Xanthe, Elysium, Eridania, Hellas* and *Isidis Regio–Libya*.

mid-disk: *Hellas* was dull at the CM, as in October–November.

Hellas was again bright at all wavelengths at the evening limb.

2002 January

a.m. terminator: *Ausonia*, N. of E. *Mare Cimmerium, Electris* (sw to McKim, Jan 19), *Hellas* (sw), *Tharsis* and *Thaumasia*.

p.m. limb: *Ausonia, Hellas* and *Isidis Regio–Libya*.

mid-disk: *Hellas* was generally dull (and showed ground details).

2002 February

a.m. terminator: S. of *Daedalia, Electris, Eridania, Hellas* (sw to McKim, Feb 14), and *Hesperia* (Kumamori, Feb 1).

p.m. limb: *Hellas*, N. of *Mare Sirenum* (Minami, Feb 6).

mid-disk: *Hellas* was again dull.

2002 March

a.m. terminator: *Hellas* (sw, *e.g.*, to McKim, Mar 26).

p.m. limb: *Chryse–Xanthe* and *Isidis Regio–Libya*.

mid-disk: *Hellas* was dull.

2002 April–May

In April, *Hellas* brightened at the evening limb, but was otherwise just light and not cloudy (and dull in blue light). A bright S. polar hood was again seen in May.

Blue clearings

We continue to use the misnomer ‘Blue Clearing’ (BC) – for historical continuity – to describe the transparency of the atmosphere in violet light (specifically the passband of the Wratten 47 or 47B filters, or their Schott or other equivalents). Examples of images feature in Figure 8. As these data accumulate with better and better resolution, it is increasingly apparent that the visibility of *Syrtis Major* (an equatorial feature) in violet light varies inversely with that of the ECB. However, violet light observations of the temperate dark features (unaffected by ECB) also reveal an ‘opposition effect’, where transparency in violet light is enhanced at low phase angle. Nakakushi *et al.* have further comments.[35] Filter passband data were quoted in our 1997 report.[36] Visual estimates of BC with the W47 filter were supplied by Adachi, Beish, Crandall, Haas and Parker. Many observers sent suitable filter images (with infrared block), especially Akutsu, Di Sciullo, Grafton, Moore, Parker and Tan. Useful data covered 2000 Dec 12 till 2002 Mar 1 (D= 4.8 arcsec or greater).

Most of the data from 2000 Dec till 2001 Mar consistently showed a Blue Clearing (BC) of order 1–2 in both hemispheres. However, the ECB (which is very apparent in violet light) totally masked equatorial features like *Syrtis Major*. 2001 April and May were similar, but the *Syrtis* became visible from early April, owing to the ECB's decay.

The degree of BC increased to moderate or strong in June (opposition: Jun 13). The Director most often rated the BC as order 3 on images between Jun 4 and 27 (and especially during Jun 11–18), and as order 2 for the remainder of June. BC of order 2 continued to be recorded till Jul 9, after which dust enshrouded the planet. From Jul 13 till mid-Aug the BC was generally 0 in the south and 1 in the north, only the dark S. border to the NPH showing up at all. Thus on Jul 18 for instance, Parker's violet image shows no hint of *Syrtis Major* at the CM. However, *Olympus Mons* and the *Tharsis Montes* were well visible for part of this time as the exceptions to the rule, appearing (as we shall describe elsewhere) as dark spots even in violet light (their warm tint giving them even greater intensity than in red). On Aug 12 and later, even the NPH fringe disappeared in violet, with a BC of 0 across the whole disk till Aug 31.

From 2001 Sep 6 there appeared fugitive details other than the volcanoes. On Sep 6 a dark patch was seen in the south and on Sep 24–25 the *Syrtis* could be recognised weakly at the CM (hence BC 2). The volcanoes still showed up in violet light – for the last time – on Oct 14. Throughout October and until late Nov there was weak BC in the south, but on Nov 25 and later the BC was more often rated as 2 there (and sometimes generally), with recognisable but faint markings. This situation continued until the planet's disk became too tiny for routine good imaging. On 2002 Jan 13 and 26 Moore's images still showed a BC of order 2, while Parker's and Peach's images through January till Mar 1 also give BC 1–2.

Dust storms (yellow clouds)

Dust storms observed by MGS, 2000 Apr–Nov

Using MGS images, James & Cantor[7] observed numerous small and regional storms at the edge of the retreating NPC, just before the previous solar conjunction and in the early part of the apparition, all inaccessible to us.

Small-scale telescopic dust activity, 2001 April–June

Before opposition MGS imaged many local dust storms, mostly below telescopic resolution. One such event in W. *Hellas* (2001 Apr 8), illustrated elsewhere,[37] might have been within our grasp. In fact, we had no good data for that date and place, but – significantly – Adachi found *Hellas* yellowish on Apr 9. On Apr 28 Gaskell found *Chryse* 'strikingly yellow', and Melillo's image next day shows it very bright in red light, both sightings on the a.m. side: dust mixed with morning cloud? On May 20 Minami considered that a bright protrusion running from the SPH into *Hellas* (which had also been seen on May 19: see under 'white clouds') possessed a dusty component.

The HST image of Jun 26 (Figure 16C, Part II) apparently shows traces of dust both north and south of the N. polar 'ribbon' cloud, the latter streaking across *Mare Acidalium*.

The great dust storm of 2001

Introduction

No planet-encircling storm had been observed since 1982. We have given a comprehensive historical review of these phenomena elsewhere.[30] Although we shall refer to spacecraft data where they inform the following discussions, we shall concentrate primarily upon the Section's work. Figures 2 and 9–11 illustrate the great storm.

Origins

In early June, ground-based data showed *Hellas* dull but with floor details evident (Figures 3, 4). The N. edge of the basin was poorly defined. Parker's image of Jun 11 (Ls= 176°) revealed a strip of faint dust along the W. part of the basin which had concentrated to the NW on Jun 14. MGS data[2] confirm these observations, Jun 11 being the start of the activity. On Jun 19, in excellent seeing, Schumann (Figure 9A) saw a bright elongated vertical cloud strip at the W. edge of *Hellas* (long. *approx*. 314°) which contained a very small bright central core (at similar latitude to a feature that had 'flashed' on Jun 16 – see Part II) around CML= 300°. Though visually whitish, this was surely another local dust disturbance. MGS imaged a very small local dust storm N. of the SPC that moved into *Hellas* on Jun 21, and which moved clockwise around the edge of the basin, Jun 21–24.[2–4] The latter cloud was too small for our observers, but Minami saw the W. side of *Hellas* visually light on Jun 22, and next day Gaskell saw *Hellas* yellowish under oblique lighting. So, just prior to the global storm there already existed some airborne dust arising from local storms inside *Hellas*.

On Jun 24, ground-based observers in Australia, Japan and the Pacific could see that the atmospheric dust within the N. part of *Hellas* had extended east, crossing *Mare Tyrrhenum* just S. of *Syrtis Minor* and broadening and brightening the *Hesperia* gap, as shown by Minami's drawings (Figure 9B) and as imaged by Ikemura (Figure 10) and others.[21,38] The contour of *Hellas* was again not well-defined. Adachi found the SPC yellowish and not so bright. *Hellas* appeared yellowish to Minami. The dusty area showed little development on Jun 25 according to De Groff and Higa (OAA). From the USA this area was disappearing at the morning limb, and observers from western Europe could not yet view these longitudes. From India, Devadas could see *Hellas* very bright on the *p*. limb on Jun 24–25.

On Jun 26 the long ribbon of dust had brightened and extended into *Ausonia*,[14] (Figure 10) and this date we shall take to mark the emergence of the event proper at Ls=185°. (Remarkably, no-one published the news in the IAU *Circulars*.) At the same time Valimberti's images (Figure 10) show patches of dust escaping from NE *Hellas* into *Iapigia*. On Jun 26 and 27 the whole disturbance was an approximately M-shaped arc, particularly well shown on the Jun 27 images by Akutsu (Figure 10), Morita and Pace. Note that the event primarily developed from *Hesperia*, not from dusty *Hellas*. During the first week, the event expanded to the east, and spread in latitude. The HST imaged Mars on Jun 26 (Figure 16C) but virtually all this

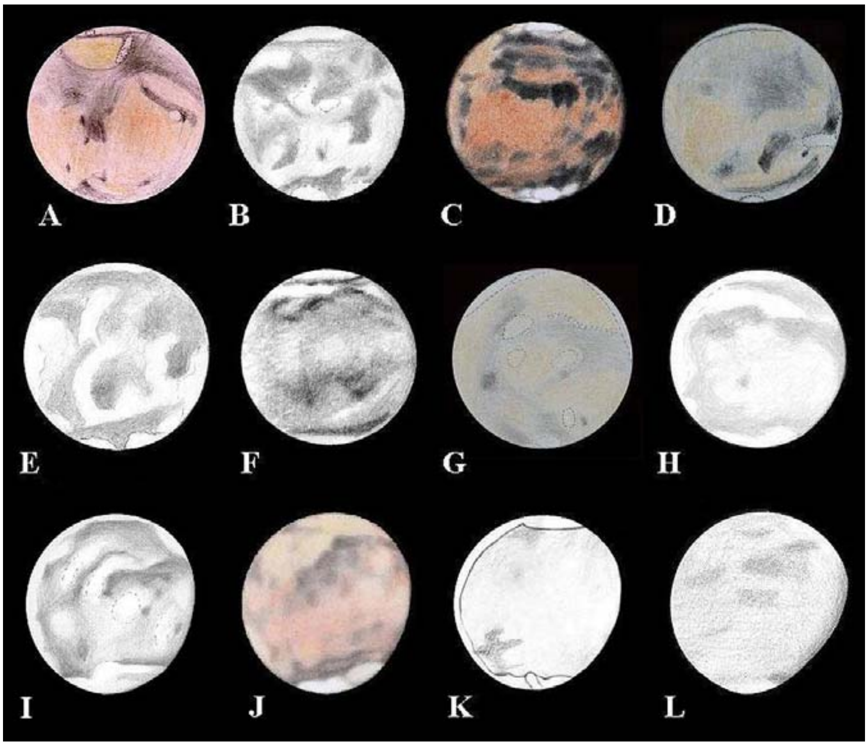

Figure 9. Drawings of the dust storm.

A 2001 Jun 19d 12h 15m, 229mm OG, ×275, CML= 306°, *Schumann*. Thin N–S dust streak in W. *Hellas*.
B 2001 Jun 24d 12h 30m, 200mm OG, ×600, CML= 266°, *Minami*. Dust in *Hesperia*.
C 2001 Jun 30d 21h 38m, 256mm refl., ×333, CML= 346°, *Biver*. Yellow cloud in *Hellas*. Activity in NPH much increased.
D 2001 Jul 1d 14h 00m, 229mm OG, ×275, W21, CML= 225°, *Schumann*. Fading of *Mare Tyrrhenum*, other S. maria, and all of *Syrtis Major* except the north. *Aetheria* secular darkening enlarged in both **D** and **E**.
E 2001 Jul 1d 15h 30m, 200mm OG, ×400, CML= 248°, *Minami*. *Mare Cimmerium* bisected by dust cloud. Fresh dust outburst over *Elysium*.
F 2001 Jul 3d 12h 20m, 310mm refl., ×400, CML= 183°, *Adachi*. Dust streak in far south, extending east. Details around the darkening *Elysium*, at the CM, are confused.
G 2001 Jul 8d 09h 15m, 229mm OG, ×275, W21, W47, CML= 93°, *Schumann*. Low contrast. *Solis Lacus* invisible. Small NPH. Bright dust cloud in *Syria*.
H 2001 Jul 8d 12h 40m, 250mm refl., ×420, CML= 144°, *Minami*. *Olympus Mons* appears as an anomalous dark spot.
I 2001 Jul 16d 13h 30m, 250mm refl., ×420, ×530, CML= 84°, *Minami*. Two parallel streaks of dust clouds run from *Syria* to *Thaumasia*. Volcanoes appear as dark spots. Active NPH.
J 2001 Jul 24d 20h 35m, 203mm SCT, ×297, CML= 114°, *Biver*. *Syria–Thaumasia* source bright with yellow cloud. *Syria–Claritas–Daedalia* darkening at CM. NPH a.m. protrusion.
K 2001 Jul 28d 20h 08m, 130mm OG, ×280, W23A, W80A, CML= 70°, *Stellas*. Note N. *Mare Acidalium* visible, and the bright NPH protrusion.
L 2001 Aug 7d 04h 28m, 102mm OG, ×230, W15, CML= 109°, *Schmude*. Decline in both NPH and *Syria–Thaumasia* activity. *Claritas–Daedalia* darkening persists.

activity was beyond the evening limb: only the slightly dusty nature of *Hellas* could be seen. The event then developed more quickly: dust expanded from *Hesperia* (long. 270°) and remained inside *Hellas* (300°). *Mare Tyrrhenum* faded significantly after Jun 27. Images on Jun 28 by Tan (Figure 10) and others showed an additional outburst of dust in *Libya*, with diffuse dust starting to mask *Syrtis Major* and environs. Devadas saw the region preceding *Hellas* heavily veiled. There were other excellent images by Akutsu, Kumamori and Morita, as well as the first comments about a more general loss of contrast in that part of the S. hemisphere due to the spreading of more diffuse dust. The *Libya* cloud was followed most of the way across the disk without apparent change during the martian day. The cloud showed a tendril of dust connecting it with *Hesperia*: it was not bright in blue light, but appeared brilliant in red. The evening orographic cloud over *Elysium Mons* was weak by Jun 28.

A further considerable development took place on Jun 29: the *Libya* cloud expanded and the S. hemisphere dust-band branched northeast to cut *Mare Cimmerium* in half (Figure 9E). *Mare Tyrrhenum* was hardly visible on images by Akutsu and Pace. On Jul 1 Japanese observers found the whole disk yellow in both hemispheres (except at the poles), with the southern front of dust developing eastward, especially at high S. latitudes, and yellow cloud already covering *Phaethontis–Electris*. Also on Jul 1 a new burst of dust occurred inside *Elysium*, which caused an anomalous darkening on the slopes of *Elysium Mons* and also disturbed the *Aetheria* dark patch. (Figures 9D–F, 10) Now only the N. part of *Syrtis Major* looked unaffected. On Jul 2 *Propontis* began to fade; there was a small new dust cloud S. of *Aetheria*, with a streak running to *Phlegra*. On Jul 3 *Propontis* faded out, and a large new dusky patch marked the W. end of *Mare Cimmerium*: an anomalous darkening, given that it had already been dust-covered (Figure 10). This patch was still visible to the Director on Aug 13. *Elysium* continued to actively produce dust, patterns of albedo there constantly changing (well shown by Morita's Jul 1–4 daily RGB image sets). Observers in the USA observed small dust clouds E. of *Elysium* on Jul 3–4, with *Phlegra* disappearing on Jul 4. The *Libya* cloud itself did not exist long, and faded out after Jul 2.

Activity further west of *Hellas* was best seen from Europe and, later, from the USA. On Jun 28 the Director (Figure 2G) could see that the evening limb (under CML= 357–014°) was dusty and light. On Jun 30 the S. part of *Syrtis Major* was faded, and *Hellas* was light and yellow; west of its W. border all was still normal. On Jul 1 a similar picture, but the boundary between *Hellas* and the SPC was lost, and a bright dust core was seen in the N. of the basin. On Jul 3 the Director (Figure 2H) saw no contrasty surface detail E. of *Syrtis Major*; but the SPC still had a dark fringe. An image set by Proctor and a single image by Peach on Jul 2 (Figure 10) realistically show the views on successive nights from the UK. On Jul 4 Cidadão's work showed the planet still normal W. of the *Syrtis* and *Hellas*, with dark and completely normal details especially in infrared images (Figure 4): dust had not crossed *Hellespontus*. As Strausberg *et al*. note,[3] there was essentially no propaga-

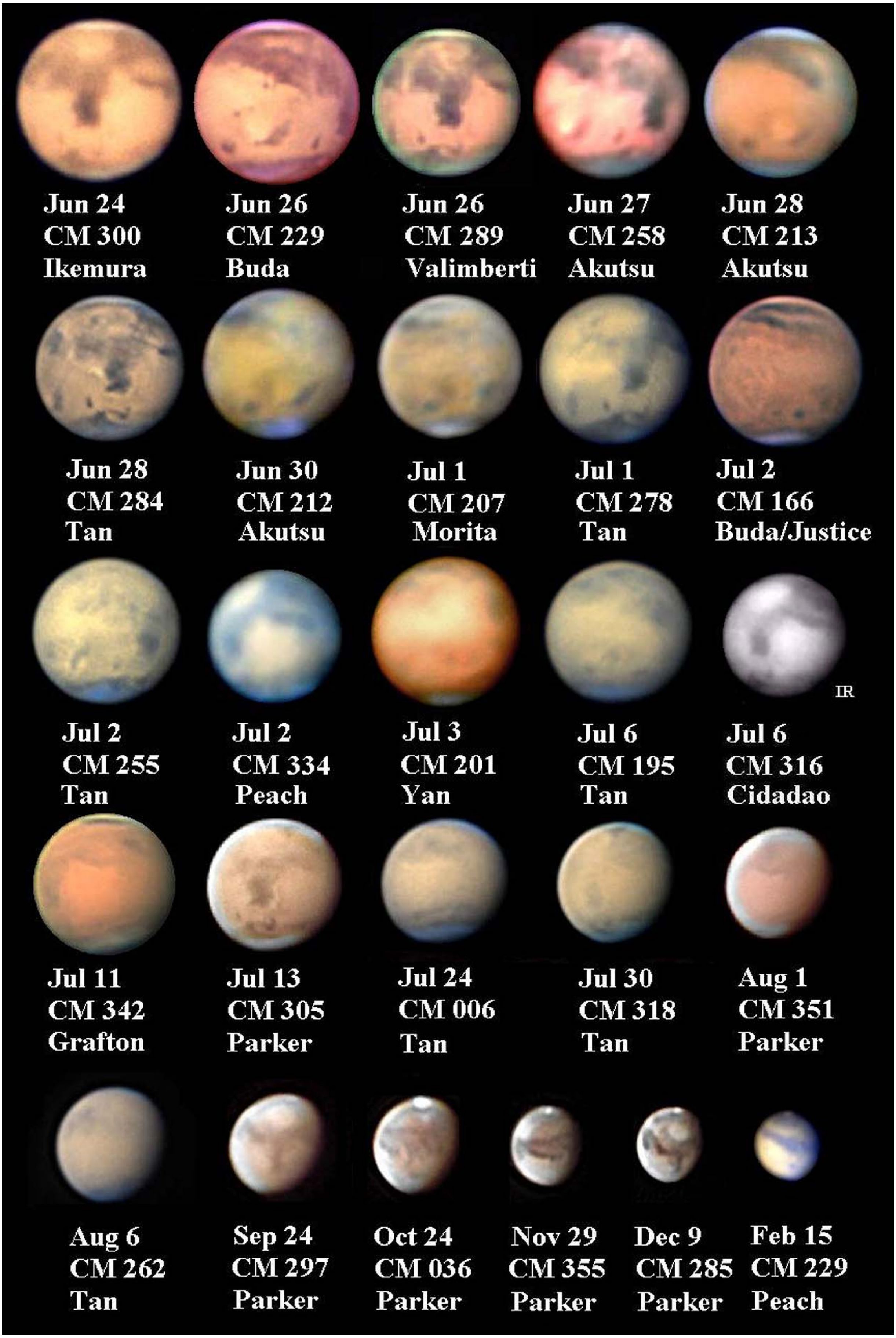

Figure 10. Dust storm images: the *Hellas* hemisphere emergence sites. Most images are RGB or R(G)B composites. Jul 6 by Cidadão is an infrared one. Full details upon the images; for instruments see Table 1.

tion to the west (on this occasion). Observing from Prague's public observatory on Jul 6, the Director (Figure 2I) found the SPC no longer clear, *Syrtis Major* faint, *Mare Tyrrhenum* invisible, with *Mare Serpentis* the darkest area remaining: the orange tint on the right of the disk gave way to yellow on the left. This scene was confirmed by Cidadão's images. Other European observers also enjoyed good views. On Jun 29 Adamoli, Frassati and Stellas, and on Jun 30 Biver (Figure 9C) found bright cloud cutting diagonally across *Iapigia*/E. *Sinus Sabaeus* into *Aeria*.

There were some other specific bright yellow clouds. On Jul 1 Schumann observed a small cloud over *Nilosyrtis* (Figure 9D). On Jul 2 Frassati saw a specific bright dust cloud in S. *Aeria/Arabia*. Next day, a secondary disturbance began.

Secondary activity and encirclement

The initial storm propagated to the east more rapidly at higher latitude, and activity had reached *Phaethontis* by Jul 1. As the storm front reached the longitude of E. *Mare Sirenum*, a secondary disturbance began in the form of a new bright dust core over *Daedalia*, south of and roughly at the longitude of *Arsia Mons*. It was imaged on Jul 3 by De Groff and T. J. Parker, and on Jul 4 by De Groff, Ikemura and Valimberti[15] (Figure 11). Nothing had been seen the previous day (*e.g.* in Moore's images). Haas and Minami drew several new dust clouds around *Solis Lacus* on Jul 4, which were imaged by several observers. On Jul 3–4 Adachi (Figure 9F) saw this activity on the *p.* limb, connected to a bright southern belt of dust which was still spreading east from the primary source. On Jul 5 Parker found dust starting to distort *Aurorae Sinus* and to cross the E. border of *Thaumasia*, and Grafton imaged the two discrete bright dust clouds around *Solis Lacus*. Over the next few days the new event rapidly expanded primarily to the east to cover *Solis Lacus* (by Jul 7; Figures 9G, 11), the entire length of *Valles Marineris* and to affect much of *Mare Erythraeum* (*etc*.). This region would now appear bright throughout the storm, (Figures 9I–J, 11) showing that dust continued to be raised and moved. A particular appearance proved frequent and long-enduring, especially at the start: from Jul 6–7 (Moore and Parker, Figure 11) to Aug 2 two parallel dust-streaks often occupied the region, running in a *Np*. to *Sf.* sense from *Aurorae Sinus/Syria* to S. *Thaumasia*. (Figures 9I, 11)

As we noted earlier, an albedo anomaly soon developed, adjacent to these dust features.[15] On Jul 8 a massive new dark area, now fully developed (but its true intensity as yet veiled by the dust), was observed to have formed between E. *Syria* and *Claritas–Daedalia*, ending near long. 130° (Figures 2, 9H–J, L, 11). This dark area was very stable during July–August. As dust settled, *Syria* was brighter, with light dust deposited there, whilst the new *Claritas–Daedalia* darkening persisted.[39] The parallel dust-streak aspect was generally not seen after Aug 2: after that, a single bright dusty area (implying continuing dust-raising) persisted through August. By early September, activity was declining, with only small bright dust clouds on Parker's Sep 3 and 6 images: the final record.

Returning to the narrative of early July, the secondary storm front crossed *Noachis* to link with the dust activity over *Hellas* further east. By Jul 9 *Meridiani Sinus*, all but the E. end of *Sinus Sabaeus* and most of *Mare Erythraeum* had disappeared (Grafton, Moore, Parker, *etc*.). By Jul 10 the planet was encircled by dust in the south and contrast was low everywhere. Encirclement in the north would take a few more days: Cantor[2] gives a date of Jul 17 when dust coverage was complete between latitudes –59° and +60°. From Jul 15 till early August, low resolution data showed an albedo anomaly: an apparent dusky belt that united the just-visible E. end of *Sinus Sabaeus* with the location of W. *Pandorae Fretum* (a feature invisible in 2001).

A pair of HST images (Jun 26 (Figure 16), Sep 4)[19] gives a graphic representation of the extent of the dust. All evidence of white cloud activity was suspended for months, no diurnal clouds being seen from Jul 4 in our data, as confirmed by MGS.[6] The limb brightening became softer and less marked. We have charted the initial evolution of the principal emergence sources in Figure 12. Strausberg *et al*.[3] provide MGS-based maps.

The far north of the planet was less affected. *Mare Acidalium* began to fade, at least in the south, about Jul 8, but the detail surrounding it was still clearly evident on (for example) Akutsu's Jul 15 images (especially in the infrared), Tan's of Jul 15–24 (Figure 11) as well as later images and drawings (Figure 9K), though all became very faded south of *Callirrhoes Sinus*.

After July 2 the only specific bright telescopic clouds were over *Hellas* and *Syria–Thaumasia*. The dust veil extended down to latitude approx. +50°, so that the north polar hood was not hidden, indeed it became extremely active during July. (See the NPR section in Part II for details.) Until mid-August *Hellas* and *Thaumasia* remained bright and the overall dust coverage remained total. McKim still rated the yellow-white *Hellas* as very bright on August 10 (Figure 2L). The global storm and the NPH gradually became less active in August, though the latter's decline could equally be influenced by the southward movement of the subsolar point. For nearly two months the planet's appearance was rather monotonous.

From Earth it was impossible to see what was happening in the far south. The SPC was tilted away from us so that the cap, though large, was foreshortened. Dust did not cover the entire SPC (see the aforementioned HST image for Sep 4) but nevertheless did cover its northern extremities, as mapped elsewhere.[2,3]

More spacecraft data

MGS TES 15-micron data reveal a warming that began on Jun 24, strengthening after Jun 28, and first appearing in northern mid-latitudes on Jun 29**.** By Jul 2 a warming of the planet's entire atmosphere was apparent. The MGS camera confirmed the visual start date of the event as Jun 26.[4] The dust had a significant warming effect upon the martian atmosphere south of lat. +60°, to the extent of 40K or more between latitude +20° up to the S. pole by late Jul at storm maximum. Following encircling status of the storm at Ls= 193°, the dust opacity peaked in the S. hemisphere about Ls= 200°, and in the north at 210°. The amplitudes of the atmospheric thermal tides and Hadley circulation were increased.

Gurwell *et al.*[5] measured atmospheric and surface brightness temperatures from measurements of H_2O and CO_2 rotational line data from the Submillimeter Wave Astronomy Satellite during 2001 May 23 – Sep 13. The lower and middle atmosphere up to *ca*. 45km showed rapid heating of up to 40K, as Smith *et al.*[4] noted, but the surface temperature fell by *ca*. 20K at the peak of the storm. At the height of the storm, MGS TES temperature data showed a fall of 23K compared with the previous martian year.

The MGS and thermal imaging data make it clear that dust plumes were raised simultaneously in many separate locations on the surface. At the same time, dust was not raised everywhere. In addition to the initial major storm centres, *Hesperia* and *Hellas*, dust was raised over *Arabia* and *Nilosyrtis*. In addition to the secondary outbreak just described, another event was raising dust plumes in N. *Noachis*/SW *Meridiani Sinus*. These longitudes – the last to be covered by the storm – seemed from a telescopic perspective to become overlaid by dust arriving from the west. The *Syria–Thaumasia* source was seen to raise dust plumes on 86 successive sols.[2] Once the storm had become encircling, the latter source continued to raise dust, but *Hellas* was quiescent.[3]

Naked eye appearance

By mid-July the colour of the planet was more yellow than orange and to the naked eye too the change was evident. Naked eye data by Beaumont during Jul 10–24 (on holiday in Crete) show that the planet's normal red colour was already much less obvious. Phelps on Jul 15 noticed a 'mustard' yellow hue to the naked eye, McKim on Jul 17–23 found it distinctly less red and Sheehan on Jul 5 already found Mars more yellow than in June. Schmude's photoelectric magnitudes show a brightening of about 0.3 mag during Aug 12–16, decreasing in September. On Sep 25 Haas found Mars and the Moon a few degrees apart and 'an excellent match in their yellow colour'. By Oct 28 McKim found the colour normal.

Olympus Mons and Tharsis Montes

From Jul 5 until as late as Oct 24, many observers sketched or imaged *Olympus Mons* as a conspicuous dusky brown or reddish-brown spot (Figures 2P, 9H–J, 11). The spot represents the hole made by the windswept caldera in the surrounding swirling yellow clouds rather than an albedo feature as such. It was visible all day long, though it appeared more intense during the martian afternoon. The other *Tharsis Montes* likewise appeared as dusky spots from Jul 9 (*Ascraeus Mons*) and 13 (*Arsia Mons*) onwards. As the dust settled, the calderas became indistinguishable (Figures 5, 11).

Schmude[23] measured the diameter of the *Olympus Mons* dark spot upon CCD images by Di Sciullo and Parker (Jul 14–Sep 6) which suggest, by comparison with altitude contour maps, that the maximum altitude of the opaque dust layer was 9km. Strausberg *et al.*[3] trigonometrically measured very similar heights of the dust clouds over *Hellas* to *ca*. 8km at the start of the storm.

Schmude's work[23] also demonstrated that the dust had made the planet up to 0.3 mag (V band) brighter than normal in July and August, and that the degree of dust-loading varied with CM longitude.

The NPH during the global storm

The positive sign of D_e offered a very rare chance to view the NPH during a global storm. Unusually, the NPH did not retreat to the north, as it had often done with seasonally later (and even during smaller, regional) storms. Instead, it remained bright and its activity actually increased from Jul 2 onwards, the hood often consisting of several patches of different brightness. The hood often went down to lower latitude on the morning side, mirroring the persistent small white cloud seen on the SW limb (see the dust storm and SPR sections). Its dark S. rim from July till early August suggests a surface interaction at the storm boundary; Minami even found the rim intensely blue-black on Jul 7. The hood failed to brighten in red light, remaining largely dust-free. Indeed, Smith *et al.*[4] found that dust did not spread north of lat. +60°, and that the strong thermal gradient generated at lat. +55° produced jetstream winds of up to 150 ms^{-1}.

Most activity (in the shape of near-daily southward protrusions and bright spots) was limited to longitudes between *Mare Acidalium* and *Ascraeus Mons*. Some of these features were seen before dust reached those longitudes: thus there was a bright evening cloud in the hood around *Baltia*, Jul 1–3.

We list the larger NPH features of the storm period: Jul 9, 'divided by a small brown cloud' (Gaskell); Jul 10, Tan, detached bright cloud following CM at CML *ca.* 155°; Jul 13–15, southward bulge towards *Ascraeus Mons* (several Japanese observers: Figure 11); Jul 17, brilliant white oval patch at S. edge (Minami, long. *ca*. 94°) that faded out approaching the CM and was best seen in blue light; Jul 20, another bright protrusion at long. *ca*. 50° (Ikemura *et al.*); Jul 25, Devadas, NPH divided into two lobes at similar CML; Jul 21, a less evident bright protrusion near long. 64° (OAA); Jul 22, Adachi saw a bright protrusion over *Baltia* at a.m. terminator; Jul 23 and 25, a protrusion towards *Mare Acidalium* (OAA and Devadas, respectively); Jul 28, Stellas, bright protrusion near CML= 70° (Figure 9K); Jul 29, McKim (Figure 2J) very bright morning terminator projection over Tempe; Jul 30, Adachi, a.m. protrusion over Utopia; southward bulge towards *Ascraeus Mons* to US observers including Di Sciullo, Jul 31 (Figure 11); Aug 8, Parker, v. large, bright morning projection over *Tempe*; Aug 9, Parker, protrusions over N. *Mare Acidalium* and *Tempe*.

From late July onwards the N. part of *Mare Acidalium* could be seen, due to thinning of the hood. Shortly after the first week of August the hood became less bright and less active, losing its dark fringe, and mirroring the declining vigour of the global storm; it did not however retreat to the north.

The SPC during the global storm

During the most vigorous phase of the global dust storm, the SPC was followed by a persistent morning cloud, which was often larger in diameter than the cap, and which sometimes had a sharp outline. Minami observed the cloud from Jul 7 to Aug 17. Devadas' drawings show it clearly from Jul

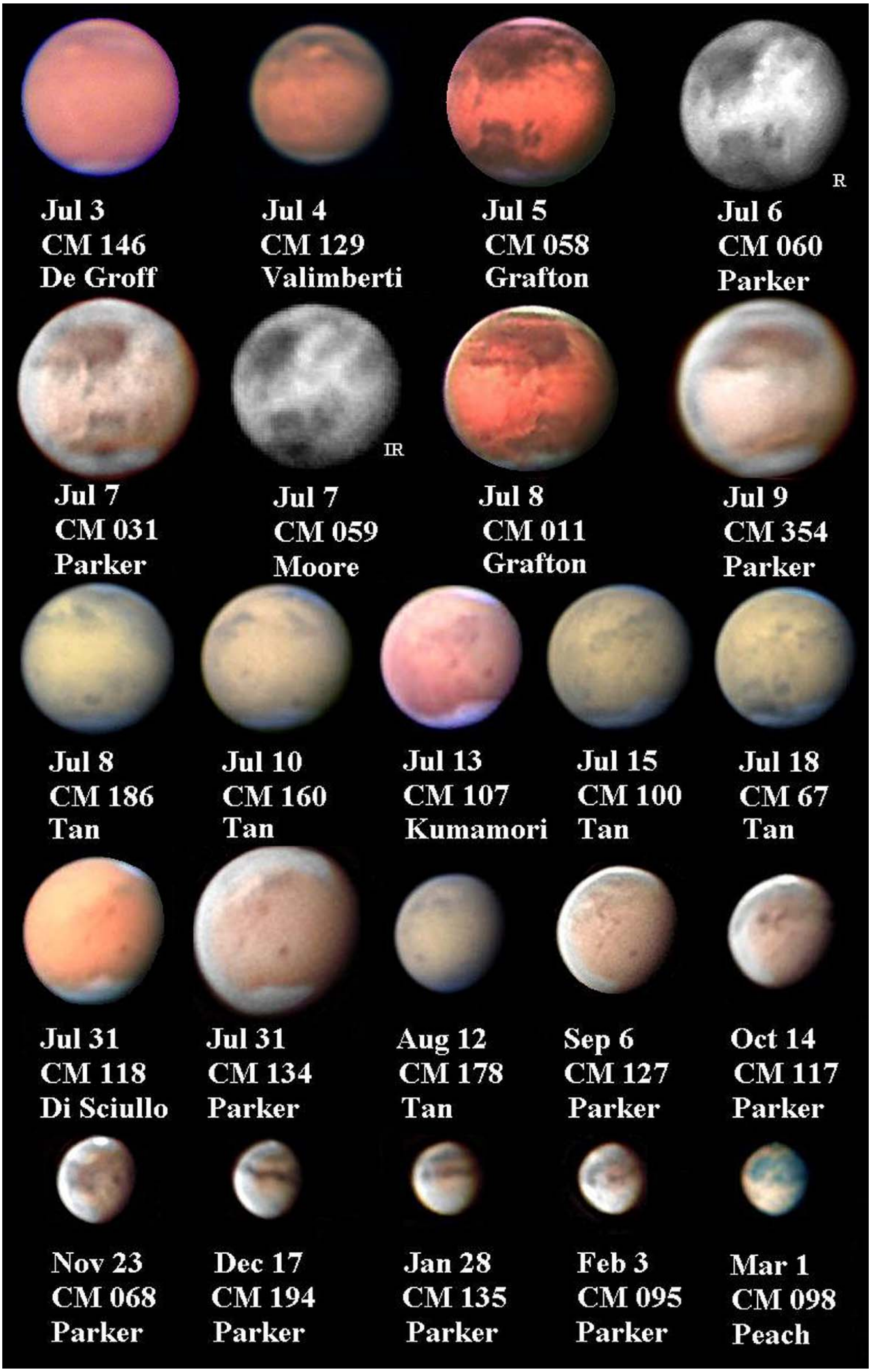

Figure 11. Dust storm images: the Syria–Thaumasia emergence site. Most images are RGB or R(G)B composites. Jul 6 by Parker is a red image in poor seeing, and Jul 7 by Moore is an infrared image. On 2002 Mar 1, D = 4.8". Other details upon the images; for instruments see Table 1.

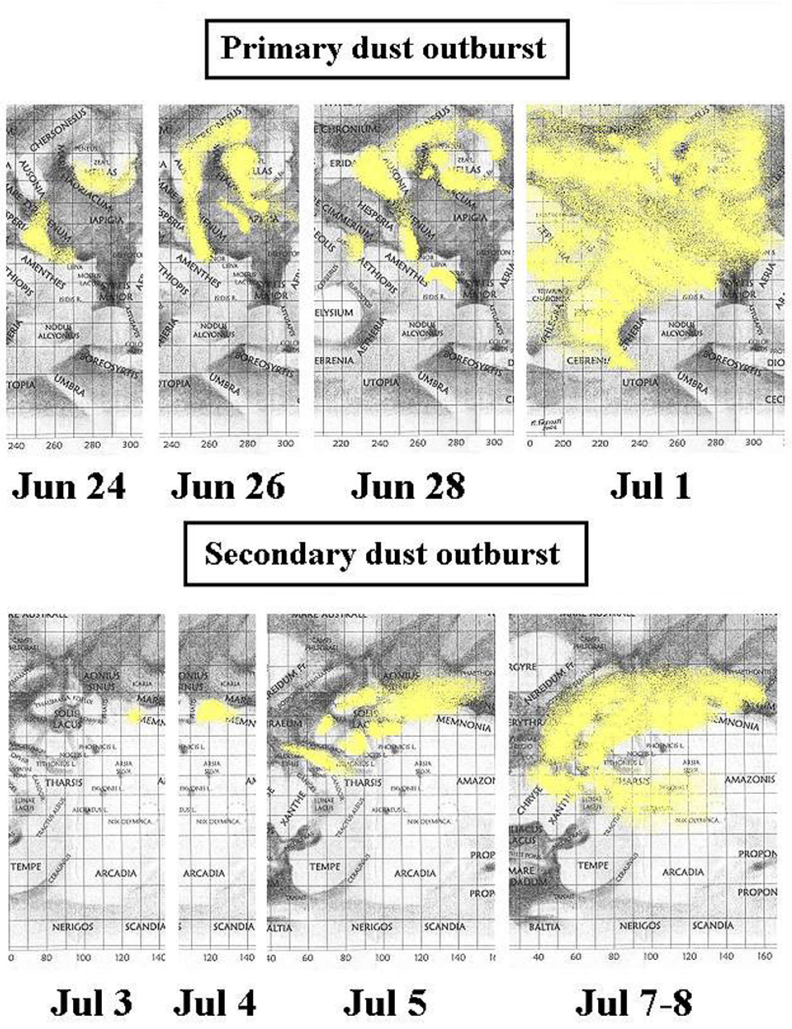

Figure 12. Hand-drawn charts of the initial development of the great dust storm of 2001, showing the primary and secondary emergence sources; *R. J. McKim*. UAI (Figure 1) basemap.

11 to Aug 14. Adamoli likewise independently recorded it during Jul 13 to Aug 13, commenting that it was often – but not always – easier to see in blue light. Indeed, the CCD images recorded it best in blue, and only weakly in green, showing that it was atmospheric. Imaging data confirm that it existed weakly from Jul 7, strongly from Jul 10 till the end of the first week of August, fading out on Aug 17. Thus the area declined as the NPH and the storm also declined: a truly global change.

At the height of the storm the value of D_e was positive and the cap was greatly foreshortened. The best drawings and images showed that the southern part of the cap never entirely disappeared, although at times it was but a glint at the southern limb. By early July the cap was already losing its brilliance and taking on a yellowish tone at some longitudes, with the *Hellas* dust apparently having propagated over it (as illustrated elsewhere[3]). A few days later it became completely veiled, and the SPC northern edge was not glimpsed again until about Aug 12 (Parker), the dark fringe following within a few weeks. As late as Sep 26 Minami found the a.m. side yellowish under CML= 65°. Unambiguous measures of the cap size were again possible from October.

Intensity estimates

We extracted intensities for *Syrtis Major* (cross-equatorial, easily recognised and typically intensity 5–6) for 2001 May–2002 Jan, excluding occasions when it was too near the limb. We limit the contributors to those who made several observations of it before and during the storm, namely Adamoli (A), McKim (M), Meredith (Mr) and Schmude (S):

2001 May 29–30 M 6; Jun 4 M 6.75; Jun 5 S 6; Jul 1 A 6.5, M 5, Mr 4; Jul 2 A 5.5; Jul 3 M 4.4; Jul 4 M 3.75; Jul 6 M 4; Jul 7 A 5; Jul 9–10 A 4; Jul 15 S 2.5; Jul 16–17 S 3.5; Jul 19 S 3; Aug 5 A 4; Aug 6 A 3.5; Aug 7 A 3; Aug 10 A 2.5, M 3; Aug 12 A 3; Aug 13 M 3.25; Aug 14 Mr 3; Aug 17 S 3.5; Aug 23–24 S 3; Sep 23 S 4; Sep 30 S 3.5; Nov 26 M 5; Dec 1 M 4; Dec 29 M 6; 2002 Jan 2 M 6.

Note the quick onset of the great dust storm – causing a sharp fall in intensity (already achieved by the end of the first week of July) – and the slow return to normality (not fully achieved till December) as dust settled.

Clearance

The first sign that the storm would soon decay came when the discrete dust sources faded. *Hellas* was still bright and yellowish into November whilst the *Syria–Daedalia* site was (according to our data) no longer actively lofting dust after Sep 6. (Strausberg *et al.*[3] made an estimate of Ls= 210–214° (Aug 8–15), which to the writer seems too early.)

According to MGS data,[4] dust settlement began at high southern latitudes sooner than at the equator. According to BAA data, the northern edge of the SPC did not reappear until Aug 12, but the cap was not seen in sharp contrast till late next month.

From mid-August onwards a gradual clearing was generally underway, with the ghosts of the albedo markings a trifle easier to glimpse. The process was however very slow, and throughout September the ground markings (discernable with attention) remained hard to see well. Clearance did not occur evenly at all longitudes. The E. end of *Mare Cimmerium* was still weakly visible throughout August, and from around Aug 10 *Mare Sirenum* could also be faintly recognised. On Aug 19 Parker felt that the albedo features around *Syrtis Major* were slightly darker on his images: Melillo on Aug 24 agreed, and *Mare Serpentis* was the darkest area in that region but W. *Sinus Sabaeus–Meridiani Sinus* remained weak. On Aug 31 *Propontis* was again vaguely visible, but *Elysium* and environs remained obscure. During August a bright dusty area was seen over *Electris*. (*Hellas* remained visible as another discrete bright area.) *Solis Lacus* was totally invisible throughout August due to the bright *Thaumasia–Daedalia* cloud. *Depressiones Hellesponticae* persisted at the edge of the SPC in late August but had been weakened by dust. The volcanoes still appeared as anomalous dark spots throughout August and September.

Parker's images on Sep 3 showed that the W. end of *Mare Sirenum* from long. 160–180° (the part that had been invisible since the 1986 apparition) had returned to visibility as a dark feature; Beish and Biver saw it on Sep 25 and McKim's drawing of Sep 29 (Figure 2P) confirmed it. The E. part of *Mare Sirenum* would remain faint until mid-October. Parker on Sep 6 found that dust clouds continued to erupt around the still-invisible *Solis Lacus*, and that the *Phasis* 'canal' had appeared as a dark, curved streak. *Tithonius Lacus* reappeared in the first week of September, but *Solis Lacus* was not observed again until Sep 21 when Parker imaged it. It was oval, but with its long axis rotated clockwise so that it extended to the NW. *Nectar* was invisible. Kumamori and Minamia caught a dust streak along *Coprates* following *Aurorae Sinus*, Sep 23–24, but by then the two parallel dust streaks over *Thaumasia–Daedalia* had disappeared. On Oct 6 McKim confirmed the reappeared *Solis Lacus*, the darkened *Claritas–Daedalia* and the bright settled dust that hid *Nectar*.

On Sep 24 Parker's images (Figure 10) showed *Deltoton Sinus* to have become clearly visible following *Syrtis Major*. On Sep 28 under CML= 215°, Sheehan could easily make out pale, vague shapes of the returning markings, but still no fine details, even with the large refractor of the Union Observatory, Johannesburg. Throughout September *Hellas* remained large, bright and yellowish, but the cloud declined in October.

White cloud activity was seen to have resumed on Oct 3 by Haas (a dull whiteness over morning *Hellas*), whilst by Oct 31 McKim noticed that the evening limb had returned to its customary brightness. After the first week of October the W. part of *Sinus Sabaeus* and *Meridiani Sinus* reappeared. On October 13 *Mare Chronium* could be seen again. Thus by early October all albedo features could at least be recognised. The summits of *Olympus Mons* and *Arsia Mons* were still imaged as dark patches by Kumamori on Oct 24, but this was to be the final such report. On Oct 24 too, Parker's images showed *Meridiani Sinus* near-normal, but small light patches – presumably dust fallout – were scattered over *Margaritifer Sinus* via *Mare Erythraeum* to *Aurorae Sinus*. During October brighter, dusty (presumably atmospheric) patches in the S. hemisphere were seen over *Electris* and S. *Ausonia* in addition to northern *Hellas*, though as we have seen *Hellas* also showed diurnal cloud. On Oct 28 Beish found the *Hellas* dust confined to the NW corner.

Visual impressions of contrast and colour were important, because a few observers tended to produce over-contrasty images. On Sep 29 and Oct 6 McKim found the planet to be losing its yellow tint, and on Oct 12 under CML= 42°, he found the disk colour reddish and normal to the west, but still yellowish to the east, but the yellow tint remained evident to him in late Oct and early Nov at different longitudes. Minami noticed a pinkish ground tint in the northern hemisphere on Oct 19, the rest of the disk being yellow.

Ebisawa considered that the visibility of the surface markings still had not completely returned to normal at the end of his programme on Nov 4. Minami wrote of a further clearing of the *Syrtis Major* region on Nov 10. The consensus was that telescopic contrast was not back to normal until the second half of November; however, the diminished disk hindered observation. Nor did the storm clear equally quickly at all longitudes. Thus the Director's first observation of a normal level of visual contrast was on Nov 19, and on Nov 21 Minami found all the desert areas to have returned to their normal reddish tint, but on Nov 27 Parker still felt the markings a little muted.

Signs of bright dust were also detectable at *Argyre–Ogygis Regio* (2001 Sep–2002 Feb) (after which the disk was too small) (Figures 2R, 10, 11) and *Edom* (2001 Nov–2002 Feb). A greater brightness in red and green light suggests that these were actually dust patches settled upon the surface.

Northern *Hellas* was still bright and the whole basin continued to show diurnal cloud in addition to the dust. In Kumamori's Nov 10–11 images it was still strikingly bright, yellow and complex. In Akutsu's images of Nov 11 it was brightest in red and infrared. In late November and at the very start of December N. *Hellas* (and to a lesser extent, *Ausonia*) was still visually creamy-yellow and bright through a red filter, but there was no other concentration of active dust clouds, and by late November *Hellas* had begun to show ground markings like *Zea Lacus*. (Figure 10) The Director had his last view of brightness in *Hellas* on Nov 26 and Dec 1 (Figure 2S). Parker from Dec 8 found no dust in *Hellas*, as did the writer on 2002 Jan 2 (Figure 2V) and later. Dec 1 seems a good visual estimate of the last indication of suspended dust.

As we have seen, intensity estimates also suggested a return to normal during December. Schumde's polarisation data[23] suggest that the effects of the storm lasted from Jun 24 till about mid-December, but with much uncertainty in the final date. We shall take the visual impression, and therefore finally estimate a duration of 159 days (Jun 26–Dec 1).

MGS TES data analysed by Cantor[2] showed that the dust optical depth did not return to normal till around Ls= 304° (2002 Jan 6). Daytime surface and atmospheric temperatures did not return to normal values for longer still, owing to dust deposition and increased surface albedo.

Summary and discussion

The great storm of 2001 had centres of activity and an evolutionary history entirely typical of past events. However, it was also seasonally the earliest-ever recorded among all past encircling events. It was also one of the most enduring storms. Given that a further global storm would occur in 2007,[33] it may have marked the return to the sort of dusty climate seen

Table 2. Planet-encircling dust storms, 1909–2001

Emergence date	*Duration (days)*	*Ls (°) at start*
1909 Jun 3	119	207
1924 Dec 9	68	311
1956 Aug 19	73	249
1971 Sep 22	161	260
1973 Oct 13	91	300
1975 Jul 14	100	270
1977 Feb 15	60	204
1977 May 27	158	268
1982 Oct 14	110	208
2001 Jun 26	159	185

during the 1970s.[40] Compare the data in Table 2 (where the storm length is necessarily approximate), compiled by the writer using identical criteria from original sources. For 1909 the emergence date could be marginally earlier.[30]

The longest events occurred close to either the S. spring equinox (Ls= 180°), or to perihelion (Ls= 250°) or the S. summer solstice (Ls= 270°). Otherwise there is no direct relationship between Ls and duration. The two longest encircling events (1971 and 2001) were classified as global rather than merely planet-encircling because they obliterated all albedo features in both hemispheres; furthermore, in 1971 dust covered the SPC completely. The likely effect upon cap recession of dust settled upon the SPC has recently been modelled by Bonev *et al*.[41]

The development of 2001's global storm was similar to many past regional and encircling storms. It began with what at first appeared to be a large regional event. In this respect the storm was not seasonally early: regional storms from *Hellas* have begun at even lower Ls. (The Director's *Memoir*[30] lists regional events that started there as early as Ls= 163°, and it is further noted that in the last century, *Hellas* regional storms showed a tendency to begin earlier and earlier.[19])

The event had the opportunity to become planet-encircling only after a secondary S. hemisphere dust cloud had arisen over *Daedalia* on Jul 3, which together with the initial dust outbreak carried activity around the globe. All great storms have become encircling when a secondary (or further) source supported an initial outbreak.[30] The event also had bursts of dust over *Libya/Isidis Regio* on Jun 28 and *Elysium* on Jul 1.

The event showed a more vigorous expansion to the north than the recent encircling events, but its development in the S. hemisphere in the first few days was unusually slow. Recall that D_S was positive at the time, favouring northern hemisphere activity. The insolation of the S. hemisphere was clearly not yet adequate to force a vigorous expansion. Also, the SPC had hardly begun to regress. The encircling storms of 1956, '71 and '73 had expanded more rapidly, but their seasonal dates had been later and therefore much more favourable. The events of 1956, '71 and '73 all covered the S. polar cap. The 2001 storm covered it in part.

In looking for a trigger for the early seasonal emergence of the 2001 storm, we note that the SPC seemed to free itself from the hood marginally earlier than in some past years. (As we shall see later, this year the SPH cleared by Ls= 176°, whilst in 1986 with no encircling storm,[31] it had become hood-free at Ls= 180°.) However it is much more likely that the event was triggered by one or more small dust storms at the SPC N. edge moving north into *Hellas*. Strausberg *et al*.[3] compared the statistics of such local storms, and found a sudden increase in storm frequency and area at Ls= 178° (Jun 15) in 2001, compared with 1999. Was this the critical factor?

The considerable activity of the NPH in 2001 is unusual, and we shall discuss it further in the NPR section. In the seasonally later encircling storms (and in some regional events) the hood typically retreated or disappeared. The northern hemisphere activity at *Elysium* is also fairly rare: we have had telescopic local and regional events there most recently only in 1982 and 1993,[30] though the region is known to act as a dust source in encircling storms. The S. of the region has clearly been acting as a dust-sink recently, given the fading of *Cerberus* since the later 1980s.

For visual observers the 2001 storm was the most opaque since 1971, although the latter threw dust to higher altitudes so that the *Tharsis Montes* were completely veiled for much longer before they appeared as dark spots. Ebisawa wrote that the decrease in polarisation recorded by him in 2001 was somewhat less than in 1971 and 1973. This is in accord with the visual impression that it was a less dense event than 1971. Smith *et al*.[4] found it to have been optically deeper than the two 1977 storms.

The high resolution nature of the 2001 observations showed that (vindicating the work of A. Dollfus & S. Ebisawa[42]) there is little or no observable daily change in the specific bright dust clouds as they cross the martian disk; a good example being the *Libya* cloud of Jun 28 which was followed from early morning till early afternoon (CML= 218–285°). Minami[42] recalls an earlier notion (due to C. F. Capen & L. J. Martin) that storm-clouds expand considerably as they leave the morning terminator, and the likelihood that it arose through the inadequate resolution of the 1970s photos, where morning cloud could not be distinguished from dust.

The albedo changes accompanying the storm are typical, and have already been described. The great dark curve of *Nepenthes* has been regenerated by past dust storms in *Libya–Isidis Regio* (such as with a regional storm in 1911), but in 2001 the *Libya* cloud did not have such an effect (except insofar as *Moeris Lacus* became enlarged), doubtless owing to the settling of dust from the global storm.

Later activity: 2001–'02

As the *Solis Lacus* returned to visibility in 2001 Sep, as noted earlier there was a persistent bright area over *Nectar*–NE *Syria* lasting many months. It is shown in the best images and drawings from late September till early March. Given the absence of movement or change of form, this must have been a large area of dust fallout on the surface.

MGS imaged several N. hemisphere events, mostly associated with the N. polar region, when ground-based resolution had already become inadequate. In 2002 Mar it imaged a regional event which had begun near the NPC, evident in the form of a long, bright arc centred upon *Chryse Planitia* with tendrils running *Np*. and *Nf*. over *Mare Acidalium* and *Tempe*.[43] Similar events would be witnessed by Section members during the next few oppositions.

Acknowledgments

I thank Johann Warell for kindly making the colour composite of Jean Dragesco's 1986 Mars photograph that appears in Figure 5H. As ever, data compilations by Jean Meeus[44] were especially useful sources of numerical information. Michael Smith kindly provided Figure 7, which he has previously published.[8]

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Editor's note: Part II of this paper, covering bright 'flashes' seen in 2001 June, and descriptions of the North and South Polar regions, will appear in the August Journal.