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1973 DUST STORM ON MARS: MAPS FROM HOURLY PHOTOGRAPHS

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Manuscript totals 31 pages, plus seven figures.

ABSTRACT

The hourly progress of the 1973 major Martian storm has been mapped using photographic images from the International Planetary Patrol. The outlines of brightened areas were definable for about three weeks, which is about the same amount of time that could be mapped in this manner during the 1971 major storm. Two series of 20 daily maps show the semi-hourly positions of the storm brightenings in red light and blue light. The maps indicate that the 1973 storm had many similarities to the 1971 storm, as well as a number of significant characteristics of its own.

The variations in color and location of several initial clouds that developed during the 1973 storm are compared using Patrol photographs taken through red, green, blue, and ultraviolet filters. The positions of the 1973 initial clouds are shown on a map together with the initial clouds that developed into the well-known storms of 1956 and 1971.

The 1973 storm developed more of the characteristics of the 1971 storm after 8 to 10 days, when it was reaching a mature stage. Separate maps of every two hours showing the progression of the storms on their 11th days portray the extent of the similarities.

The storm was mapped through its 22nd day (November 3), by which time it had begun to decay: the brightened areas had diminished in size and contrast. All Patrol photographs through November 21, 1973, were examined, and the remainder for that Martian apparition (through February 8, 1974) were spot-checked. The storm's gradual dissipation was not uniform around the planet and included at least one minor rejuvenation.

ABSTRACT (continued)

A summary map shows which areas on Mars were most affected by the brightenings seen during this storm. The map is more comprehensive than could be developed from the 1956 and 1971 photographs, although the areas which were active throughout these three major storms were very similar. Not only was the general latitudinal belt the same, but also the irregularities or indentations in the belt occurred at nearly the same places.

The 1973 major storm weakened several of our previous ideas regarding the nature of Martian dust storms while strengthening other beliefs and determining several new characteristics. We are now less certain where, when, or even in what colors we can expect to find initial storm clouds; whereas the areas most affected and the motions of a mature storm are now more predictable. The complex relationships of brightenings seen on blue-filter photographs provide new questions for theoreticians.

INTRODUCTION

During 1973, Earth-based photographs from the International Planetary Patrol (Baum, 1973) gave us the best record to date of a major Martian dust storm from development through dissipation. Two previous papers were, in part, based upon these photographs of the 1973 storm. The first paper was primarily a daily comparison of the initial development and expansion of the storms of 1971 and 1973, as well as a report on contrast changes of various albedo features throughout the 1973 storm (Martin, 1974b). The second paper examined the effects of major storms upon the Martian polar hood (Martin, 1975). The present paper reports on a more comprehensive study of the hour-to-hour changes of the storm-brightened areas, in the same manner that Patrol photographs were utilized to study the 1971 dust storm (Martin, 1974a).

The general descriptions and older references for Martian dust storms and yellow clouds are well covered by the above papers, as well as by Gierasch (1974), Capen (1971, 1974), and Capen and Martin (1972a, 1972b). Such descriptions will be repeated here only when there is a need to change or modify them. The 1973 daily storm maps were compiled with a planet image projector using the same methods described by Baum (1973) and Martin (1974a). All transient brightenings and some darkenings were mapped as probable "clouds." The background map, except for Figure 5, is the 1973 Lowell map (Inge, 1974), which portrays Martian albedo features just prior to the onset of this storm and to opposition (October 25, 1973). All feature names used in this paper are shown on the Figure 5 map.

Capen (1974) identified three "stages" of the July 1971 cloud which he called "initial," "mature," and "decay." Gierasch (1974) included the major storms of 1971 and 1973 to categorize three "phases" he called "initial," "expansion," and "decay." The 1973 daily maps provide the means to distinguish among the four separate phases that are used in this paper and designated as (1) initial, (2) expansion, (3) mature, and (4) decay. Because of the planetwide nature and complexity of the storm, these phases identify the most prominent characteristics but are not mutually exclusive; we find new clouds during the expansion and decay phases, expansion during the other three phases, mature areas during the decay phase, and some decay or recession taking place from the first day.

The initial phase lasted four days (as it did during the 1971 major storm), during which the expansion was limited to approximately 115° of longitude and between the equator and -50° latitude. By Day 3, several closely spaced initial clouds had combined into a single storm system.

The expansion phase, also lasting four days, began with several new outbreaks of brightenings and a noticeable acceleration in the expansion of the original storm area. Some of the new areas also expanded and coalesced both with each other and with older cloud systems.

The mature phase covers the five days on which the brightenings probably encircled the planet, shifting westward with Mars' rotation and with few interruptions. Expansion beyond the areas that already had been actively bright was limited, and there were fewer excursions

north or south of the more active areas than during the expansion phase.

The decay phase began on Day 14, when brightened areas divided into two parts seen during the same hour. Much of the storm continued its hourly shifting as during the mature stage, but the continuous chain of apparent motion had been broken and was not restored.

THE DAILY MAPS

The 20 maps in Figures 1 and 3 show brightened areas seen at two-hour intervals on red-filter (6200 Å) photographs. Figures 2 and 4 show brightenings from blue-filter (4340 Å) photographs during the same 20 days. Each map is numbered in terms of days based upon rotations of Mars, starting with the first day that the storm could be identified. The beginning of each Martian day was defined as the time the subsolar point crossed the 180° meridian. The Earth dates (UT) are shown below the day number in Figures 1 and 3.

The time scale used on the maps is Martian Apparent Solar Time at the 0° meridian. The Martian days were divided into 24 hours, each hour representing 15° of rotation. Noon (or 12) is therefore the time the Sun's path crossed the 0° meridian. The boundaries of the brightened areas are labeled to the nearest hour, with intervals between them of about two hours. The boundaries shown on the maps were selected from preliminary maps showing one-hour intervals whenever usable Planetary Patrol photographs existed. Gaps which exceeded 60° of longitude between central meridians of usable photographs (or four hours)

are shown by dashed lines along the equators of the daily maps.

Small triangles point to the brightened side of boundaries where clarification was needed and were primarily placed on open-line boundaries that portray the edge of a brightening that was partially out of view or ill-defined. The triangles were also sometimes used to differentiate the outlines of dark areas (Figure 1, Days 7 and 10; Figure 2, Day 4).

All areas which appeared abnormally bright were outlined, with no attempt to differentiate between storm-connected brightenings and non-storm brightenings. Although this differentiation was made on the maps for the 1971 major storm, the 1973 storm includes too many borderline cases to accurately make that distinction. Non-bright obscurations or hazes that were related to the storm were not mapped (see Figure 6).

The sub-Earth longitude or central meridian (CM) at 12 hours (Martian Apparent Solar Time at 0° longitude) is shown on each map as a simple reference for estimating the approximate visible disk on the photographs.

Initial Phase (Days 1-4)

The earliest photograph that is known to show the beginning of the major 1973 storm was taken by Planetary Patrol observer Phil Crump of Mauna Kea Observatory. This red-filter photograph shows a bright cloud near the morning limb measuring 400 kilometers from north to south. It is labeled "14-20" on Figure 1, Day 1 map. The time was

0701 UT on October 13, 1973. (Also see Figure 5.) The planetocentric longitude of the Sun (L_s) was 300°, which is equivalent to January 20 on Mars, or midsummer in the southern hemisphere. The subsolar point was at 15°W longitude and 21.3S latitude. The green-filter (5560 Å) photograph taken one minute later showed a brightening over the same area. The blue-filter and ultraviolet-filter (3800 Å) photographs both showed extensive limb clouds that exhibited eastward bulges over the area of the first cloud (Figure 2). The surface at that spot had been dark (Solis Lacus); Mariner 9 photographs show it as a relatively smooth, upland plain (Topographic Map of Mars, 1975).

Earlier the same day (on Mars), Hellas had appeared bright within a small area on the north (labeled "10" on map) on both red- and green light photographs. This brightening had existed for some time without expanding into a storm and is normally bright during that season. Two hours before the first storm cloud was recorded, the blue- and ultraviolet-light photographs showed a large morning limb cloud that is believed to have been associated with storm activity. The limb cloud was not on the photographs from the previous day. The same blue-filter images showed an isolated brightening (labeled "12") near the center of the disk, which probably was not related to the storm.

A second bright cloud (hours 16-22) was mapped from photographs taken two hours following the first pictures of the Solis Lacus cloud (Figures 1 and 5). The second cloud was centered about 30° west of the first at the same latitude and over the eastern tip of the new

darkening over the Claritas area. This red-green brightening did not appear on the ultraviolet-filter photographs, and its visibility on blue-light images was limi ed to one hour (17). The second cloud was therefore "redder" and not as bright and white as the first (Solis Lacus) cloud. It should be noted that the second and redder cloud later became more active than the Solis Lacus cloud. The same is true of the Sinus Meridiani "red" cloud that began on Day 4 (see Figure 5) and which developed into the most powerful sector of the expanding 1973 dust storm.

A third but dimmer cloud appeared slightly west of the first two on Day 1 (hour 20). The third cloud was visible only on red- and green-light photographs, although brightenings in blue and ultraviolet were in several nearby areas. It appeared to shift to the northwest (hour 22), while the second cloud expanded southward. By early afternoon (locally), the first cloud was no longer visible. It had disappeared in blue light by local noon and in red and green two hours later, only to reappear the following morning over the same area.

The eastern hemisphere brightenings in Hellas, Ausonia, and Eridania were only marginally mapable during the initial phase and may not have been atmospheric, although occasionally they could be identified on blue-filter photographs. Of these, Hellas showed the strongest contrasts and seemed to pulsate in size from day to day.

The brightening in southwest Noachis on Day 2 also failed to develop, although the storm expanded into that area on Days 5 and 8 and throughout

its mature phase. The only notable activity on Day 2 was still in and around Solis Lacus. The earliest signs of the storm on the second day were blue- and ultraviolet-light morning limb clouds at 9, 11, and 13 hours. The expanding storm cloud over Solis Lacus (hours 13-21) was again the first seen in red and green light and again disappeared before mid-afternoon.

The larger and more rapidly expanding cloud that appeared several hours later southwest of Solis Lacus (hours 15-24) is believed to be the same disturbance described as the "second cloud" on Day 1. It had moved south about 1200 kilometers (center to center) during one rotation of Mars and expanded to about five times its original size. Day 1's "third cloud" also reappeared on Day 2 (hour 21) and again showed minor movement (hour 24), although it had not expanded as the other clouds had. All three of these clouds showed some brightening in blue light at least part of the time.

The complex relationship between blue- and red-light brightenings is well demonstrated by the small morning cloud (Figure 2, Day 2, hour 15) which protruded into the indentation seen on the west side of the Solis Lacus red-light cloud (Figure 1). Two hours later the situation was completely reversed, with the blue brightening (hour 17) coinciding with the red cloud, but then disappearing by the following hour. Numerous blue- and/or ultraviolet-light brightenings made brief appearances around the peripheries of the red- and green-light clouds throughout the initial phase of the 1973 storm.

The more southerly or "second" cloud was the first to appear on the third day (hour 13). It continued to expand more rapidly than the Solis Lacus cloud (hours 15-17), although within a few hours the storm appeared as a single, combined cloud. The combined cloud was not bright in blue, although part of the Solis Lacus cloud did appear in blue light earlier (hour 15). Various other brightenings in blue light were in and around the storm, both before and after the red-light storm clouds combined. The north polar hood protruded to 30°N latitude in both blue and ultraviolet light (Martin, 1975). The area between the polar hood and the storm brightenings was very dark on the ultraviolet-filter photographs compared to the bright clouds.

A new cloud appeared in the afternoon of Day 4. Photographs taken until local noon showed no sign of this cloud. Figure 5 includes photographs of this cloud, which showed as a darkening in both blue and ultraviolet. Although this cloud was not yet bright in red light on Day 4, the eastern half of Sinus Meridiani was obscured from view by a material that was notably lighter (in red and green) than the normal albedo of that feature. The Sinus Meridiani cloud developed into a second major storm system within a few days and expanded into the Solis Lacus storm system on Day 8.

On Day 4 the morning limb clouds, seen east of the storm each day in blue light, were divided into two sections that moved through and north of the storm area seen in red. During the 1971 major storm's initial stage there was also brightening activity in blue light over

the same sector of the planet, although all of the red- and green-light storm brightenings were well to the east (Martin, 1974a).

The main storm cloud continued to expand in several directions during the fourth day. Actual movements to the east were usually not photographed, but rather the brightenings were seen in more easterly locations as they rotated into view each morning. Eastern boundaries of the cloud generally tended to remain in nearly fixed positions over a number of hours each day during the initial and expansion phases; whereas they shifted westward during almost every hour throughout the mature and decay phases. The western expansion on Day 4 was during Martian daytime and displayed more hourly motion than had been seen on the previous three days.

The thumb-like extension of the Day 4 brightening that had moved out to the northeast is another example of blue- and red-light clouds being seemingly drawn toward each other. This new extremity was over the same spot that had been bright only in blue light on Day 3 (hour 15). The main storm cloud had been pushing toward the area of the blue brightening since Day 2. Note also that later (Day 5) this cloud partially withdrew from the area, having merged with the blue-filter cloud. The prominent cavity in the main storm cloud which was created by the Day 4 thumb (to its northwest) was probably caused by the dynamics of the storm itself, since it has no correlation with known surface features.

Expansion Phase (Days 5-8)

Storm activity was erupting nearly all around the planet by Day 5. The brightening labeled "7" over Ausonia was photographed in four colors (red, green, blue, and ultraviolet) and was the earliest discrete cloud in that vicinity, although it appeared only during a single hourly observation. The Hellas brightening (hours 7-11), however, appeared on photographs over more hours than on previous days, possibly indicating an increase in dust activity. The small spot (hour 9) west of Hellas was also seen in green light but only for a single hour and was not identifiable thereafter. The red-light brightening over Aeria (hours 11-13) continued to be intermittently active over the next few days, but is not known to have ever merged with the main storm. The Aeria cloud was the most northerly brightening that was identified in red light during the 1973 major dust storm. The Sinus Meridiani cloud had become bigger and brighter and had expanded southward since Day 4. It could not be identified as either dark or light on blue- and ultraviolet-filter photographs. The largest new brightening on Day 5 was plotted over southwest Noachis (hours 9-13) in about the same area that was bright briefly on Day 2. On Day 5, however, it expanded westward across a narrowing path (hour 15) and joined the main storm. The connecting neck between clouds was identified on red-filter photographs from three times earlier that day in addition to the one shown. The same neck of red-light brightening spanned the northern third of the Argyre basin. Since this basin became very actively bright during later stages of

these storms, the rapid passage across Argyre, without expanding into it or remaining until the next day, may be another indicator of the storm's early strength. The Noachis-Argyre clouds did not appear on Day 6 photos, and the main storm's southeast boundary retreated to near its Day 2 position.

Most of the storm activity is difficult to correlate with known Martian surface features; the finger pointing east on Day 5 (hours 13-15) along the Coprates Canyon is an exception. Part of the northern boundary of the storm had been adjoining or just over the canyon for several days, but the Day 5 boundary followed it over a greater distance. Cloud activity in blue light was also observed a number of times in the Coprates area. The northeast finger also retreated to the west (in all colors) prior to the Day 6 observations, but expanded again on Day 7.

Massive expansions to the west and southwest began on Day 5 and continued through the expansion phase or until the globe was spanned (probably Day 9). The sudden increase in the rate of expansion is similar to one which occurred on Day 5 of the 1971 major storm (Martin, 1974a).

An unusual darkening that possibly was an initial cloud appeared on Mare Tyrrhenum on Day 6. Figure 5 shows its map location, together with photographs in four colors. It is not shown on Figures 1 or 2 because it was distinct enough to map in red and blue only during hour 9 (which was not selected). It was also on the hour 8 ultraviolet

photographs and hour 10 green photographs. Based upon earlier storm activity, it is speculated that this darkening may have brightened in red light and moved southeast into Eridania, where it was seen on Day 7 (hour 6). The same cloud expanded both to the east and to the west on Day 8 and into Hellas on Day 9. These short-lived darkenings are rarely seen and are apparently very unstable.

The Hellas brightening remained confined through Day 6 but had expanded to the north by the early hours of Day 7, while being rapidly approached by the bigger storm cloud that had expanded to the east. After these clouds merged on Day 8, Hellas did not remain bright as the planet rotated, although its eastern boundary was fairly stable for about four hours.

The Day 6 position of the central storm cloud (hours 10-16) was displaced to the west, enlarged from Day 5, and showed some brightening in blue light. By Day 7, its eastern boundary had advanced to the western edge of Mare Serpentis (hours 8-14). The main direction of the easterly expansion of the central storm cloud was almost directly toward the same area that had been covered by the expansion in the Hellas cloud. During the seventh day the central storm cloud advanced hourly to the southwest and west, while its other boundaries remained nearly static. The movement westward of the central cloud on Day 7 was toward the northeast tip of the original (western) storm cloud which had again been expanding eastward (hours 14-16). An area between the two storm systems appeared as a very dark spot (hours 14-16)

on both the red- and green-filter photographs. Although we cannot rule out contrast effects, nothing else on the planet appeared that dark at that time, nor was there a similar effect on Mare Serpentis, which had also been between two bright clouds that day.

On Day 8, the western and central storm systems also merged (hours 15-17), but at a point considerably south of their near approach on the previous day. The darkest area on Day 8 was the large indentation in the storm brightening directly south of Solis Lacus (hours 15-17).

The ultraviolet-filter photographs from Days 7 and 8 show brightenings adjoining the storm brightenings in red light. Ultraviolet brightenings were along the southern boundaries of the central storm area and even cut across the dark area mentioned above. Most of the ultraviolet brightenings photographed on Days 7 and 8 did not show in blue light; whereas the main storm areas appeared bright in blue, but only in limited areas and only for brief periods.

Mature Phase (Days 9-13)

Gaps in the photographic coverage occurred each day during the mature phase, but it is a reasonable speculation that the storm did completely circle the planet on each of those days. With few exceptions, both east and west boundaries of red-light brightenings shifted westward hourly at varying rates and following the same general latitudinal belt. Figure 6 shows Day 11 as an example of the semi-hourly progression of storm brightenings as Mars rotated during the

mature phases of both the 1971 and 1973 storms. Comparing these two map series provides graphic evidence of the similarities between these two storms during their mature phases. (The similarities between the 1971 and 1973 storms were fewer during their other phases.) The apparent movement of the brightenings seems to have been influenced by the path of the subsolar point during both storms. In both storms the afternoon brightenings were slightly predominant part of the time, as were the morning brightenings at other times. Although the cloud configurations varied between the two storms, they both followed nearly the same central paths from east to west. These paths were not due west, but swung slightly north at about 320°W, south near 350°W, and back to the north at around 30°W. The Day 11 brightenings during the 1971 and 1973 storms both conformed very closely to the "most active area" shown in Figure 7. The other days of the mature phase also showed brightenings that generally conformed to the "most active areas" with some extensions into the "more active."

The mature phase began on Day 9, when the brightenings from the east merged into Hellas, shown as hours 6 and 8 (returning to Figure 1). The merger probably did not occur on Day 8, since hour 8 of that day (not selected) shows a separation between these clouds at about 270°W. The gap that separated the clouds shown on Day 9 (hours 14 and 16) was covered by brightenings seen on green-light photographs from several different hours and also would have been only half as wide, had the red-filter hour 15 boundary been included.

Day-to-day changes in the storm during the mature phase were minimal, and a similar pattern was repeated each day. Expansion into new areas was very limited, and there were no major shifts in the overall configurations. In the Hellas area there was a gradual expansion that continued into the decay phase. The darkening labeled "9" on Day 10 was also mapped for hours 8 and 10 and can be seen on several of the photographs in Figure 6 (Day 11). This dark region was most prominent near local noon and within a general area that was avoided by the brightenings which swung northward, then southward during each day of the mature phase (also see Figure 7).

Cloud activity in blue light was at a minimum during the mature phase, primarily consisting of small bright clouds near the morning limb. Day 9 (Figure 7) included a continuous progression of one limb cloud (hours 8, 10, 12, 14) that appeared to stay nearly fixed over the limb as the planet rotated. It was latitudinally centered on the red-light storm brightenings but stayed ahead of them as both red and blue brightenings shifted westward. The limb cloud (that showed in both blue and ultraviolet) was not associated in time with the western sector of the storm, since it disappeared on or after the 15th hour. A number of blue brightenings were photographed on hours 21 and 22 during Day 12 (Figure 4), but it was the only day within the mature phase that Patrol photographs did not have a gap in coverage during equivalent hours.

The mature phase had weakened by Day 13. The bridge between the eastern and western storm sectors had narrowed (hour 11) at the same

location that became a separation on Day 14. The location was also about the same storm area which narrowed on Day 12 and separated on Day 13 of the 1971 major storm (Martin, 1974a). The same area appears in Figure 7 as "most active," although this activity was primarily within the mature phase. The summary map for the 1971 storm shows the same area as a separation between storm cores since that storm remained in the mature phase for only two days. Several contour maps (Conrath et al., 1973; Topographic Map of Mars, 1975; Hord et al., 1974) agree that this general area is a higher part of Noachis with downslopes both to the north and south.

Decay Phase (Days 14-20)

The separation between brightenings that appeared on Day 14, hour 11, remained through Day 22 (last day mapped), although there was some east and west shifting of these cloud boundaries. The storm showed several other signs of being weaker during the decay phase. One of these was that its apparent motions became more due westerly with a reduced tendency to swing north and south. Motions were therefore more closely associated with rotation or the relative position of the Sun. Also, the irregularities in the boundaries had a correlation with the albedo features as they appeared prior to the storm, in that there seemed to be a preference for the lighter areas and a retreat from the darker areas. This may suggest further dependence of the storm upon solar heating, since these areas would probably be reflecting

more of the morning Sun's heat back to the atmosphere (Kieffer et al., 1973). Another correlation which became more positive during the decay phase was the storm's apparent preference for lower elevations, but within the general latitudinal band south of the dark albedo features. The Hellas and Argyre basins seemed to be increasingly influential as the brightenings became less inclined to shift around the planet. The northward protrusion shown for hour 20, Day 16, and hours 16 and 18, Day 17, also may be partially shaped by relief. Two contour maps (Conrath et al., 1973; Topographic Map of Mars, 1975) both indicate increases in elevation to the immediate north and west of that protrusion.

The Patrol film coverage became increasingly weak as the weather at key Patrol stations deteriorated, causing large time gaps. This limitation was more severe in blue light, probably due to longer exposure times. Also since blue-light clouds are not generally visible over periods of more than a few hours or less, the Figure 4 maps are very incomplete. They do seem to indicate that cloud activity in blue light increased during the decay phase, although most of these clouds had no apparent relationship to the dust storm. The sector of Mars most affected by activity in blue light on Day 17 is the same part of the planet that was active in blue on Day 1 and earlier.

A series of blue and ultraviolet limb clouds is shown on Day 14 as hours 11 and 15 and the same hours on Day 15. The clouds originated over the Coprates Canyon area, moved with the rotation, but shifted

northward and over the Tharsis uplands. The original photographs indicate a continuous hourly progression across the area in a pattern that was repeated on both of these days and possibly began as early as Day 11.

POST-MAP PERIOD (NOVEMBER 2-21)

All Planetary Patrol film through November 21, 1973, was visually inspected for further storm activity, although mapping was discontinued after November 3. During this period the decay phase continued and contrasts of albedo features were slowly returning to normal (Martin, 1974b). Most of the brightening was confined to the Hellas and Argyre basins. A brightening was seen in Libya on November 5 and 6, but not on succeeding days. On November 14 and 15 a new brightening was spreading east across Noachis from Argyre I. This brief resurgence of storm activity had faded by November 16. It was the last brightening identified on the red and green photographs that was outside of Hellas and Argyre I, both of which remained bright through November 21.

The blue- and ultraviolet-filter photographs showed the north polar hood continuously; the period of partial disappearance had ended (Martin, 1975). The number of clouds photographed in blue and ultraviolet was not unusual; they were mostly near the limb and probably not a part of the dust storm.

Sinus Meridiani was still obscured on November 6, but was visible by November 16. Pandorae Fretum, which is known as a prime location

of seasonal darkening (Slipher, 1962; Dollfus, 1973), had not been dark prior to the storm but had become dark by November 6, as the storm cleared. This darkening took place later in the Martian summer than would be expected from earlier studies, but then so did the major dust storm. The dark area in Claritas, seen before the storm, was again as prominently dark by November 12 (Capen, 1975). Syrtis Major, which had a very irregular appearance before the storm (Capen, 1975), seemed to be more normal on November 21, although the photographs did not have very good resolution and Mars' phase was 22°.

The South Polar Cap had disappeared during the storm's expansion phase. (See the photographic images on various figures in the earlier papers on the 1973 storm.) Probably due in part to its small seasonal dimensions (Fischbacher et al., 1969), the cap was not identified again on the photographs until November 9 and 10. At that time it appeared small and weak. The cap was not positively identified again during that apparition, although the planet's apparent diameter was decreasing and its phase was increasing, making small, dim features difficult to photograph.

SUMMARY

Major Martian dust storms are complex events, whether studied using earthbound equipment or from spacecraft. Hourly photographs using four different filters have revealed a number of previously unknown characteristics of dust storms and provide opportunities for

much more detailed analyses of their nature, as well as their effects upon local Martian environments. Similarities between the storms of 1971 and 1973 during their mature phases were very striking after seeing how dissimilar they were in the earlier phases. Initial clouds of the 1973 storm varied in both color and location from the 1956 and 1971 storms with their very similar initial clouds. Even the season in which we expect these storms is a little longer than had been previously estimated (Capen and Martin, 1972b). International Planetary Patrol observations are scheduled to begin in 1975 at the same Martian seasonal date on which the 1973 storm began (L_s 300°). If another major storm occurs this late in the season, we may get photographs of it, although Mars will be far from opposition and therefore small and at a large phase angle and will be available for only a few hours each night. The 1975-76 apparition will, however, give us the opportunity to look for similar events through about the first one-third of northern spring on Mars (L_s 28°). This will be later than southern storms are normally expected and too early for possible northern storms related to summer solstice, but we do not know enough about these large dust storms to exclude the possibility of their occurring in any season. Even minor dust storms or cloud activities will be studied in their own right, as well as for correlations with major storms. Unfortunately, the photography will be less continuous and overall reduced in quality and quantity than that acquired during previous Patrol years, since the apparition will be less favorable

and the Patrol has been reduced to four observing stations. The chances of catching these possible dust storms in their initial stages or following them hourly for very long will still be more likely than during the previous apparitions of Mars which occurred during these seasons, when there was no Patrol.

ACKNOWLEDGEMENTS

C. F. Capen, H. M. Ferguson, and R. L. Millis have provided generous assistance in the preparation of this paper. This research has been supported by NASA research grant NGR-03-003-001.

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FIGURE CAPTIONS

Figure 1. Bright cloud outlines determined from red-filter (6200 Å) photographs from the International Planetary Patrol during the first ten days of the dust storm. The base map is the 1973 Lowell Mars map showing the appearance of the albedo features in red light at the onset of the storm. The maps do not portray the progressive obscuring of these features that took place both within the brightened areas and beyond their limits.

Figure 2. Outlines of brightenings seen on blue-filter (4340 Å) Patrol photographs covering the same ten-day period shown in Figure 1. Boundaries are numbered in hours of Martian Apparent Solar Time. Each "day" represents one Mars rotation, and the "hours" are divisions of those rotations, as described in the text. The albedo features shown on the base maps are not usually seen in blue light. The dashed lines on the equator indicate gaps between available photographs, as explained in the text.

Figure 3. A continuation of Figure 1 showing the storm brightenings through Day 20 in red light. The CM at the top of each map locates the sub-Earth meridian at 12 hours Martian Apparent Solar Time. Some cloud boundary lines include small triangles to denote their bright side. Universal Time Earth dates are given below each day number. See Figure 5 for another portrayal of Day 11.

Figure 4. A continuation of Figure 2 showing blue-light brightenings through the storm's 20th day. Note that the north polar hood clouds are not continuous, even where there are no gaps in the photography; compare Days 2 (Figure 2) and 16. The text describes the storm's progress as seen on these first four figures.

Figure 5. Locations and appearances of several initial dust storm clouds as plotted on the Lowell Albedo Features and Topography Map (Inge, 1973) and as seen on International Planetary Patrol photographs using four different filters. The initial cloud of the 1956 storm was not photographed in ultraviolet or blue. The 1971 cloud appeared as slightly bright in blue (Martin, 1974a), but was not photographed in ultraviolet. The brightest storm cloud of October 13, 1973, was bright in all four colors, while the cloud just to the west was bright only in red and green light. The cloud of October 16, 1973, was dark (or light absorbing) in blue and ultraviolet light. In red and green it was neither light nor dark, although it obscured the eastern half of the dark albedo feature Sinus Meridiani. The darkening over Mare Tyrrhenum on the 18th is not conclusively atmospheric, although it appeared dark (or light absorbing) in all four colors. The text describes the subsequent progression of these 1973 clouds. All of the names of albedo features used in this paper are shown on the map.

Figure 6. Day 11 of both the 1971 and 1973 dust storms is shown at two-hour intervals as plotted from the adjoining red-filter photographs from the International Planetary Patrol. The outlines were plotted from the original negative images and may not agree in all cases with the impressions of the brightenings seen on these photographic reproductions of composite images. The dashed lines indicate the positions of the subsolar meridians (local noon) for each two-hour step. The meridian positions have been rounded to the nearest two-hour interval, but are within 7°, or less than one-half hour, of the true times for the measured photographs. The thin solid lines on the 1971 maps represent the central meridians of those photographs. Since Day 11 was just two days before the 1973 opposition, the central or sub-Earth meridians were only 1° to the east of the subsolar meridians and therefore are not separately shown. The approximate longitudinal ranges of the photographs are shown by the east and west limits of the map sections. This range was 144° for the 1971 photographs and 178° for 1973 (due to the difference in phase angles). The photographs from 1971 are matched to those from 1973 by the positions of the subsolar meridians and not by the sub-Earth meridians. Note that the normal albedo markings were apparently obscured by dust or haze that extended well beyond the brightenings shown on the maps, making most known features unrecognizable in spite of good quality images, as indicated by the sharp limbs. The apparent motion of the

Figure 6 (continued)

brightenings as the planet rotates is typical of the mature phase of major dust storms.

Figure 7. The map summarizes the brightenings seen in red light through 21 days of the 1973 storm. The 1956 and 1971 major dust storm brightenings were active over these same areographic locations and generally to the same degree. The arrows point out areas where the storms deviated from their main latitudinal band. "Active" areas were bright on more than one day during the 1973 storm. The outlines shown here do not seem to have much correlation to either the traditional albedo features or known topography or elevations, although the text describes several minor correlations which occur primarily during the expansion and decay phases. The brightening boundaries between Syrtis Major and Hellas were in nearly the same position each day; whereas the southeast boundaries were seldom repeated. The base map is the 1973 Lowell Mars map, which shows albedos as they were prior to the storm.

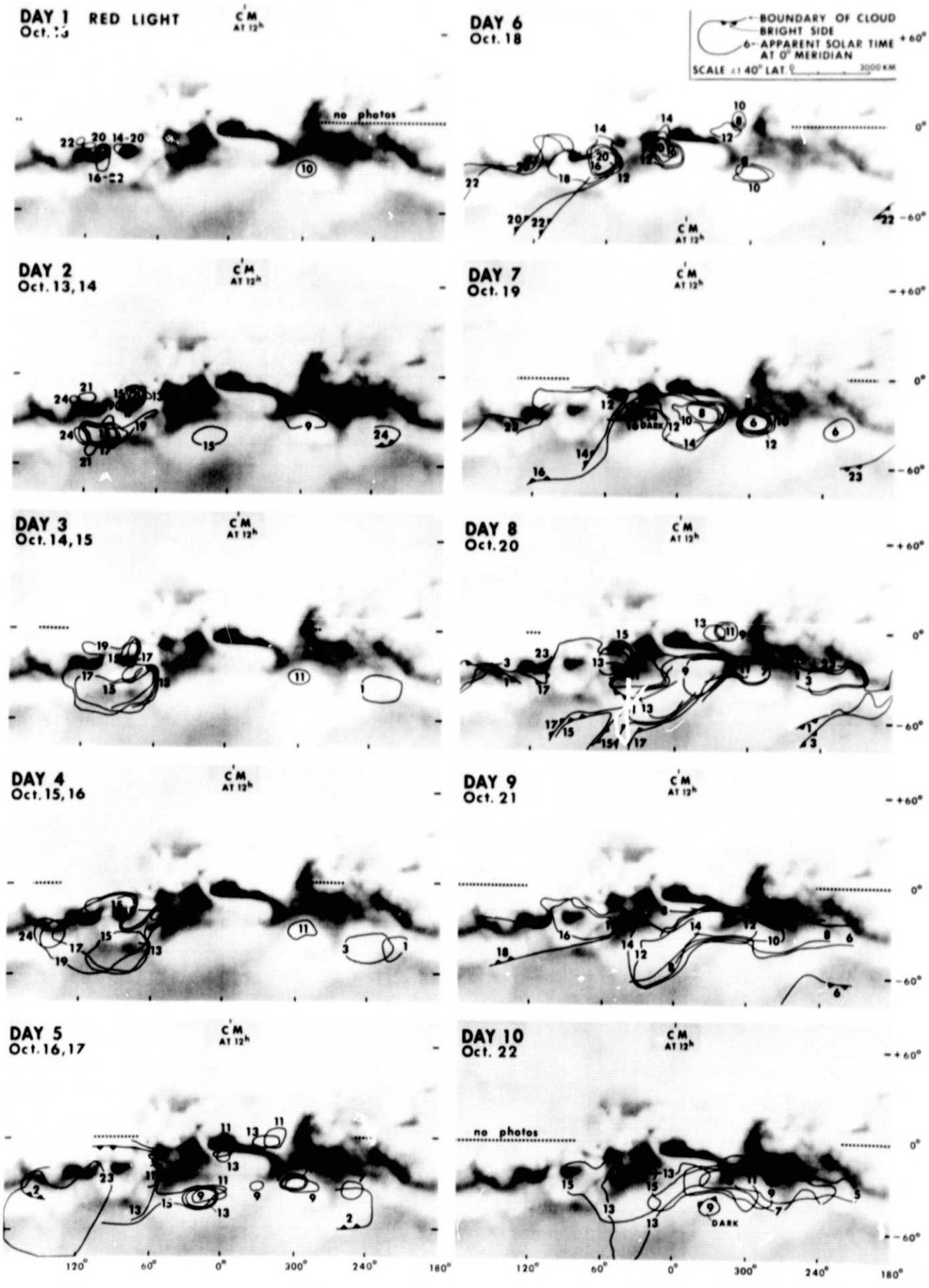

DAY 1 RED LIGHT
Oct. 13
CM AT 12h
no photos
DAY 2
Oct. 13, 14
DAY 3
Oct. 14, 15
DAY 4
Oct. 15, 16
DAY 5
Oct. 16, 17
DAY 6
Oct. 18
BOUNDARY OF CLOUD BRIGHT SIDE
6 APPARENT SOLAR TIME AT 0° MERIDIAN
SCALE AT 40° LAT. 3000 KM
DAY 7
Oct. 19
DARK
DAY 8
Oct. 20
DAY 9
Oct. 21
DAY 10
Oct. 22
no photos
DARK
+60°
0°
-60°
120°
60°
0°
300°
240°
180°

FIG. 1

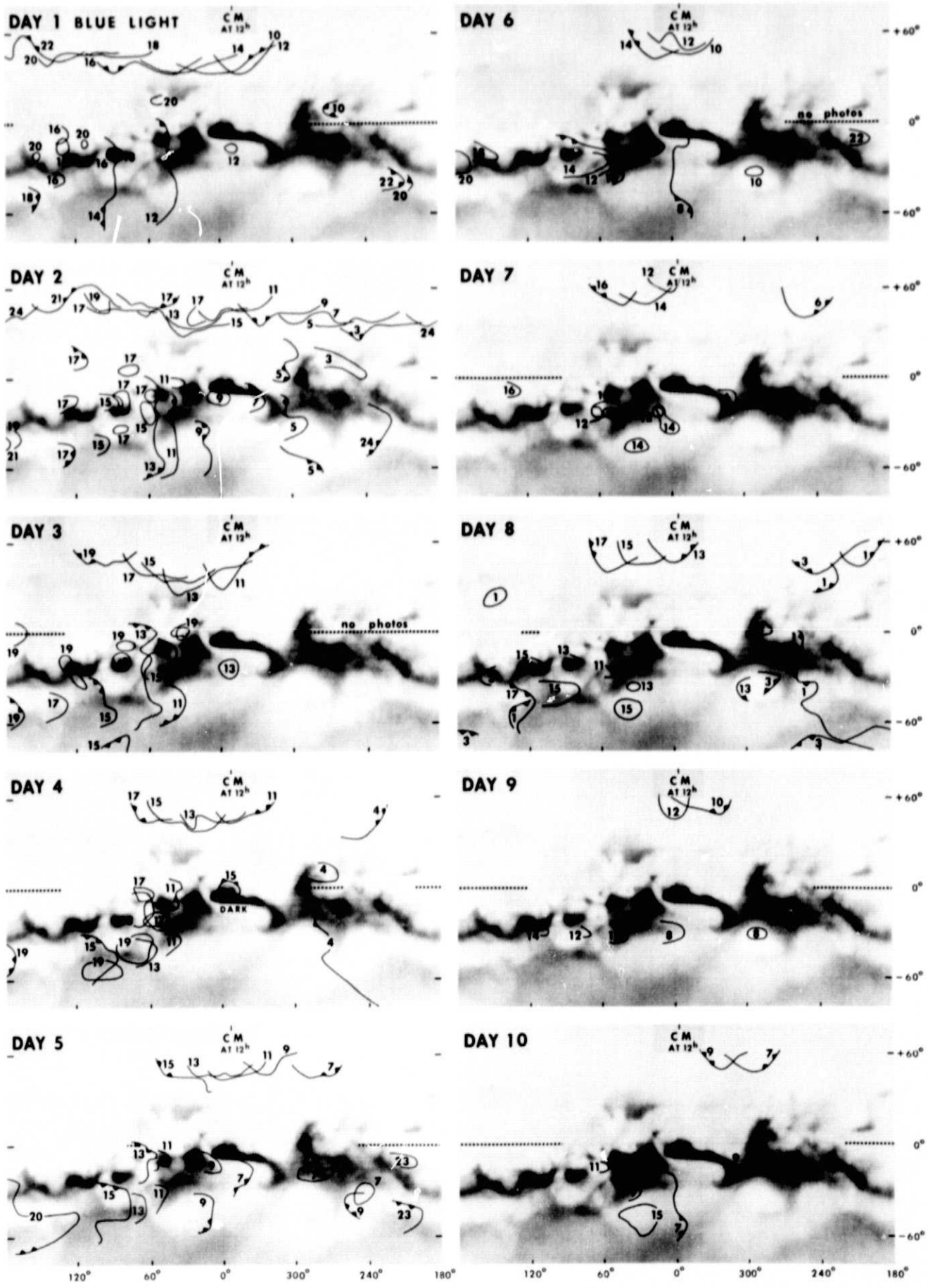

DAY 1 BLUE LIGHT
DAY 2
DAY 3
DAY 4
DAY 5
DAY 6
DAY 7
DAY 8
DAY 9
DAY 10
CM AT 12h
no photos
DARK
+60°
0°
-60°
120°
60°
0°
300°
240°
180°

FIG. 2

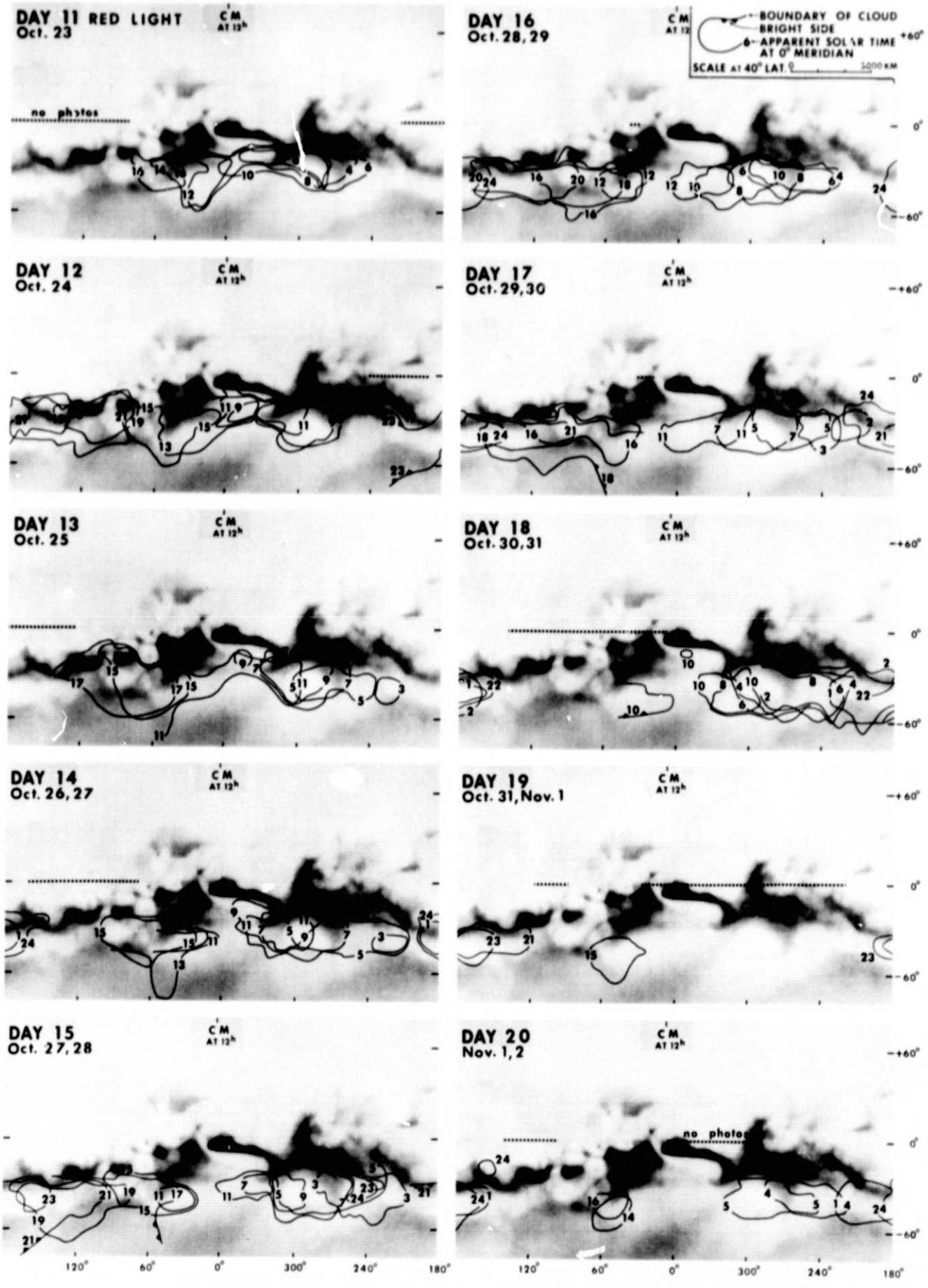

DAY 11 RED LIGHT
Oct. 23
CM AT 12h
no photos
DAY 16
Oct. 28, 29
BOUNDARY OF CLOUD
BRIGHT SIDE
APPARENT SOLAR TIME AT 0° MERIDIAN
SCALE AT 40° LAT.
5000 KM
DAY 12
Oct. 24
DAY 17
Oct. 29, 30
DAY 13
Oct. 25
DAY 18
Oct. 30, 31
DAY 14
Oct. 26, 27
DAY 19
Oct. 31, Nov. 1
DAY 15
Oct. 27, 28
DAY 20
Nov. 1, 2
+60°
0°
-60°
120°
60°
0°
300°
240°
180°

FIG. 3

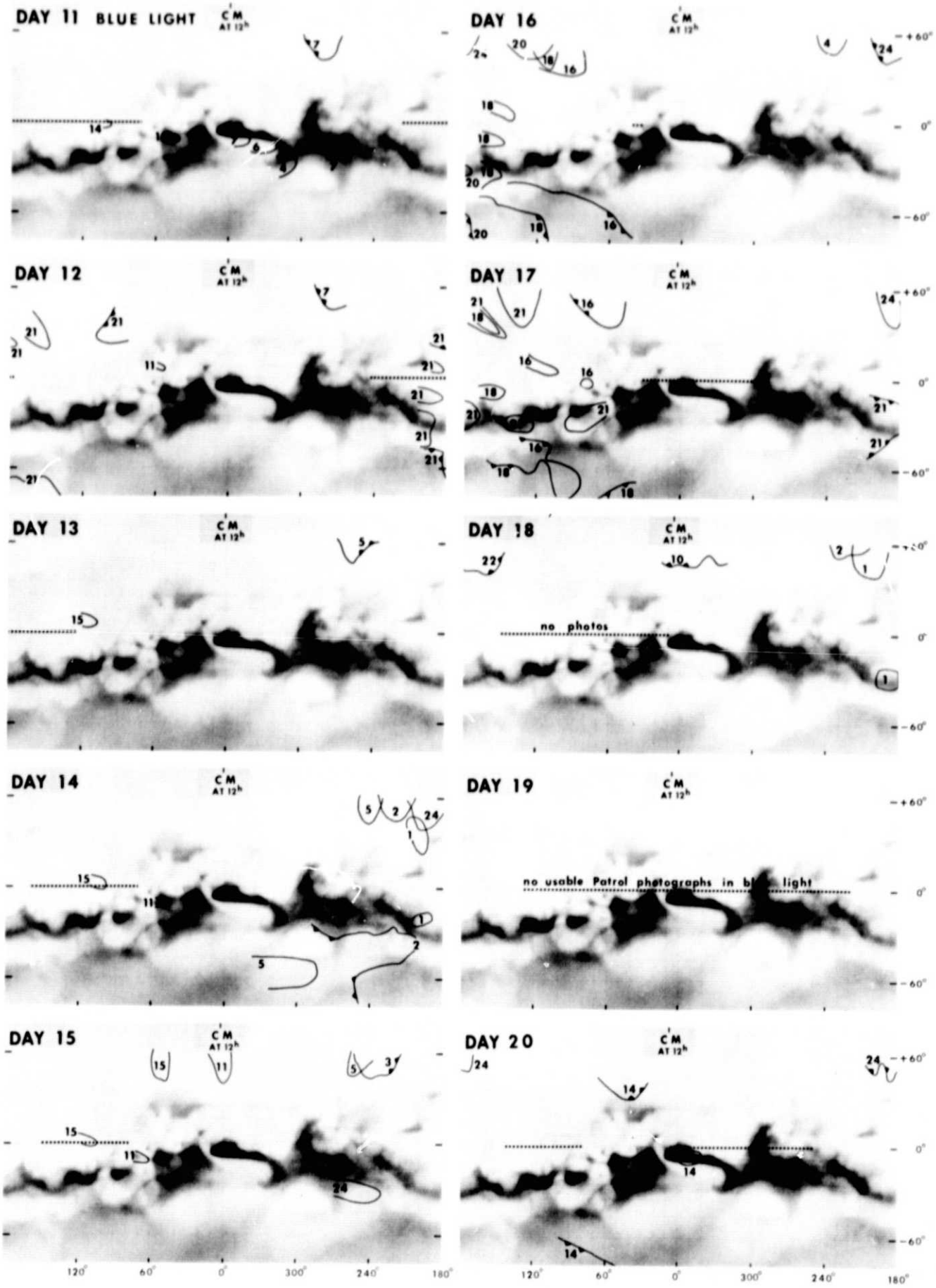
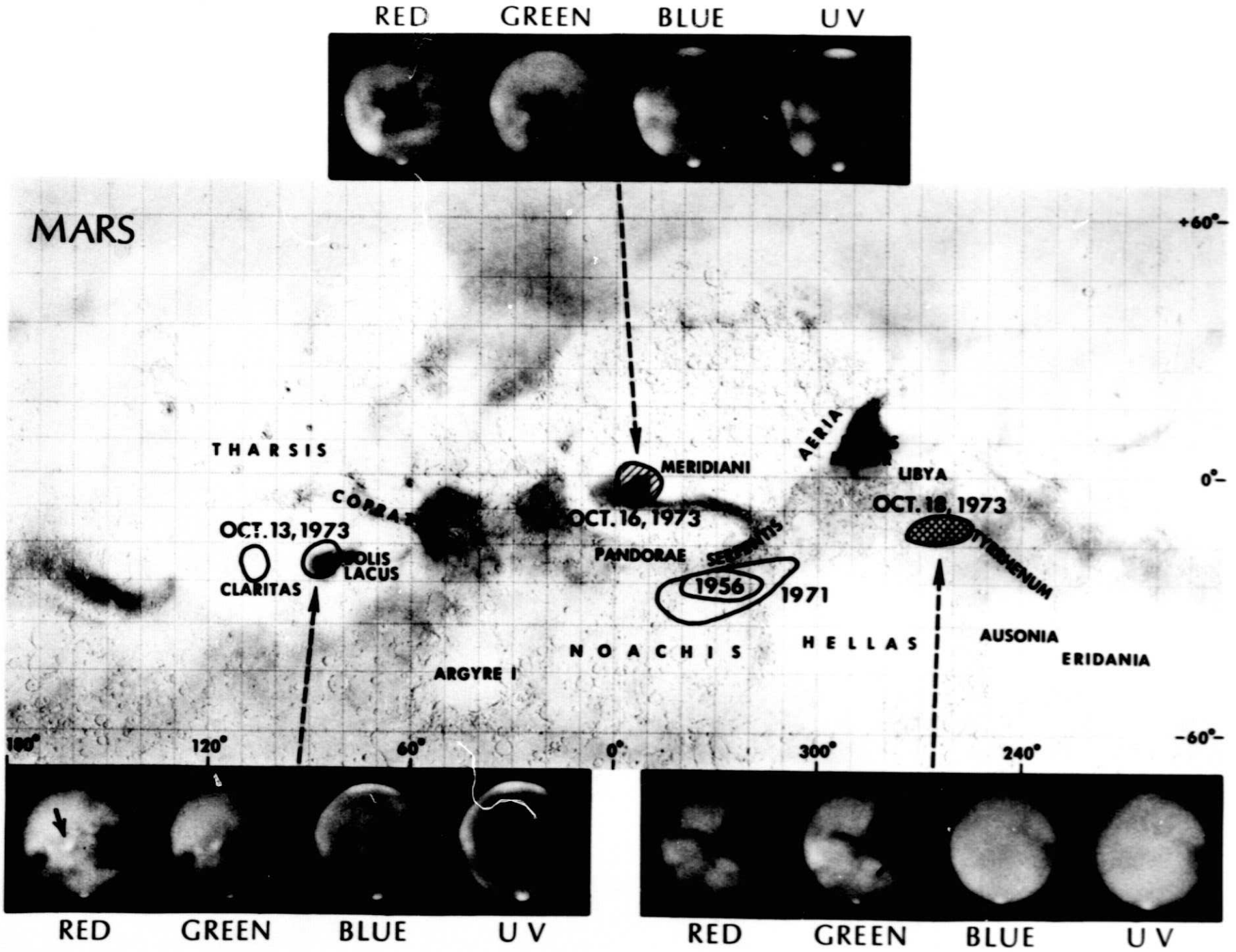

DAY 11 BLUE LIGHT
DAY 12
DAY 13
DAY 14
DAY 15
DAY 16
DAY 17
DAY 18
DAY 19
DAY 20
CM AT 12h
no photos
no usable Patrol photographs in blue light
+60°
0°
-60°
120°
60°
0°
300°
240°
180°

FIG. 4


RED
GREEN
BLUE
UV
MARS
+60°
0°
-60°
THARSIS
AERIA
MERIDIANI
LIBYA
CORRA
OCT. 16, 1973
OCT. 18, 1973
OCT. 13, 1973
PANDORAE
SEPTENTRIONALIS
1956
1971
CLARITAS
LACUS
TYRRHENUM
NOACHIS
HELLAS
AUSONIA
ERIDANIA
ARGYRE I
180°
120°
60°
0°
300°
240°
RED
GREEN
BLUE
UV
RED
GREEN
BLUE
UV

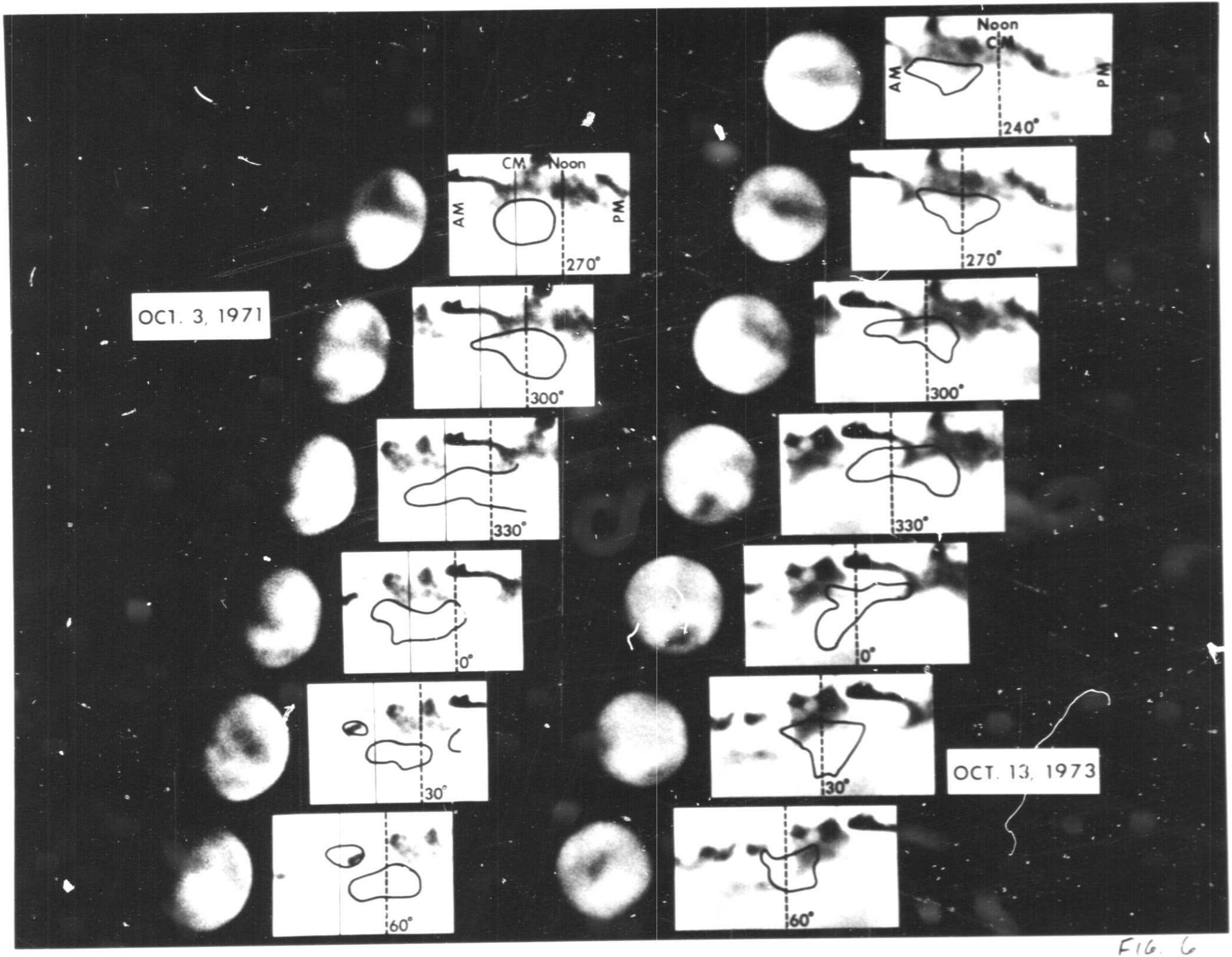

OCT. 3, 1971
CM
Noon
AM
PM
270°
300°
330°
0°
30°
60°
Noon
CM
AM
PM
240°
270°
300°
330°
0°
30°
60°
OCT. 13, 1973

FIG. 6

MARS - 1973

Oct. 13 - Nov. 2